24

Management of Forests for Mitigation of Greenhouse Gas Emissions

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CONTENTS

Executive Summary 775

24.1. Introduction 776

24.2. Role of Forests in the Global Carbon Cycle 776
24.2.1. Status and Change in Forest Area 776
24.2.2. Forest Carbon Pools and Flux 777

24.3. Carbon Mitigation Options 780
24.3.1. Conservation Management 780
24.3.1.1. Controlling Deforestation 780
24.3.1.2. Protection and Conservation of Forests 780
24.3.2. Storage Management 781
24.3.3. Substitution Management 781

24.4. Assessment of C Mitigation Options 782
24.4.1. Steady-State Potential 783
24.4.2. Transient Potential 783
24.4.2.1. Analytical Approach 783
24.4.2.2. Quantities of C Conserved and Sequestered 784

24.5. Projected Costs and Benefits of C Conservation and Sequestration 786
24.5.1. Reducing Deforestation and Protecting Forests 788
24.5.2. Expansion of C Pools and C Transfer to Products 788
24.5.2.1. Carbon Components 790
24.5.2.2. Cost Components 790
24.5.2.3. Monetary Benefits 790
24.5.3. Carbon Sequestration through Silviculture 791
24.5.4. Global Costs 791

24.6. Impacts of Future Climate, Atmospheric CO_2, Land Use, and Human Population on C Conservation and Sequestration 792
24.6.1. Impact on Land Suitability and Availability 792
24.6.2. Impact on Rates of C Conservation and Sequestration 793

24.7. Research and Data Needs 794

References 794

EXECUTIVE SUMMARY

Three categories of promising forestry practices that promote sustainable management of forests and at the same time conserve and sequester carbon (C) are considered in this chapter: (1) management for conservation of existing C pools in forests by slowing deforestation, changing harvesting regimes, and protecting forests from other anthropogenic disturbances; (2) management for expanding C storage by increasing the area and/or C density in native forests, plantations, and agroforestry and/or in wood products; and (3) management for substitution by increasing the transfer of forest biomass C into products such as biofuels and long-lived wood products that can be used instead of fossil-fuel based products. Since the 1992 assessment, significant new information has been developed that improves estimates of the quantities of C that can be conserved or sequestered—and the associated implementation costs of forest sector mitigation strategies—and better identifies limits to the amount of lands available for such mitigation strategies.

- The most effective long-term (>50 years) ways in which to use forests to mitigate the increase in atmospheric CO_2 are to substitute fuelwood for fossil fuels and for energy-expensive materials. However, over the next 50 years or so, substantial opportunities exist to conserve and increase the C store in living trees and wood products (High Confidence).
- Under baseline conditions (today's climate and no change in the estimated available lands over the period of interest), the cumulative amount of C that could potentially be conserved and sequestered over the period 1995–2050 by slowing deforestation (138 Mha) and promoting natural forest regeneration (217 Mha) in the tropics, combined with the implementation of a global forestation program (345 Mha of plantations and agroforestry), would be about 60 to 87 Gt—equivalent to 12–15% of the projected (IPCC 1992a scenario) cumulative fossil fuel C emissions over the same period (Medium Confidence).
- The annual C gain from the above program would reach about 2.2 Gt/yr by 2050, or about four times the value of 0.5 Gt C/yr estimated in the 1992 assessment. The gradual increase over time occurs because of the time it takes for programs to be implemented and the relatively slow rate at which C accumulates in forest systems (Medium Confidence).
- Uncertainty associated with the C conservation and sequestration estimates is caused mainly by high uncertainty in estimating land availability for forestation and regeneration programs and the rate at which tropical deforestation can actually be reduced; estimates of the net amount of C per unit area conserved or sequestered under a particular management scheme are more certain (High Confidence).
- The tropics have the potential to conserve and sequester the largest quantity of C—45–72 Gt—more than half of which would be due to promoting natural forest regeneration and slowing deforestation. Tropical America has the largest potential for C conservation and sequestration (46% of the tropical total), followed by tropical Asia (34%) and tropical Africa (20%). The temperate and boreal zones could sequester about 13 Gt and 2.4 Gt, respectively—mainly in the United States, temperate Asia, the former Soviet Union (FSU), China, and New Zealand (Medium Confidence).
- The cumulative cost—excluding land costs and other transaction costs—to conserve and sequester the above amounts of C range from US$247 billion to $302 billion at a unit cost of about $2–8/t C. These unit costs are considerably lower than those in the 1992 assessment, which ranged from $8/t C in tropical latitudes to $28 in non-U.S. Organisation for Economic Cooperation and Development (OECD) countries. Transaction costs may significantly increase these estimated costs (Low Confidence).
- Costs per unit of C sequestered or conserved generally increase from low- to high-latitude nations (High Confidence) and from slowing deforestation and promoting regeneration to establishing plantations (Low Confidence). The latter trend may not hold if transaction costs of slowing deforestation are excessive.
- These cost estimates, although benefitting from improved data and methodology since the first assessment, generally represent only the cost of direct forest practices. These costs could be several times higher if land and opportunity costs and/or the costs of establishing infrastructure, protective fencing, training programs, and tree nurseries were included; on the other hand, costs could be offset by revenues from timber and non-timber products. No complete cost estimates are available (Medium Confidence).
- Under conditions of climate and land-use change as projected by the IMAGE 2.0 model ("conventional wisdom" scenario, akin to the IPCC 1992a scenario), the carbon conservation and sequestration potential may be somewhat less than estimated under baseline conditions because less land may be available in the tropics, unless land was secured for mitigation measures or sustainable agriculture/agroforestry systems were widely adopted, and sequestration by new forests in temperate and boreal regions may be offset by transient decline and the loss of carbon from existing forests in response to climate change (Medium Confidence).

24.1. Introduction

Forest ecosystems merit consideration in biogenic mitigation strategies because they can be both sources and sinks of CO_2, the most abundant greenhouse gas (GHG). Currently the world's forests are estimated to be a net C source, primarily because of deforestation and forest degradation in the tropics. Temperate and boreal forests are a C sink because many are recovering from past natural and human disturbances, and they are actively managed (Dixon *et al.*, 1994a). However, there is the potential to lessen projected C emissions by protecting and conserving the C pools in existing forests; to create C sinks by expanding C storage capacities, by increasing the area and/or C density of native forests, plantations, and agroforests, and by increasing the total pool of wood products; and to substitute fossil fuels with fuelwood from sustainably managed forests, short-lived wood products with long-lived wood products, and energy-expensive materials with wood (Grainger, 1988; Dixon *et al.*, 1991; IPCC, 1992; Winjum *et al.*, 1992a, 1992b; Nilsson and Schopfhauser, 1995; Trexler and Haugen, 1995). This chapter reviews the potential magnitude of forest-based CO_2 stabilization options based on various assessments in recent years; the costs to implement such programs; and the effects of a changed climate, atmospheric composition, and human demographics on the potential amount of C conserved and sequestered. The chapter also suggests how to devise improved assessments to formulate practical strategies.

The first supplemental report to IPCC (Houghton *et al.*, 1992) suggested that aggressive forest-sector mitigation strategies involving planting trees on 1 Gha (Gha = 10^9 ha) of land, combined with phasing out net deforestation by 2025, could create a net C sink of about 0.5 Gt/yr (10^{15} g = 1 Pg) by 2050—a value that could then be maintained through the rest of the 21st century. Since 1992, new research results and information have improved the accuracy of estimates of the quantities of C that potentially can be conserved (maintain C on the land) and sequestered (increase C on the land) through the implementation of forest-sector mitigation strategies, provided new estimates of the costs associated with the mitigation options, and made more-accurate estimates of the land available for such strategies. A review and analysis of new research results and information are the main purposes of this chapter.

Scope of the Chapter

This chapter reviews the potential to manage present and potential forest lands capable of supporting tree cover to conserve and sequester C. Urban forests are not included because they contain and accumulate a very small amount of C compared to other forest lands, although they can contribute to reduced energy consumption (Rowntree and Nowak, 1991). Forest management here includes an array of practices in native forests and on nonforested lands—such as protection, forestation (afforestation and reforestation), intermediate silvicultural treatments (e.g., thinning, fertilization), harvesting, and agroforestry—that promote sustained production of goods and services. These promising forestry practices are considered in arriving at national, regional, and global estimates of forest-sector potential for mitigating the accumulation of primarily CO_2, and to some degree other GHGs, in the atmosphere.

Forest lands are divided into three latitudinal belts: high or boreal (approximately 50–75° N and S latitude), mid or temperate (approximately 25–50° N and S latitude), and low or tropical (approximately 0–25°N and S latitude). Nations or regions are grouped into these belts on the basis of the approximate geographic location of their forests.

The key parameters in any assessment of mitigation strategies are the amount of C per unit area of land that can be conserved or sequestered in vegetation and soil under given site conditions and a given management option; the time period over which this C can be conserved or sequestered; the amount of suitable and available land; the mitigation costs; and the different lifetimes of the end wood products. Literature data and discussions on these factors are presented in this chapter, although large uncertainties exist in some data (Houghton *et al.*, 1993; Iverson *et al.*, 1993; Trexler and Haugen, 1995). Estimates of the mitigation potential and costs of the various options are generated from literature sources. Because no studies to date have addressed the mitigation potential of forests under a changed climate and atmosphere, the mitigation potential could be assessed only under a baseline condition, with no effects of climate change or increased atmospheric CO_2. More briefly, the effects of a changed climate, atmospheric composition, demographics, and land use on the mitigation potential are considered based on interpretation of trends from a global integrated assessment model (Alcamo, 1994). A discussion of new research directions to improve assessments concludes the chapter.

24.2. Role of Forests in the Global Carbon Cycle

24.2.1. Status and Change in Forest Area

Forests cover about 4.1 Gha of the Earth (Dixon *et al.*, 1994a, with revisions based on Kolchugina and Vinson, 1995). Most of the forests are in the low latitudes (43%), followed by the high latitudes (32%) and mid-latitudes (25%). Forest plantations are currently estimated to occupy about 0.1 Gha of land. Although the technology for managing forests is well developed, today only about 11% of the world's forests are managed for goods and services (World Resources Institute, 1990; Winjum *et al.*, 1992a). The extent of management, however, varies by region: About 20% of the mid-latitude forests, 17% of the high-latitude forests, and less than 4% of the low-latitude forests are managed. In addition, large areas of land technically suitable for forests are degraded or are otherwise underproducing because of human misuse (Winjum *et al.*, 1992a). Even though some degraded lands are unsuitable for forestry, there is considerable potential to mitigate CO_2 by better management of forest lands for C conservation, storage, and substitution. However, a balance between objectives for

mitigation and other uses of forests must be achieved (see Section 24.3).

The status and areas of forests change, even in the absence of human interference. However, humans influence the pace and extent of change as forests are subjected to controlled and uncontrolled uses (overharvesting and degradation); large-scale occurrence of wildfire; fire control; pest and disease outbreaks; and conversion to non-forest use, particularly agriculture and pastures. At the same time, some areas of harvested and degraded forests or agricultural and pasture lands are abandoned and revert naturally or are converted to forests or plantations. In high latitudes, the area of forests is undergoing little change (Kolchugina and Vinson, 1995). In mid-latitudes, there is a net gain of about 0.7 Mha/yr of forests, mostly in Europe and China (Dixon *et al.*, 1994a). Furthermore, many of the forests in high and mid-latitudes have been harvested (clear cut or selective cut) in the far to near past and are now generally in a stage of regeneration and regrowth (Apps and Kurz, 1991; Birdsey, 1992; Heath *et al.*, 1993; Kauppi *et al.*, 1992, 1995; Kolchugina and Vinson, 1993, 1995).

Low-latitude forests are experiencing high rates of loss—currently estimated to be about 15.4 Mha/yr during 1980–90, but with large uncertainties (FAO, 1993). Much of the deforested area is converted to new agricultural or pasture lands, which often replace degraded agricultural lands that may or may not be capable of supporting tree cover (Brown, 1993; Dale *et al.*, 1993). However, in a few tropical countries, deforestation has decreased during the last decade [e.g., India (Ravindranath and Hall, 1994; see also Section 24.3.1.1), Brazil (Skole and Tucker, 1993), and Thailand (Dixon *et al.*, 1994a)]. In addition to deforestation, large areas of forests are harvested and degraded. For example, about 5.9 Mha/yr of low-latitude forests were logged during 1986–90, and most logging occurred in mature forests (83%) rather than secondary forests (FAO, 1993). These harvested forests can regenerate and accumulate C if they are protected or are relatively inaccessible to human populations, but many of them become degraded (e.g., Lanly, 1982; Brown *et al.*, 1993b, 1994). Forest degradation, resulting in a loss of biomass C, occurs through damage to residual trees and soil from poor logging practices, log poaching, fuelwood collection, overgrazing, and anthropogenic fire (Goldammer, 1990, 1993; Brown *et al.*, 1991, 1993b; FAO, 1993; Flint and Richards, 1994). Similar anthropogenic disturbances most likely have occurred and are still occurring in other forest regions of the world. This means that few forested areas in the world are presently undisturbed by humans; this fact has implications for their present role in the global C cycle and future C sequestration potentials (Lugo and Brown, 1986, 1992; Brown *et al.*, 1992; Wood, 1993).

24.2.2. *Forest Carbon Pools and Flux*

The world's natural forests contain vast quantities of organic C, with an estimated 330 Gt C in vegetation (live and dead, above and belowground), 660 Gt C in soil (mineral soil plus organic horizon) (Table 24-1), and another 10 Gt C in plantations. Estimates of all C pool components, using published factors (see Dixon *et al.*, 1994a), were made in arriving at these C pool estimates. However, some components are poorly known, such as the C pool in woody detritus and slash and dead roots—which undoubtedly adds to the uncertainty in the estimated total C pool. Most of the C pool in vegetation is located in the low-latitude forests (64%), whereas most of the soil C pool is located in high-latitude forests (52%). Country-level analyses demonstrate that forests already play an important role in the C budget of some countries by offsetting significant amounts of fossil fuel emissions (Box 24-1).

Table 24-1: *Estimated C pools and flux in forest vegetation (above and belowground living and dead mass, including woody debris) and soils (O horizon and mineral soil to 1-m depth) in forests of the world. Dates of estimate vary by country and region, but cover the decade of the 1980s. Estimates are based on complete C budgets in all latitudes, using data from original source or from adjustments for completeness.*

Latitudinal Belt	C Pools (Gt) Vegetation	C Pools (Gt) Soils	C Flux (Gt/yr)
High			
FSU[1]	46	123	+0.3 to +0.5
Canada[2]	12	211	+0.08
Alaska[3]	2	11	*
Subtotal	**60**	**345**	**+0.48 ± 0.2**
Mid			
USA[3]	15	21	+0.1 to +0.25
Europe[4]	9	25	+0.09 to +0.12
China[5]	17	16	-0.02
Australia[6]	18	33	trace
Subtotal	**59**	**95**	**+0.26 ± 0.1**
Low			
Asia[7]	41–54	43	-0.50 to -0.90
Africa[8]	52	63	-0.25 to -0.45
America[8]	119	110	-0.50 to -0.70
Subtotal	**212**	**216**	**-1.65 ± 0.40**
Total	**331**	**656**	**-0.9 ± 0.5**

* Included with USA.
[1] FSU = Former Soviet Union; Kolchugina and Vinson, 1993, 1995.
[2] Apps and Kurz, 1991; Kurz and Apps, 1993; Kurz *et al.*, 1992.
[3] Birdsey, 1992; Birdsey *et al.*, 1993; Dixon *et al.*, 1994a; Turner *et al.*, 1995a.
[4] Dixon *et al.*, 1994a; Kauppi *et al.*, 1992; includes Nordic countries.
[5] Xu, 1992.
[6] Gifford *et al.*, 1992.
[7] Brown *et al.*, 1993b; Dixon *et al.*, 1994a; FAO, 1993; Houghton, 1995.
[8] Dixon *et al.*, 1994a; FAO, 1993; Houghton, 1995.

Box 24-1. Estimates of Current C Sequestration Rates by Forests in Relation to the Size of their C Pool and Annual Emissions from Fossil Fuel Burning

Some countries that signed the Framework Convention on Climate Change have made detailed calculations of the amounts of C currently being sequestered by their forests, taking into account the historic rates of forest planting and harvesting, and the dynamics of forest growth and the flow of C to litter and forest product pools (see Table 24-2 for a sampling). In Britain, New Zealand, and India, C is being sequestered as a result of recent forestation programs—whereas in Finland, C is being sequestered by natural regeneration and regrowth of forests because the annual growth is greater than the annual harvest. In Canada, carbon sequestration is occurring as a result of recovery from previous fires. In 17 West European countries, forestry offsets from 1–2% (The Netherlands, Britain, Germany) to about 90% (Sweden) of fossil fuel emissions (Burschel *et al.*, 1993; Kauppi and Tomppo, 1993).

Table 24-2: *Carbon storage and C sequestration rates in forests, and national C emissions.*

Country	Year	Carbon Stored in Trees and Litter (Mt)	Fossil Fuel–C Emissions (Mt/yr)	Rate of C Removed by Forests (Mt/yr)[1]	Source
Britain	1990	60[2]	164	2.5 (1.5)	Cannell and Dewar, 1995
New Zealand	1990	113	8	3.5 (44)	Maclaren and Wakelin, 1991
Finland	1992	978	18	5.0 (28)	Karjalainen and Kellomäki, 1993
Germany	1990	1500–2000	268	5.4 (2)	Federal Ministry for Env., 1994
Canada	1986	12000	136	51.0 (37.5)	Kurz *et al.*, 1992
India	1986	10000	137	5.0 (3.6)	Makundi *et al.*, 1996
Poland	1990	1113	131	8.0 (6)	Galinski and Kuppers, 1994
USA	1990	18585	1300	80 (6)	Turner *et al.*, 1995a

[1]Value in parentheses is the percentage of fossil fuel emissions removed by forests.
[2]Plantation forests only; all forests and woodlands contain ~87 Mt C in the trees alone (Milne, pers. comm.).

Mid- and high-latitude forests are currently estimated to be a net C sink of about 0.7 ± 0.2 Gt/yr because forests at these latitudes are, on average, composed of relatively young classes with higher rates of net production as they recover from past disturbances such as abandonment of agricultural land, harvesting, and wildfires; a larger proportion of these forests are actively managed (i.e., established, tended, and protected); and some areas may be responding to increased levels of atmospheric CO_2 and nitrogen (N) (fertilization effect) (Apps and Kurz, 1991; Birdsey, 1992; Kauppi *et al.*, 1992, 1995; Xu, 1992; Heath *et al.*, 1993; Kolchugina and Vinson, 1993, 1995; Kurz and Apps, 1993; Turner *et al.*, 1995a). Because secondary forests in the mid-and high latitudes are rebuilding C pools, there is a finite potential over which this C sequestration can occur. For example, the current C sink in European forests may disappear within 50 to 100 years (Kauppi *et al.*, 1992), although others suggest that it may take forests as long as several centuries to millennia to reach a C steady state in all components (Lugo and Brown, 1986).

Low-latitude forests are estimated to be a relatively large net C source of 1.6 ± 0.4 Gt/yr in 1990 (Table 24-1), caused by deforestation, harvesting, and gradual degradation of the growing stock. Although this is the best estimate available in the literature, we use this value with recognition that there are many reasons to believe that the uncertainty is larger than shown (Lugo and Brown, 1992). Unlike the high- and mid-latitude forests—where estimated C fluxes are based, for the most part, on data from periodic national inventories (i.e., field measurements)—the estimated C flux for low-latitude forests is based on a model that tracks only forests that are cleared or harvested with regrowth. In the model, C accumulates in regrowing forests for up to 50–100 years. Furthermore, the model assumes that all other forests not reportedly affected by humans during the period of model simulation (about 1850–1990) are in C steady state (Houghton *et al.*, 1987). Recent work questions this steady-state assumption and implies that the net tropical C flux could be higher or lower than that reported here, depending upon the relative contribution of forest lands that are still gaining C through recovery from past human disturbances or are losing C through continued human use (Brown *et al.*, 1992; Lugo and Brown, 1992).

The error terms associated with the C flux estimates in Table 24-1 are derived from the range of values resulting from the use of different assumptions in the C budgets for a given country or region. They do not represent errors derived from statistical procedures. Error enters the flux estimation procedure through uncertainties and biases in the primary data, and these compound as the data are combined to draw inferences (Robinson, 1989). Many estimates for components of the forest-sector C budget are probably known no better than ±30% of

their mean, and others may be known no better than ± 50% or more of their means (Robinson, 1989). These errors are compounded in making global estimates of C flux—perhaps to large proportions—but to what extent is presently unknown. Clearly, there is a need to apply error-estimation techniques to calculations of the forest-sector C budgets to provide more precise estimates of the C flux.

The global average net C flux and uncertainty term from the world's forests reported here of -0.9 ± 0.5 Gt/yr (a net C source; Table 24-1) is less than that reported in Schimel *et al.* (1995) of -1.1 ± 1.1 Gt/yr. The main reason for this difference is in the interpretation and use of results from the literature. A major difference exists between the respective estimates used for the C flux of boreal forests, particularly for the FSU. In this chapter (Table 24-1), the studies of Kolchugina and Vinson (1993, 1995) were used, which include a complete forest-sector C budget and use more current data; Schimel *et al.* (1995) relied more on the work by Melillo *et al.* (1988) and Krankina and Dixon (1994). These two latter studies were not used in arriving at the estimate in Table 24-1 for the mean C flux for boreal forests because the Melillo *et al.* (1988) results were for an earlier period (prior to 1980) and the Krankina and Dixon (1994) study did not consider all components of the C budget. The main source of difference in the uncertainty term is the error assigned to the tropical net flux: We report an uncertainty term around the tropical flux of ± 0.4 Gt/yr based on Houghton (1995), whereas Schimel *et al.* (1995) report a term of ± 1.0 Gt/yr based on an assumption that the uncertainty was greater than 50% for reasons given above. However, as discussed above, none of these uncertainty terms may reflect the true precision of the estimates.

Substitution of the net C flux for forests reported here (Table 24-1) into the global C budget (Schimel *et al.*, 1995) results in an imbalance of 1.2 ± 1.0 Gt/yr. Because the primary data for C budgets for temperate and boreal countries originate from national forest inventories, any increased growth of forests due to CO_2 and N fertilization and climatic effects is already included in the net flux estimates. In other words, the reported C sink for mid- to high-latitude forests (Table 24-1) includes all these factors already because the data, for the most part, come from repeated forest inventories. In contrast, the tropical forest C flux is based on a model and not on repeated forest inventories. Furthermore, the model does not include effects of CO_2 and N fertilization and climate. This leads to the conclusion that a large part of the imbalance in the global C budget must be due to a C sink in tropical latitudes, which also has been suggested by others (Lugo and Brown, 1992; Taylor and Lloyd, 1992; Schimel *et al.*, 1995). This could be due to a combination of stimulated regrowth from CO_2 and N fertilization and climate, as well as more extensive forest regrowth. It is clear that to resolve this issue, repeated national forest inventories, with permanent plots, are needed in tropical latitudes.

Most biomass burning in tropical forests is intentional and is associated with land-clearing practices. However, wildfires also occur in tropical moist and dry forests; these also are largely of anthropogenic origin (Goldammer, 1990). Factors contributing to increased wildfires in tropical moist forests are the drying of organic materials (fuel) on the forest floor of degraded forests (increased exposure to solar radiation) and changes in the microclimate of forest remnants surrounded by deforested areas (Fearnside, 1990; Kaufman and Uhl, 1990). Significant areas of temperate and boreal forest also are burned by wildfires of natural or anthropogenic origin or prescribed (controlled) fires (Levine, 1991; Auclair and Carter, 1993; Dixon and Krankina, 1993).

The destruction of forest biomass by burning releases, in addition to CO_2, GHGs that are byproducts of incomplete combustion—namely, methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), and nitrogen oxide (NO_x), among others. Whereas complex accounting models and forest inventories are needed to estimate the losses and gains of C over different timescales, the emissions of these other gases from biomass burning are instantaneous, absolute transfers from the biosphere to the atmosphere (Crutzen *et al.*, 1979; Crutzen and Andreae, 1990). Globally, biomass burning contributes about 10% of total annual CH_4 emission, 10–20% of total annual N_2O emission, and about half of the CO emission—and so has a significant effect on atmospheric chemistry, especially on tropospheric ozone levels (Houghton *et al.*, 1992). Biomass burning also transfers a fraction (up to 10%) of the C to an inert form (charcoal) with a turnover time that is practically infinite.

Many boreal forests grow on peat or organic soils that contain very large amounts of C. Undisturbed anaerobic, northern peatlands are sinks for CO_2 and sources of CH_4 (Matthews and Fung, 1987; see Chapter 6). Drainage of these soils to improve forest productivity virtually stops CH_4 emissions but initiates rapid CO_2 loss by aerobic decomposition. Draining peat soils for forest establishment can produce a C loss from these soils that exceeds C stored in the forest if 20–30 cm of peat decompose as a result of the drainage (Cannell *et al.*, 1993). There also are vast areas of forested peatlands in the tropics; how they will be affected by drainage is largely unknown (see Chapter 6).

In addition to managing forest vegetation to conserve or sequester C, there also is an opportunity to manage forest soils for the same purposes (Johnson, 1992; Lugo and Brown, 1993; Dixon *et al.*, 1994a). Regional and national programs to conserve soil, including organic matter, have been implemented worldwide (Dixon *et al.*, 1994a). Management practices to maintain, restore, and enlarge forest soil C pools include (after Johnson, 1992) enhancement of soil fertility; concentration of agriculture and reduction of slash-and-burn practices; preservation of wetlands; minimization of site disturbance during harvest operations to retain organic matter; forestation of degraded and nondegraded sites; and any practice that reduces soil aeration, heating, and drying. Several long-term experiments demonstrate that C can accrete in the soil at rates of 0.5 to 2.0 t/ha/yr (Dixon *et al.*, 1994a).

24.3. Carbon Mitigation Options

It should be emphasized at the outset that the objective of the practices presented here—that is, to foster C conservation and sequestration in forests—is but one of a variety of objectives for forest management that needs to be balanced with other objectives. However, most forest-sector actions that promote C conservation and sequestration make good social, economic, and ecological sense even in the absence of climate-change considerations. Other objectives for managing forests include sustainable development, industrial wood and fuel production, traditional forest uses, protection of natural resources (e.g., biodiversity, water, and soil), recreation, rehabilitation of damaged lands, and the like; C conservation and sequestration resulting from managing for these objectives will be an added benefit. For example, although the primary reasons for the establishment of plantations on non-forested land have been economic development, provision of new wood resources (e.g., Portugal, Swaziland), replacement of diminishing or less-productive natural forests (e.g., Australia, Brazil, Malaysia), import substitution (e.g., United Kingdom, Zimbabwe), generation of export income (e.g., Chile, New Zealand), or rehabilitation projects (Evans, 1990; Kanowski and Savill, 1992; Kanowski *et al.*, 1992), they also are considered an important means for sequestering C.

There are basically three categories of forest management practices that can be employed to curb the rate of increase in CO_2 in the atmosphere. These categories are:

1) Management for conservation (prevent emissions)
2) Management for storage (short-term measures over the next 50 years or so)
3) Management for substitution (long-term measures).

The goal of conservation management is mainly to conserve existing C pools in forests as much as possible through options such as controlling deforestation, protecting forests in reserves, changing harvesting regimes, and controlling other anthropogenic disturbances such as fire and pest outbreaks. The goal of storage management is to expand the storage of C in forest ecosystems by increasing the area and/or C density of natural and plantation forests and increasing storage in durable wood products. Substitution management aims at increasing the transfer of forest biomass C into products (e.g., construction materials and biofuels) that can replace fossil-fuel-based energy and products, cement-based products, and other building materials.

24.3.1. Conservation Management

24.3.1.1. Controlling Deforestation

Slowing the rate of loss and degradation of existing forests could reduce CO_2 emissions substantially. The most significant C conservation clearly would occur in the tropics, where each Mha of deforestation produces about a 0.1 Gt C net flux (flux from Table 24-1, divided by area of deforestation of 15.4 Mha/yr). Because the burning of biomass usually accompanies deforestation, slowing deforestation also would reduce emissions of other GHGs.

Reducing tropical deforestation and forest degradation rates would require action to reduce the pressures for land and commodities while increasing the protection of remaining forests for the purposes of conservation and timber production. Most deforestation and degradation is caused by the expansion and degradation of arable and grazing lands and subsistence and commodity demand for wood products—which in turn are a response to the underlying pressures of population growth, socioeconomic development, and political forces. Thus, programs to reduce deforestation must be accompanied by measures that increase agricultural productivity and sustainability, as well as initiatives to slow the rate of population growth (Grainger, 1990; Waggoner, 1994; see also Chapters 13, 15, and 23) and deal with the socioeconomic and political issues.

Although reducing deforestation in the tropics may appear to be a difficult task, there are countries where this is happening (e.g., Brazil, India, Thailand). An example of note is India, where net deforestation has been reduced significantly. Despite its high population density and growth rate, India has succeeded in stabilizing the area under forest during the last decade at about 64 Mha, about 19% of its land area (Ravindranath and Hall, 1994). This stabilization does not mean deforestation of native forests has ceased but rather that loss of native forests is balanced by establishment of plantations (see Chapter 15). This has been achieved by strong forest conservation legislation, a large forestation program, and community awareness.

Past international efforts to curb deforestation, such as the Tropical Forestry Action Plan, have met with limited success (Trexler and Haugen, 1995). Major factors are the absence of comprehensive agricultural policies that meet the needs of resource-poor farmers and the growing global demand for food, fiber, and fuel for the increasing human population (Brown, 1993; Grainger, 1993). Deforestation has been viewed as largely a forestry and conservation problem, and tackling the symptoms rather than the root causes is an incomplete strategy. Global action to mitigate emissions of C by conserving C pools may lead to more interest and success in controlling deforestation and making agriculture more sustainable.

24.3.1.2. Protection and Conservation of Forests

In recent years, there has been significant expansion of "protected areas" into areas of both mature and secondary forests for conservation of biodiversity and sustainable timber production (presently about 10% of the forest land; World Conservation Monitoring Centre, 1992). Carbon pools should remain the same or increase in size in these areas, depending on their present age-class distribution. New protected areas should include those that contain large C pools, such as forests growing on peat soils at high and low latitudes, and high-biomass old-growth forests.

Two biologically significant forest regions that have received attention as C reservoirs in recent years are the Amazon Basin of Brazil and the forests of the FSU (Fearnside, 1992; Kolchugina and Vinson, 1993, 1995; Krankina and Dixon, 1992). The largest contiguous area of C-dense forests in the world is found in the FSU. These forests are subject to future environmental degradation and harvesting, accelerating the loss of C (Brown *et al.*, 1996). Protection of these forests from harvest without regeneration, uncontrolled fires, and pollutants is a priority of the FSU, but infrastructure and resources there are underdeveloped.

The management of tropical forests for sustainable timber production is likely to increase over the coming decades due to collective action under the auspices of the second International Tropical Timber Agreement (agreed to in January 1994). It also is likely that a trend toward management for sustainable timber production in all of the world's forests will occur in the future. Using forests for sustainable timber production—including extending rotation cycles, reducing waste, implementing soil conservation practices, and using wood in a more C-efficient way—ensures that a large fraction of forest C is conserved. Paper recycling is another strategy with the potential to reduce harvest levels and promote greater C conservation (Turner *et al.*, 1995b).

24.3.2. *Storage Management*

Storage management means increasing the amount of C stored in vegetation (living, above and belowground biomass), soil (litter, dead wood, mineral soil, and peat where important), and durable wood products. Increasing the C pool in vegetation and soil can be accomplished by protecting secondary forests and other degraded forests whose biomass and soil C densities are less than their maximum value and allowing them to sequester C by natural or artificial regeneration and soil enrichment. Other approaches are to establish plantations on non-forested lands; promote natural or assisted regeneration in secondary forests, followed by protection; or increase tree cover on agricultural or pasture lands (agroforestry) for environmental protection and local needs. The C pool in durable wood products can be increased by expanding demand for wood products at a faster rate than the decay of wood and by extending the lifetime of wood products. These measures include timber treatment and the production of long-lasting particle boards (Elliott, 1985).

Sequestering C by storage management produces only a finite C sequestration potential in vegetation and soils, beyond which little additional C can be accumulated. The process may take place over a time period on the order of decades to centuries, depending upon the present age-class of forest, the attainable maximum C density, forest type, species selection, and latitudinal zone. In the long run, this is less helpful than substitution options (see Section 24.3.3), given the expected continuous need to offset future C emissions.

Expansion of C pools through the establishment of plantations is becoming less socially and politically desirable, especially with the global concern for biodiversity and other social, cultural, land-tenure, and economic factors (Nilsson and Schopfhauser, 1995). However, in many situations plantations are the only option, and they can increase local biodiversity through the reestablishment of native species in the understory when they are established on highly degraded lands and are subject to no further management (Lugo *et al*,. 1993; Parrotta, 1993; Allen *et al.*, 1995). These forests can then contribute to the development goals of national forest sectors. Furthermore, if more native forests are to be protected and/or harvesting levels reduced, plantation establishment may become more necessary to offset wood reductions (see Chapter 15).

24.3.3. *Substitution Management*

Substitution management, which has the greatest mitigation potential in the long term (>50 years) (Marland and Marland, 1992; Swisher, 1995), views forests as renewable resources. It focuses on the rate of C sequestration or the transfer of biomass C into products that substitute for or lessen the use of fossil fuels, rather than on increasing the C pool itself (Grainger, 1990; Mixon *et al.*, 1994). This approach involves extending the use of forests for wood products and fuels obtained either by establishing new forests or plantations or by increasing the growth of existing forests through silvicultural treatments (Table 24-3). However, a consideration of growth rates and initial standing stocks of biomass C is critical in determining which existing forests should be used for this purpose (Marland and Marland, 1992). For example, it is better not to convert forests with a large initial standing biomass C and slow growth rates (e.g., old-growth forests) to managed stands because it may take a very long time (up to centuries) until the net C sequestered returns to its initial value (Harmon *et al.*, 1990; Marland and Marland, 1992)—or never, if they are harvested on a rotational basis (Dewar, 1991; Vitousek, 1991; Dewar and Cannell, 1992; Cannell, 1995). In contrast, forests with high growth rates and low-to-medium initial biomass C standing stocks are amenable for conversion to managed forests, with considerable quantities of C sequestered if the harvested wood is directly used (Marland and Marland, 1992). When presented with cleared or disturbed forest lands, any forest management practice that increases the C pools and cycles the C by harvesting wood for substitution of energy-intensive products or fossil fuels will remove CO_2 from the atmosphere on a continuing basis.

In the case of forests established on non-forested lands for energy products such as fuelwood, not only is there an increase in the amount of C stored on the land (Grainger, 1990; Schroeder, 1992) but, if the wood burned as fuel displaces fossil fuel usage, it creates an effective rate of C sequestration in unburned fossil fuels (Hall *et al.*, 1991; Sampson *et al.*, 1993; see also Chapter 19). There must, however, be a net energy return in the total system (Hall *et al.*, 1986; Herendeen and Brown, 1987). The extent to which fuelwood plantations are able to displace fossil fuel use in developed countries will depend on the continued development of highly efficient technologies (e.g., Williams and Larson, 1993) for converting

Table 24-3: Sequestration potential of different forest types (from Nabuurs and Mohren, 1993).

Forest Type	Long-Term Average Quantity of C in All Living Biomass and Forest Products (t/ha)	Long-Term Average Quantity of C in Litter, Dead Wood, and Soil to 100 cm (t/ha)	Average Net Annual Rate of C Accumulation[1] (t/ha/yr)
Tropical Forests			
Heavily logged evergreen rainforest	144	92	2.4
Selectively logged evergreen rainforest	207	102	2.9
Logged rainforest hampered by vines	125	92	0.8
Heavily logged semi-evergreen rainforest	76	76	1.1
Selectively logged semi-evergreen rainforest	151	98	2.0
Pinus caribaea in Brazil and Venezuela	89	90	5.1
P. elliotii in Brazil	111	80	3.9
Temperate Forests			
Picea in central Europe	137	117	2.0
Pseudotsuga in northwest USA	196	143	3.4
P. radiata in New Zealand and Australia	126	97	4.5
P. taeda in southeast USA	59	81	3.2
Mixed deciduous in central Europe	110	105	1.4
Broadleaf forests on old agricultural land	62–111	75–84	2.2–3.4
Boreal Forests			
Picea in Russia	53	139	1.0

[1] C sink over first rotation through net primary production minus decomposition of soil organic matter, litter, dead wood, logging slash, and products.

wood into clean forms of energy like electricity. The extent to which fuelwood plantations will be established on degraded lands in developing countries for the generation of electricity will depend more on other incentives such as rural employment and income generation.

When forests are used to produce sawtimber, plywood, or other industrial wood products, C can be sequestered for long periods. The length of time depends on how the timber is treated and used. The production of wood products often requires much less energy than does production of alternative products like steel, aluminum, and concrete, and there can be a large energy return on investment in wood products. For example, the substitution of composite solid-wood products with load-bearing capacities for steel and concrete can save large amounts of fossil fuels. However, an analysis of the full life cycles of wood products is required to appreciate the impact on net C storage and net C emissions. Over long time periods, the displacement of fossil fuels either directly or through production of low-energy-intensive wood products is likely to be more effective in reducing C emissions than physical storage of C in forests or forest products. For example, substitution of wood grown in plantations for coal in the generation of electricity can avoid C emissions by an amount up to four times the amount of C sequestered in the plantation, depending upon the time period over which coal resources are expected to last (Ravindranath and Hall, 1995). Furthermore, if the wood resource is derived from sustainably managed plantations, other benefits, such as rural jobs and land rehabilitation (if the project is on degraded lands), will accrue (Ravindranath and Hall, 1995).

24.4. Assessment of C Mitigation Options

The potential land area available for the implementation of forest management options for C conservation and sequestration is a function of the technical suitability of the land to grow trees and the actual availability as constrained by socioeconomic factors. Determining the technical suitability of land is conceptually less difficult, being based generally on the region's climatic and edaphic characteristics. However, moving from what is suitable to what is actually available is more difficult because of institutional, economic, demographic, and cultural factors—all of which influence present and future land-use decisions (Trexler and Haugen, 1995).

This section is divided into two parts: steady-state potential, based on estimates of the amount of C that could be conserved and sequestered when all actually available lands (in some cases, only technically suitable lands are considered) are under management and contain their maximum C density for a given

practice; and transient potential, based on estimates of the amount of C that could be conserved and sequestered on all available land subject to reasonable rates of establishment of forest management practices over time.

24.4.1. Steady-State Potential

Most previous estimates of the C sequestration potential are simply the product of the suitable or available land area and the maximum or time-averaged C density (e.g., Grainger, 1988; Postel and Heise, 1988; Sedjo and Solomon, 1989; Winjum *et al.*, 1992a). Using this approach and approximate estimates of areas of land available for reforestation and natural and assisted regeneration, Winjum *et al.* (1992a) estimate that 2.2–5.6 Gt C could be sequestered in the entire high-latitude zone over a 50-year period. In Russia alone, Krankina and Dixon (1994) estimate a potential sequestration of 4.5 Gt C over a 50-year period by replacing hardwood stands with conifers, increasing the productivity of existing forests, and establishing plantations on technically suitable lands. Furthermore, they estimate that exercising fire management and reducing harvest could account for an additional potential C savings of 7.2 Gt over a 50-year period.

On estimates of available land in mid-latitudes, 13.5–27.0 Gt C could be sequestered by forestation and natural regeneration over a 50-year period (Winjum *et al.*, 1992a). In the United States alone, an aggressive program of tree planting on marginal agricultural lands (crops and pastures), increasing windbreaks and shelter belts, and forest management could sequester up to 15 Gt C over about a 40-year period (Sampson, 1992).

At low latitudes, a combination of forestation, agroforestry, and natural or assisted forest regeneration on an estimated 300 to 600 Mha of land considered to be available by Winjum *et al.* (1992a) could conserve and sequester about 36–71 Gt C over 50 years. If all technically suitable lands are considered, more than double this amount could be conserved and sequestered by plantation establishment, converting arable/degraded lands to agroforestry, and protecting existing forests (Houghton *et al.*, 1993; Iverson *et al.*, 1993; Unruh *et al.*, 1993).

Recent country-specific estimates for China, India, Mexico, and Thailand indicate that the available land for establishment of plantations and agroforestry is 172 Mha, 175 Mha, 44 Mha, and 7 Mha, respectively (Masera *et al.*, 1995; Ravindranath and Somashekar, 1995; Wangwacharakul and Bowonwiwat, 1995; Xu, 1995). These estimates of land availability are based on national forest-cover targets for China and India and on technical availability for the other two countries. The C sequestration potential on these lands could be up to about 5 Mt/yr.

24.4.2. Transient Potential

Although the studies cited in Section 24.4.1 set a useful upper bound for the potential for C conservation and sequestration, only a few studies consider the issues of land availability, socioeconomic barriers, the timescale over which C may be sequestered, or realistic or feasible rates of forest establishment or regeneration. At the present rate of successful plantation establishment in the tropics of only 1.8 Mha/yr (FAO, 1993), it would take many decades to achieve the levels of sequestration suggested by Winjum *et al.* (1992a). Similar time frames would be needed for the establishment of agroforestry, as well as large areas of mid- and high-latitude plantations. Once established, reaching maximum C storage would then take up to many decades.

A study by Grainger (1990) focuses on the tropics only. He considers a range of scenarios for conserving and sequestering C, including a combination of forestation and deforestation control, and assumes that all wood harvested from the new plantations would be converted into long-term storage as industrial wood. The study does not consider woody detritus or belowground C, is not regionally explicit, and gives only a partial treatment to land availability. The analysis suggests that sequestering about 3 Gt C/yr (the rate at which it was increasing in the atmosphere in 1980) would require 600 Mha of new forest plantations—roughly the area of degraded lands regarded by Grainger (1988) as physically suitable for plantation establishment.

24.4.2.1. Analytical Approach

Nilsson and Schopfhauser (1995) and Trexler and Haugen (1995) are the only studies suitable for global analysis of the mitigation potential of forests. These studies have been chosen because they are global in nature, include an extensive literature review of the land availability issue, and include feasible rates of establishment of management options. These two studies have been combined to arrive at a global estimate of the potential amount of C that could be conserved and sequestered by different regions of the Earth on an annual and cumulative basis between 1995 and 2050. Nilsson and Schopfhauser (1995) estimate the potential for C sequestration through a feasible global forestation program (Table 24-4). Trexler and Haugen (1995) focus on the tropics only and include the options of slowing deforestation and natural or assisted regeneration of land (followed by protection). Both studies assume aggressive, but unspecified, policy and financial interventions in the forestry sectors, with no future change in climate that might interfere with the proposed strategies. The combined analysis uses data for forestation from Nilsson and Schopfhauser (1995) and data for slowing deforestation and regeneration from Trexler and Haugen (1995).

Nilsson and Schopfhauser (1995) estimate for different countries/regions the amount of land likely to be available, feasible annual planting rates, likely growth rates, and rotation lengths (Table 24-4). They use a growth model, without intensive management, to estimate the quantity of C fixed in aboveground and belowground biomass, litter, and soil organic matter for the period 1995 to 2100. Because the focus of the study was to estimate how much C could be sequestered by a global forestation

Table 24-4: Regional estimates of land availability, average mean annual increment (MAI), rotation length, and planting rate for a global forestation program, including establishment of plantations and agroforestry, to sequester C (data from Nilsson and Schopfhauser, 1995).

Region/ Country	Land Available[1] (Mha)	MAI (m^3/ha/yr)	Rotation Length (yr)	Planting Rate[2] (Mha/yr)
High Latitudes				
Canada[3]	28.3	2.5–8.0	60	1.14
Nordic	0.35	5	60	0.014
FSU	66.5	3	80	1.66
Mid-Latitudes				
USA	21.0	6–15	15–40	0.70
Europe	7.74	6–10	20–60	0.31
China	62.5	2.3	80	2.5
Asia	12.5	12	40	0.50
South Africa	1.9	16	30	0.075
South America	4.6	15	25	0.18
Australia	4.3	6–23	30	0.123
New Zealand	5.0	25	25	0.1
Low Latitudes				
Tr. America	40.8	8–25	20	0.74
Tr. Africa	31.6	8–16	30	0.58
Tr. Asia	57.7	8–16	20	1.05

[1]Full details of sources are provided in Nilsson and Schopfhauser (1995); many of the sources originate from individual countries.
[2]Includes rate of establishment of both plantations and agroforestry systems.
[3]Canada includes not satisfactorily restocked (NSR) forest areas in addition to marginal agricultural lands (Van Kooten, 1991); the low end of the MAI was used for NSR forests.

program only, they make no assumptions about the life expectancy of the wood produced. Further, the amount of C sequestered by this program will be realized only if the forests are harvested at their designated rotation lengths. Considerably higher yields than those reported in Table 24-4, though often possible in plantations, require more intensive management than is likely to be achieved for a large-scale program such as that proposed by Nilsson and Schopfhauser (1995). Similar arguments can be made for shortening the rotation times.

For most high- and mid-latitude countries, the area of actually available land is equated with that technically suitable, or about 215 Mha (Table 24-4). The rather large amount of land available in Canada is from a combination of large areas of not satisfactorily restocked forest lands (19.7 Mha) and marginal agricultural lands (8.6 Mha; Van Kooten, 1991). In low-latitude countries, Nilsson and Schopfhauser estimate actual availability (130 Mha) to be only 6% or so of those lands deemed suitable (2,228 Mha) because of additional cultural, social, and economic constraints (Trexler and Haugen, 1995). The global estimate of 345 Mha of actually available lands for plantations and agroforestry is similar to the low end of the estimated range of 375 to 750 Mha offered by Winjum *et al.* (1992a) for the same forestry practices.

The assumed establishment rates of 8.3 Mha/yr for plantations and 1.4 Mha/yr for agroforestry [estimated from land available, plantation period, and rotation length; see Nilsson and Schopfhauser (1995) for more details] are not unrealistic based on present establishment rates. For example, the assumed annual rate of plantation establishment in the tropics used in Nilsson and Schopfhauser is about 65% of the actual rate for 1980–90 (FAO, 1993). For China, the assumed rate of 2.5 Mha/yr also is lower than the reported rate of 3.9 Mha/yr (Xu, 1992).

Trexler and Haugen (1995) use country-level estimates for each decade from 1990 to 2050 for 52 tropical countries accounting for virtually all of the tropical forests. For each country and decade (based on detailed country-by-country analysis), they estimate current and projected future deforestation rates, the potential reduction in deforestation based on feasible implementation of alternative land uses, and the area presently available for natural or assisted forest regeneration (native forests) followed by protection, as well as likely rates of implementation. Based on these estimates, Trexler and Haugen (1995) project that by the year 2050, deforestation could be reduced by only 20% of the business-as-usual scenario—equivalent to about 138 Mha—and a further 217 Mha of land will be available for natural or assisted regeneration. They also estimate the change in aboveground biomass C associated with each land-use change. We have added estimates of belowground biomass, soil, and litter C (see footnote 2 to Table 24-5) to be consistent with the study of Nilsson and Schopfhauser (1995).

24.4.2.2. Quantities of C Conserved and Sequestered

Together, the studies suggest that 700 Mha of land might be available globally for C conservation and sequestration programs (345 Mha for plantations and agroforestry, 138 Mha for slowed tropical deforestation, and 217 Mha for natural and assisted regeneration of tropical forests). This amount of land could conserve and sequester 60 to 87 Gt C by 2050 (Table 24-5). Globally, forestation and agroforestry account for 50% of the total (38 Gt C), with about 20% of this accumulating in soils, litter, and belowground biomass (Nilsson and Schopfhauser, 1995). The amount of C that could be conserved and sequestered by forest-sector practices by 2050 under baseline conditions is equivalent to about 12 to 15% of the total fossil fuel emissions over the same time period (IPCC 1992a scenario).

The tropics have the potential to conserve and sequester by far the largest quantity of C (80%), followed by the temperate zone (17%), and the boreal zone (3% only). More than half of the tropical sink would be caused by natural and assisted regeneration followed by forest protection and slowed deforestation. Other analyses have shown that forest conservation and natural regeneration is potentially easier, cheaper (see Section 24.5), and more

acceptable to the local population than plantation-based forestation (Deutscher Bundestag, 1990; Grainger, 1990). Forestation and agroforestry would contribute less than half of the tropical total, but without them, regeneration and slowed deforestation would be highly unlikely (Trexler and Haugen, 1995).

Table 24-5: Global estimates of potential amount of C that could be sequestered and conserved by forest management practices between 1995 and 2050 (from Nilsson and Schopfhauser, 1995; Trexler and Haugen, 1995).

Latitudinal Belt	Country/ Region	Practice	C Sequestered and Conserved (Gt)
High	Canada	Forestation	0.68
	Nordic Europe		0.03
	FSU		1.76
	Subtotal		**2.4**
Mid	Canada	Forestation	0.43
	USA		3.07
	Europe		0.96
	China		1.70
	Asia		2.19
	South Africa		0.44
	South America		1.02
	Australia		0.31
	New Zealand[1]		1.7
	Subtotal		**11.8**
	USA	Agroforestry	0.29
	Australia		0.36
	Subtotal		**0.7**
Low	Tr. America	Forestation	8.02
	Tr. Africa		0.90
	Tr. Asia		7.50
	Subtotal		**16.4**
	Tr. America	Agroforestry	1.66
	Tr. Africa		2.63
	Tr. Asia		2.03
	Subtotal		**6.3**
	Tr. America	Regeneration[2]	4.8–14.3
	Tr. Africa		3.0–6.7
	Tr. Asia		3.8–7.7
	Subtotal		**11.5–28.7**
	Tr. America	Slow Deforestation[2]	5.0–10.7
	Tr. Africa		2.5–4.4
	Tr. Asia		3.3–5.8
	Subtotal		**10.8–20.8**
	Total		**60–87**

[1] This estimate differs from the one made by Maclaren (1996), because it includes multiple rotations and different data for the C budget components.

[2] Includes an additional 25% of aboveground C to account for belowground C in roots, litter, and soil (based on data in Nilsson and Schopfhauser, 1995; Brown *et al.*, 1993b); range in values is based on the use of low and high estimates of biomass C density resulting from the uncertainty in these estimates.

The total quantity and annual rates of C conservation and sequestration would vary among countries or regions (Table 24-5; Figure 24-1). The FSU accounts for more than 70% of the C sequestration potential in the boreal zone (Table 24-5). At mid-latitudes, the greatest potential for sequestering C would be in the United States (about 3.4 Gt), followed by temperate Asia (about 2.2 Gt), and China and New Zealand (1.7 Gt each) (Figure 24-1a). In low latitudes, tropical America would have the greatest potential for C conservation and sequestration (27 Gt), followed by tropical Asia (20 Gt) and tropical Africa (12 Gt) (Table 24-5; Figure 24-1b). Forestation and regeneration would likely have the greatest potential in tropical America and Asia, whereas agroforestry would be the most important activity in tropical Africa (Nilsson and Schopfhauser, 1995).

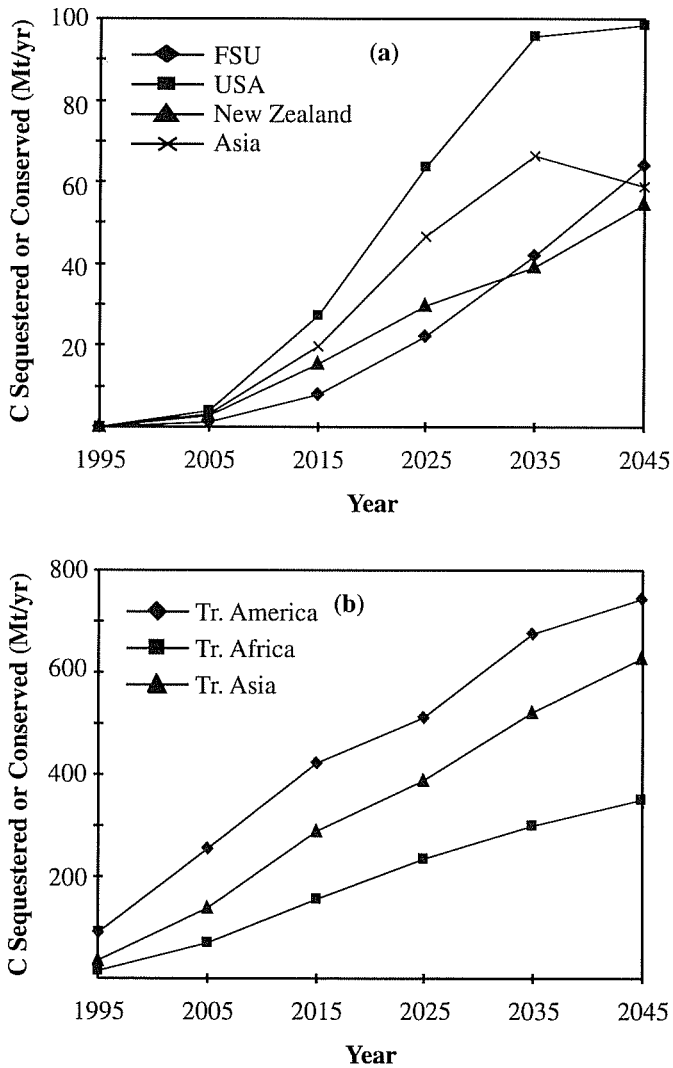

Figure 24-1: Average annual rates of C conservation and sequestration per decade through implementation of forest management options listed in Table 24-5 (a) by four countries or regions of the high- and mid-latitudes with the highest total sequestration rates and (b) for the three tropical (Tr.) regions.

Annual rates of C conservation and sequestration from the practices listed in Table 24-5 would increase over time and reach 2.2 Gt/yr by 2050 (Figure 24-2a), with C accretion in the tropics dominating the flux. Carbon savings from slowed deforestation and regeneration would be the highest initially, but from 2025 onwards—when plantations would reach their maximum C accretion—they would sequester practically identical amounts as forestation (Figure 24-2b). During this period, tropical deforestation would continue, and the tropics would remain a net C source, albeit gradually diminishing. By about 2030, the tropics would become a C sink (Trexler and Haugen, 1995). On a global scale, forests could turn from a source to a sink by about 2010 due to C conserved in other zones.

In summary, the tropics appear to have the greatest long-term potential for C conservation and sequestration by—in decreasing order of importance—protecting lands for natural and assisted regeneration, slowing deforestation, forestation, and agroforestry. The mid-latitudes also could make a significant contribution, but the potential for the high latitudes appears to be limited. The uncertainty in the estimated mitigation potential of forests has not, at present, been estimated. Like the uncertainty associated with the estimated C flux from the world's forests (see Section 24.2.2), the uncertainty in the estimated mitigation potential is likely to be high. The factors causing the highest uncertainty are the estimated land availability for forestation projects and regeneration programs and the rate at which tropical deforestation can be actually reduced. The next most uncertain term is the amount of C that can be conserved or sequestered in tropical forests; there is considerable debate about how much biomass C tropical forests contain (Brown and Lugo, 1992). The net amount of C per unit area that can be sequestered in a global forestation program is more certain. However, as discussed in Section 24.2.2, all errors are certain to be compounded when making global estimates.

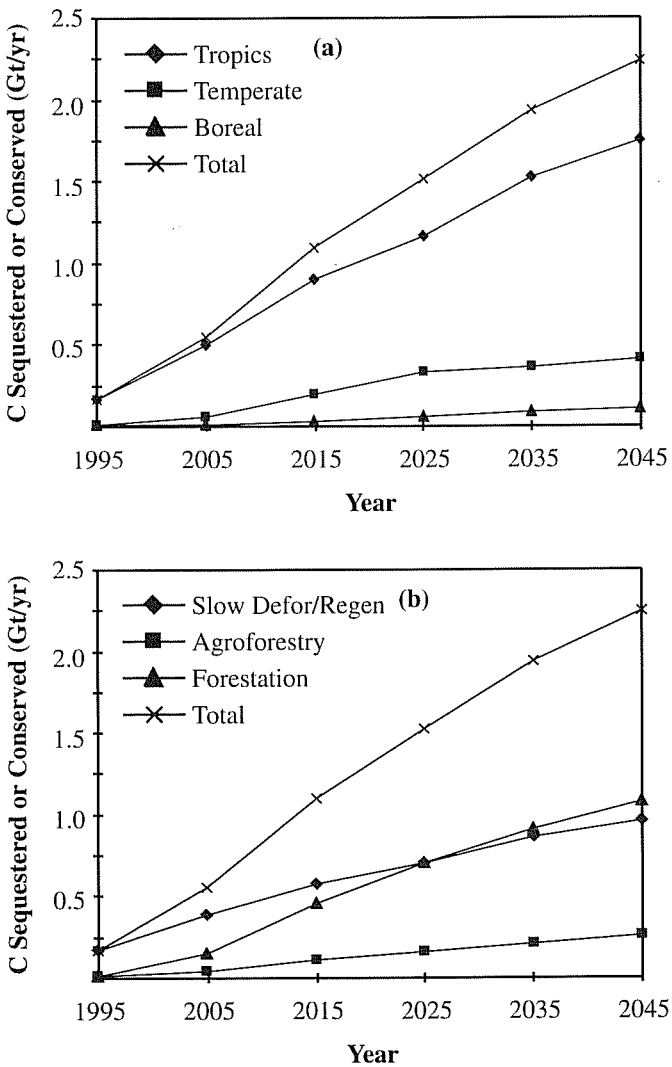

Figure 24-2: Average annual rate of C sequestration and conservation per decade through implementation of the forest management options listed in Table 24-5 by (a) latitudinal region and (b) forest management practice. Note that Defor = deforestation and Regen = natural and assisted regeneration.

The contribution of forestry to mitigation of CO_2 emissions would be considerably higher if the wood produced were assumed to be used as a substitute for fossil fuels (Section 24.3.3; Hall *et al.*, 1991; Sampson *et al.*, 1993). For example, for the forestation program described here (Table 24-5), the quantity of biomass that could potentially be produced over the 55-year period was 147 billion m^3, which is equivalent to about 39 billion tons of coal (W. Schopfhauser, pers. comm.). If the wood were substituted for coal over the same time period, the C emissions avoided would be about 29 Gt, or about 77% of the C sequestered in the forestation program (37.6 Gt) (Table 24-5).

A number of projects to conserve and sequester C along the lines described above are now being jointly implemented between developed and developing countries. They vary from C conservation by protecting forests or developing sustainable forest management practices to increasing C pools through forestation and agroforestry (Box 24-2).

24.5. Project Costs and Benefits of C Conservation and Sequestration

The previous IPCC assessment (IPCC, 1992) reported regional average annual costs of about \$8/t C for tropical forestation and reduction of deforestation, increasing to about \$28/t C for forestation in non-U.S. OECD countries. Costs for establishing a forest plantation, excluding the opportunity cost of land, were estimated to range between \$230 and \$1000/ha (Sedjo and Solomon, 1989), with an average cost of \$400/ha.

Unit cost estimates have been improved since the earlier IPCC report (see also Chapter 8, *Estimating the Costs of Mitigating Greenhouse Gases*, and Chapter 9, *A Review of Mitigation Cost Studies*, of the IPCC Working Group III volume): (1) They have been estimated for individual countries rather than by regions or for the globe as a whole; (2) they have been developed for several types of mitigation options; (3) other cost

Box 24-2. Jointly Implemented Forestry Offset Projects to Sequester C Emissions

There are several examples of C-offset projects around the world; the main characteristics of six of these projects are highlighted in Table 24-6 (adapted from Dixon *et al.*, 1993a; Kinsman and Trexler, 1993).

Table 24-6: *Jointly implemented forestry offset projects.*

Location	Main Sponsor[1]	Forestry Option	Total Cost (10^6 US$)	Carbon Sequestered (Mt)	Duration (yr)
Guatemala	AES Thames	Sustainable Agroforestry	14	15.5–58	10
Malaysia (1)	ICSB/NEP	Harvest Modification	0.45	0.3–0.6	2–3
(2)	ICSB/FACE	Forest Rehabilitation	14	5–7.5	25
Paraguay	AES Barbers Point	Protection, Sustainable Agroforestry	2–5	13	30
Russia (Saratov)	USEPA/OSU	Forestation	0.2	0.04	50
USA (Oregon)	PacifiCorp	Sustainable Forestry	0.1/yr	0.06/yr	65

[1]AES Thames is a subsidiary of Applied Energy Services (AES) Corporation (Virginia, USA); NEP = New England Power (Massachusetts, USA); FACE = Forest Absorbing Carbon Dioxide Emissions, a project of the Dutch Electricity Generation Board; ICSB = Innoprise Corporation Sdn Bhd (Yayasan Sabah, Malaysia); USEPA/OSU = U.S. Environmental Protection Agency in cooperation with Oregon State University (T. Vinson, pers. comm.); PacifiCorp is an electric utility company in Oregon, USA.

Brief details of two of these offset projects follow:

- The cooperative venture between Innoprise Corporation Sdn Bhd (ICSB), the largest logging concession holder in the state of Sabah, Malaysia, and the Forest Absorbing Carbon Dioxide Emissions (FACE) Foundation promotes the planting of trees to absorb CO_2 from the atmosphere and offset emissions from power stations. The objective is to rehabilitate 25,000 ha of degraded logged forests by enrichment planting with dipterocarps—long-lived local tree species valued for their timber—and by reclaiming degraded areas using indigenous fast-growing pioneer trees. Forest fruit trees also are being interplanted to improve the forest's value for wildlife. Over a 60-year rotation, the rehabilitated forest is expected to sequester at least 200 t C/ha more than degraded logged forest; thus, a total of 5 Mt C will be sequestered. Results achieved so far are very encouraging, with survival rates around 87% and growth rates of 1.2 cm dbh per year (P. Moura Costa, pers. comm.). The long-term nature of the project (25 years) will allow the maintenance and silvicultural treatments required to sustain the growth rates to be achieved.
- For the Reduced-Impact Logging Project, New England Power (NEP) provided funds to ICSB to train personnel and implement a set of harvesting guidelines in 1,400 ha of ICSB concessions. In return, NEP can claim the C retained due to these efforts as a C offset. The project aims to reduce by half the damage to residual trees and soil during timber harvesting. Thus, less woody debris will be produced, decompose, and release CO_2, meaning more C will be retained on-site in living trees (Putz and Pinard, 1993). Conventional selective logging in the concession provides the base for comparison. Controlling logging damage is expected to result in the retention of 25–45 t C/ha after 2 years, and a total of 35–63 kt C are expected to be sequestered, at a cost of $8–14/t C.

components, including maintenance, land rental (opportunity costs), and monitoring and evaluation, are now being addressed; (4) incremental costs have been estimated by some researchers; and (5) analytical methods have been improved to provide better insights and techniques for the evaluation of costs and benefits. Despite these improvements, most estimates do not discount the C flows. Thus, net C storage occurring at any time has the same economic value.

The IPCC (1992) report does not attempt to quantify the benefits of mitigation options to reduce or store C. The valuation of C and other benefits is essential to the successful implementation of mitigation options—particularly for developing countries, where C storage may not be a sufficient inducement for local dwellers to maintain forestation projects. There is no global consensus at present on the monetary value of reducing a unit of atmospheric C.

Incremental costs of comparable projects or programs are defined as the difference between the total costs of an alternative and those of a baseline project that satisfies the same service, such as the demand for food, fuel, fiber, watershed protection,

and habitat (Ahuja, 1993; K. King, 1993). Under the UN Framework Convention on Climate Change, a developing country may seek the incremental costs of a project to reduce C emissions or sequester C from developed countries. For the forest sector, however, few estimates are available for the incremental costs of GHG emissions reduction.

24.5.1. Reducing Deforestation and Protecting Forests

The unit cost of reducing C emissions by decreasing deforestation and protecting forests tends to be low (Table 24-7) as the C density of forested areas tends to be relatively high. Cost estimates, often obtained from government budgets, include the small direct cost of protection but generally not the comparatively larger opportunity cost of land. None of the estimates includes the potentially substantial, though as yet unknown, cost of providing an alternative livelihood and a viable lifestyle to those responsible for deforestation. Furthermore, present-day costs of forest protection will likely increase in the future as the amount of land put under protection increases (Adams *et al.*, 1993; Moulton and Richards, 1990).

Most of the costs reported in Table 24-7 are under $3/t C, but range from tens of cents/t C to about $15/t C. These costs exclude the value of local benefits that may be derived from protected forests, such as watershed protection, maintenance of biodiversity, education, tourism, and recreation; their inclusion would further offset some of the costs and in many instances result in net benefits (Dixon *et al.*, 1993b). For example, in Thailand, local benefits are estimated at $2/ha—which would almost offset the $2.1/ha direct cost of protection (Wangwacharakul and Bowonwiwat, 1995). Because direct benefits offset direct costs, the opportunity cost of land (present value $44–89/ha) represents the cost of avoiding deforestation.

Table 24-7: Cost of forest protection or reducing deforestation.

Country	Cost ($/t C)
Brazil	2.3[1]–4[2]
Cote d'Ivoire	8[1]
Indonesia	15[1]
Thailand	0.4–0.8[3]
Mexico	1–6[4]
India	0.5[5]
Central America	1–3[6]
Russia	1–3[7]

[1]Darmstadter and Plantinga, 1991.
[2]Cline, 1992.
[3]Based on Wangwacharakul and Bowonwiwat (1994), which includes government budget for protection and opportunity cost of land for agriculture production.
[4]Based on data in Masera *et al.* (1995); lower bound based on government budget for protection, and higher bound on cost of protection of tropical evergreen forests in Tabasco.
[5]Based on $5/ha cost for a tiger sanctuary and 50 t C/ha of biomass density.
[6]Swisher (1991) estimate based on cost of protected areas reported in the Tropical Forest Action Plan (TFAP) proposals for Costa Rica, Honduras, and Panama.
[7]Krankina and Dixon, 1994.

24.5.2. Expansion of C Pools and C Transfer to Products

Subsequent to the IPCC report (1992), several studies have been done that better determine the cost of expanding C pools and C transfer to products (Table 24-8). The studies have focused on deriving cost estimates of mitigation options for individual countries. The costs generally include initial or establishment costs per ton of C but do not include opportunity costs or maintenance, monitoring, and evaluation costs. The methods for obtaining cost figures include literature surveys, government sources, personal questionnaires, and some field data. At the same time, researchers have refined the methodology for estimating the amount of C sequestered by a particular mitigation option and better identified the individual components of the total cost (Sathaye *et al.*, 1995). This identification has helped improve the transparency of reported cost estimates.

Earlier studies had reported point estimates for cost of C sequestration. Moulton and Richards (1990), however, developed a cost function to reflect the rise in costs associated with large-scale tree planting rather than a simple point estimate, and refined the tree plantation establishment cost estimates by differentiating costs associated with location and site considerations. Based on their data, Cline (1992) estimates costs as rising from $12/t C for the first 100 Mt of C sequestered to $41/t C for sequestering between 700 and 800 Mt/yr. Adams *et al.* (1993) report somewhat higher costs than Moulton and Richards (1990) (Table 24-8). The Moulton and Richards (1990) analysis has been expanded by adding the potential effects of forestation on altered timber supply, stumpage prices, harvest levels, and ultimately C sequestration (Turner *et al.*, 1995b). The latter approach couples a forest economics model, a forest inventory model, and a forest C model to make a 50-year projection of the forest sector of the U.S. economy. Coupling of models permits analysis of more-complex mitigation options such as increased paper recycling, alternative harvesting schemes, and tree planting on agricultural land. One drawback of these models is that they ignore new uses of wood—such as for power or heat generation—that would minimize the impact on traditional timber markets.

Several studies conducted for developing countries (Table 24-8) evaluate the cost of sequestering C using options such as agroforestry, long- and short-rotation plantations, natural regeneration, forest management, and silvicultural practices. Based on an estimate of the technically available land area in a given country, the tropical studies have developed cost curves that show increasing marginal costs ($/t C) with higher sequestration. The curves for India, China, and Thailand, for example, indicate that the unit cost for sequestering C on 80% of the technically available area would be less than $10/t C.

Table 24-8: *Initial cost of expanding carbon sinks by different regions and practices.*

Region/Country	Practice	Cost[1] (US$/t C)	Source
Boreal	Natural Regeneration[2]	5 (4–11)	Dixon *et al.*, 1994b
	Reforestation	8 (3–27)	
Temperate	Natural Regeneration[2]	1	Dixon *et al.*, 1994b
	Afforestation	2 (1–5)	
	Reforestation	6 (3–29)	
Tropical	Natural Regeneration[2]	1 (1–2)	Dixon *et al.*, 1994b
	Agroforestry	5 (2–11)	
	Reforestation	7 (3–26)	
Central America	Regeneration	4	Swisher, 1991
	Agroforestry	4	
	Plantations	13	
Argentina	Reforestation	31	Winjum *et. al.*, 1993
	Afforestation	18	
Australia	Reforestation	5	Winjum *et. al.*, 1993
Brazil	Reforestation	10	Winjum *et. al.*, 1993
	FLORAM	3–8[3]	Andrasko *et. al.*, 1991
Canada	Reforestation	11	Winjum *et al.*, 1993
	Regeneration	6	
China	Reforestation	10	Winjum *et. al.*, 1993
	Forest Management	3–4	Xu, 1995
	Eucalypt Plantations	8	
	Agroforestry	6–21	
Germany	Reforestation	29	Winjum *et. al.*, 1993
India	Reforestation	15	Winjum *et. al.*, 1993
	Regeneration	2	Ravindranath and Somashekhar, 1995
	Teak Plantations	3	
	Agroforestry	9	
Malaysia	Reforestation	5	Winjum *et. al.*, 1993
Mexico	Reforestation	4	Winjum *et. al.*, 1993
	Plantations	5–11	Masera *et al.*, 1995
	Forest Management	0.3–3	
South Africa	Reforestation	9	Winjum *et. al.*, 1993
Thailand	Teak Plantation	13–26	Wangwacharakul and Bowonwiwat, 1995
	Eucalypt Plantation	5–8	
	Agroforestry	8–12	
USA	Reforestation	5	Winjum *et. al.*, 1993
	Afforestation	2	
	Various Options	5–43[4]	Moulton and Richards, 1990
	Various Options	19–95[5]	Adams *et al.*, 1993
FSU	Reforestation	6	Winjum *et al.*, 1993
	Regeneration	5	
Russia	Plantations	1–8	Krankina and Dixon, 1994

[1]Forest components for sequestering C vary by source: Dixon *et al.* (1994b), Krankina and Dixon (1994), and Winjum *et al.* (1993) include only C in vegetation; Xu (1995), Ravindranath and Somashekhar (1995), Wongwacharakul and Bowonwiwat (1995), and Masera *et al.* (1995) include vegetation and soil C; Swisher (1991), Moulton and Richards (1990), and Adams *et al.* (1993) account for C in vegetation, soil, and litter.
[2]Values in parentheses are interquartile ranges.
[3]Figures vary depending on land rental costs per ha from $400 to 1,000; FLORAM = Florestales Amazonia.
[4]Marginal costs include planting and land rental costs.
[5]Includes land rental costs.

24.5.2.1. Carbon Components

All the above cost estimates account for above and below-ground biomass C, but not all account for C in soil, fine and woody detritus, understory, and wood products. Estimates of the distribution of C between aboveground vegetation and soils vary significantly by ecosystem and by bioclimatic and edaphic conditions (Brown *et al.*, 1993a; Sampson *et al.*, 1993). By excluding many of the other C components, the studies reported in Table 24-8 overestimate the unit costs.

The studies summarized in Table 24-8 ignore another potentially large C benefit—that is, the possibility of substituting wood from sustainable plantations for fossil fuels (see Section 24.3.3; Hall *et al.*, 1991; Sampson *et al.*, 1993; see also Chapter 19). The extent to which wood products can displace fossil fuel depends on the products and applications for which wood is substituted. Fossil fuel savings may be considerable when wood is substituted for energy-intensive aluminum, steel, or concrete in construction (Burschel *et al.*, 1993). When harvesting wood to directly displace fossil fuels, the critical elements become the rate of tree productivity and the efficiency with which wood can be harvested and substituted for fossil fuels (Marland and Marland, 1992; see also Section 24.3.3).

24.5.2.2. Cost Components

The unit cost estimates reported in Table 24-8 include the cost to initiate a forest sector project—such as planting stock costs, planting labor, and supervision—but do not include the opportunity cost of land and growing stock, annual maintenance costs, and monitoring and evaluation costs. Of these, the latter two are generally a small fraction of the initial cost. The opportunity cost of land and growing stock, however, could significantly increase the unit cost estimates. Land rental costs are estimated at $148/ha by Moulton and Richards (1990) for the United States; a land purchase price is estimated between $400 and $1,000/ha by Sedjo and Solomon (1989). Land prices are likely to be lower in developing countries. For example, in Thailand, the present value of the opportunity cost of land is estimated to be between $44 and $89/ha (Wangwacharakul and Bowonwiwat, 1995). For degraded lands that are suitable for reforestation, which are widespread across many countries, the land price may be close to zero.

Winjum and Lewis (1993) demonstrate the significance of including the opportunity cost of the forest stock. Using the value of growing stock and revenues (i.e., negative costs), they show that without including growing stock costs, the median values (negative costs) of storing C are -$48/t C for temperate and -$32/t C for tropical plantations. With the growing stock costs included, the median values of storing C increase to -$22 and -$24/t C, respectively. Inclusion of the opportunity cost of land and of forest stock therefore may increase the cost in developed countries two to threefold, but the increase may be smaller in developing countries where degraded lands are available.

24.5.2.3. Monetary Benefits

Implementation of mitigation options will result in direct benefits derived from timber and non-timber forest products. The commercial value of these products will vary with the site and location of a project—particularly in tropical countries, where non-timber forest products provide sustenance to the local dwellers. Additional indirect benefits (nature conservation, recreation, etc.) will add to a project's value. Appropriate distribution of the total benefits among the project beneficiaries, however, is necessary to ensure the project's survival.

Trading in C credits can serve to offset the cost of an international project. Several forest sector C offset projects (Box 24-2) have been established and maintained at costs well below, or at net benefits to, the modeled estimates reported by Dixon *et al.* (1993a).

Monetary timber benefits alone often can more than offset the project costs (Winjum and Lewis, 1993). The cost offset varies depending on inclusion of indirect benefits, such as forest stock value. Other estimates of the benefit of C sequestration for developing countries (Ravindranath and Somashekar, 1995; Roslan and Woon, 1995; Wangwacharakul and Bowonwiwat, 1995; Xu, 1995) confirm that product revenue from many plantation and agroforestry projects could completely offset costs. Schroeder (1992) points out that agroforestry projects could be implemented for C sequestration across many ecological zones and practices at a positive present value of net benefit ranging from $54/ha to $6,000/ha, assuming that product prices remain unchanged in the future. The above estimates suggest that it would be possible to achieve C sequestration at a net benefit or negative cost.

The distribution of benefits plays an important role in assuring the success of either large forestation programs or individual projects. Adams *et al.* (1993) illustrate that a U.S. forestation program to sequester C on agricultural land will bestow higher benefits to agricultural producers and landowners from higher commodity prices, but the decline in timber prices will reduce timber-sale profits for private forest owners. If the distribution of benefits is to be equitable, the government will have to compensate private commercial tree planting to prevent farmers from displacing present tree plantations. For example, Saxena (1989) has shown that the losers in a rural forestry development program in India will be the local forest officers, whereas both the rural rich and the poor will gain to varying degrees from non-timber benefits and timber sales.

It is important that participants in a program aimed at sequestering C gain appropriate and adequate benefits to ensure sustained C storage. Winnett *et al.* (1993) suggest that there is a risk that the behavior of landowners will change if increased wood supply lowers stumpage prices. The result is less incentive to invest in intensive forest management. These studies, however, do not consider the case where wood is sold in energy markets rather than in traditional markets for timber.

Not harvesting timber from a forestation program is another way to avoid the impact on timber prices. For example, Barker

et al. (1995) estimate that converting 4 Mha of marginal cropland to forests and allowing 2 Mha of bottomland cropland to revert to hardwood wetlands would sequester 850 Mt C in the United States over a 50-year period, at the same time extending wildlife and wetland habitats (non-timber benefits). This example is estimated to cost about $45/t C. There are similar opportunities in Europe, where about 15% of cropland currently is set aside to reduce agricultural surpluses.

24.5.3. Carbon Sequestration through Silviculture

Silvicultural practices (thinning, fertilization, improved harvesting, genetic tree improvement, etc.) are directed to increasing both the growth and the quality of the forest resource. Increased growth *per se* does not increase mean C storage and, indeed, may decrease C storage over a given area if the growth increase is associated with a shift to a younger age-class distribution (Turner *et al.*, 1995b). Many silvicultural practices are designed to improve some aspect of the wood and/or tree form and may do little to increase C sequestration, but the longer-term, indirect effects may have significant C implications. For example, management techniques that allow greater portions of the forest to be harvested and converted to long-lived wood products may sequester a greater mass of C in the long term in both the forest itself and in the forest product stock.

Some silvicultural practices—such as thinning, extending rotation ages, and retaining high levels of coarse woody debris after harvesting—increase or at least stabilize soil C pools and tend to maintain more C on forest lands. These practices have received considerable attention in relation to maintaining biodiversity and soil productivity (Swanson and Franklin, 1992), but their C storage benefits have not been well characterized. Reduction of logging damage to residual trees can also reduce the associated releases of C (see Box 24-2).

A few studies have examined the economics of C sequestration by silvicultural practices. Hoen and Solberg (1994) assessed the efficiency of various strategies to sequester C in biomass of Norwegian forests. Carbon sequestration attributable to thinning and fertilization of stands was $71/incremental ton of C captured, even where current logging levels were maintained. Modeling efforts by Marland and Marland (1992) demonstrate that the relative C benefit of different silvicultural strategies can change dramatically depending on site-dependent characteristics such as forest growth rate, site occupancy at the time management is implemented, and the manner and efficiency with which forest products will be used.

24.5.4. Global Costs

The IPCC report (1992) estimates that the forestation costs (undiscounted) for offsetting between 5 and 26% of the 5.5 Gt C being released annually from fossil fuel combustion would range from $2.4 billion/year to $12 billion/year if accomplished over a 10-year planting period, with declining costs for longer planting periods. Dixon *et al.* (1991) report that the marginal initial cost to sequester global C increases gradually to $10/t C for a storage level of 70 Gt C, which was about 90% of the identified storage potential. Beyond 70 Gt C, the marginal cost increases rapidly. The corresponding total cost to store 70 Gt C amounts to $230 billion. Country-specific marginal cost estimates for Brazil, Russia, and the United States (Dixon *et al.*, 1991) and for India (Ravindranath and Somashekhar, 1995), China (Xu, 1995), Central America (Swisher, 1991), and Thailand (Wangwacharakul and Bowonwiwat, 1995) confirm that between 50 and 90% of the C storage potential can be tapped at an initial cost of less than $10/t C.

Using the mean unit costs for individual options by latitudinal region (from data in Tables 24-7 and 24-8), the cumulative cost (undiscounted) of conserving and sequestering the quantity of C given in Table 24-5 (for individual options, corrected for vegetation only) ranges from $247 billion to $302 billion, at an average unit cost ranging from $4.6 to $3.7/t C, respectively (Table 24-9). Average unit cost decreases as more C is conserved by slowing deforestation and forest regeneration because these are the lowest-cost options. For the forestation program alone, the unit cost would be $6.4/t C, and the total cost would decrease to $253 billion. The estimated unit cost in Table 24-9 for the forestation program is higher than that reported by Nilsson (1995), but it is consistent with new findings by others (e.g.,

Table 24-9: *Global costs of conserving and sequestering C based on the estimates in Table 24-5.*

	Zone/Forestry Options[1]						
		Low		Mid		High	
	D/R	AF	PL	AF	PL	PL	Total
Cost ($/t C)	2	5	7	5	6	8	3.7–4.6[2]
Total Costs (10^9 $)							
– Low estimate	44[3]	27	97	3	60	17	247
– High estimate	99[3]	27	97	3	60	17	302

[1] D/R = slowing deforestation and regeneration; AF = agroforestry; PL = plantations.
[2] Weighted average cost per unit (total costs/total C).
[3] Total costs based on low and high C conservation estimates given in Table 24-5.

Table 24-8). However, Nilsson (1995) argues that these costs may be underestimated by severalfold if additional costs such as establishing infrastructure, protective fencing, education and training, and tree nurseries were included. On the other hand, if timber and other products generate revenue, then the capital investment for the second and subsequent rotations will be derived from the revenue from the previous rotation, and the incremental capital investment will be a fraction of the cost. Discounting future costs also significantly reduces the total and average costs estimated above. Assuming an annual discount rate of 3% reduces the range of total costs to $77 to $99 billion and the average unit cost to $1.4 to $1.2/t C.

Land costs still tend to be excluded from cost analyses; their inclusion could increase the cost severalfold. In addition, the cost and benefit estimates presented here do not cover indirect or nonquantifiable items, such as changes in biodiversity, water resources and soil erosion, and the livelihood of forest dwellers. Their inclusion would provide a more realistic picture of the dislocation caused by strategies to protect forests or reforest suitable lands. However, even if present cost estimates for C mitigation by forestry were doubled or tripled, they would still be considerably lower than a proposed U.S. fossil-fuel tax of $100–350/t C (Rubin *et al.*, 1992).

24.6. Impacts of Future Climate, Atmospheric CO_2, Land Use, and Human Population on C Conservation and Sequestration

The direct (increased concentration of CO_2) and indirect (changes in temperature, moisture regime, growing season length, etc.) effects of a changing atmosphere and climate on forest ecosystems are discussed in more detail in Chapters 1 and A. This section discusses how these changes and future changes in human demographics are likely to affect amounts and rates of C conservation and sequestration. Because projections concerning the effects of climate change and human activities are very uncertain, only their likely range of impacts is presented here.

Environmental factors such as future climate change, increases in atmospheric CO_2, increased mobilization of other elements such as nitrogen and sulfur, and other pollutants such as NO_x and tropospheric ozone are likely to have the greatest impacts on mid- and high-latitude forests (Apps *et al.*, 1993). In the low latitudes, human factors such as changing demographics, increased demand for agricultural land, economic growth, technology, and resource management policies—all of which have the potential to lead to high rates of land-use change—are expected to be the dominant forces on forests and could overwhelm any changes caused by future environmental conditions (Brown *et al.*, 1993a; see also Chapters 1 and 15).

Each of the promising forest management options for mitigation of C emissions is likely to be affected differently under a changed climate and human population density. For regeneration and slowed deforestation in the tropics, demand by an increasing human population for more land for agriculture and wood products (e.g., for industrial and energy use) at the expense of forest cover is likely to have a major effect on land availability; direct and indirect effects of climate change on land-use potentials may be less important in comparison (Brown *et al.*, 1993a). In the mid and high latitudes, where changes in land use are relatively stable at present, the direct and indirect effects of climate change are likely to be more important (see Chapters 1 and 15). For forestation, the key factors are how a changed climate and atmosphere will affect the suitability and availability of lands for plantation and agroforestry establishment, as well as the effects on species selection, rates of tree growth, and other pathways for sequestering C (in soil, litter, roots, etc.). The impacts of the various factors are discussed briefly in Sections 24.6.1 and 24.6.2.

24.6.1. Impact on Land Suitability and Availability

The effects of future climate change on the redistribution of global forest biomes are uncertain; consequently, there are large differences in projected changes in forest area for a 2 x CO_2 climate (see Chapters 1 and 15). Furthermore, most models project instantaneous change in potential vegetation distributions only. The development of the IMAGE 2.0 model—which is one of the first efforts to link submodels of the terrestrial system, atmosphere-ocean system, and energy-industry system with geographical specificity—attempts to overcome some of the problems in projecting changes in distribution of vegetation (Alcamo, 1994). Output from the "conventional wisdom" scenario of this model (akin to the IPCC 1992a scenario with respect to projected fossil fuel use; for other aspects of the model, see Alcamo, 1994, and Chapter 25) has been used to address the possible impacts of changed land-cover patterns on C conservation and sequestration potentials. Model output has been used to provide an estimate of likely changes in land suitability (i.e., potential vegetation based on the ability to grow trees, determined by climatic and edaphic factors) and land availability (a reduction in land suitability based on the need for land to grow crops, provide fuels, and so forth for the increasing human population) (see also Chapter 15). The area of land suitable for forest-sector practices for mitigation could increase globally, with the larger gains occurring in high and low latitudes mainly because of warmer temperatures and an extended growing season (Table 24-10; see also Chapter 1). However, the potential increase in suitable lands is based on climatic factors alone and does not consider whether soils will be suitable for forest establishment. This is potentially problematic in the high latitudes, where the boreal forests are projected to migrate into the tundra; tundra soils have characteristics that can retard forest establishment.

Considering the possibility of climate change, forest-sector programs aimed at C conservation and sequestration should be targeted toward those areas, tree species, and practices that are most likely to succeed, even if climate change occurred. The best targets from this perspective of risk may be the humid tropical zone and, to a lesser extent, the boreal zone, where conditions are most likely to become favorable for tree growth in new

Table 24-10: *Likely change in areas of land suitability (technically suitable to grow trees based on edaphic and climatic factors) and availability (technically suitable lands constrained by social, cultural, economic, and political factors) by 2050, brought about by changes in climate and human demographics (data are from the "Conventional Wisdom" scenario, a simulation of the IMAGE 2.0 model[1]).*

Latitudinal Belt	Change in Land[2] Suitability	Availability
High (>50°)	1.21	1.08
Mid (25–50°)	1.15	1.05
Low (0–25°)	1.31	0.64

[1] Alcamo, 1994; model outputs grouped as in table provided by R. Leemans, RIVM, The Netherlands.
[2] Change computed as area of lands in 2050 divided by area in 1990.

plantations (but see discussion above regarding soils) (G.A. King, 1993; Table 24-10). However, in the tropical zone, a consideration of the human element and its impact on forests could change this risk perspective. Almost all of the increase in suitable lands in the high and mid-latitudes has the potential to become available (Table 24-10). In contrast, gains in land suitability in low latitudes might be unrealized because of the need for their use for agriculture, and so forth; potentially, half of the present available lands could be lost (Table 24-10). Based on the change in land availability alone, the amount of C that can potentially be sequestered in mid and high latitudes would likely change little, with possible slight gains. The potentially large decrease in land availability in low latitudes could significantly reduce the amount of C conserved or sequestered in this region.

It has been proposed that during the transient response—in the first 100 years or so following climate warming—the processes of forest dieback and other disturbances could have major impacts on the C balance of forests (Smith and Shugart, 1993; see also Chapter 1). Gains in C sequestration from forestation programs at mid and high latitudes could be offset in the transient period by the release of C from unmanaged forests, resulting from the processes of migration and regeneration being slower than dieback and other disturbances. However, dieback problems in plantation forests are likely to be relatively less important because these will be managed forests with relatively short rotations, and species substitution could occur.

24.6.2. Impact on Rates of C Conservation and Sequestration

Results from the IMAGE 2.0 model—which incorporates the effects of CO_2 fertilization, temperature, and moisture on plant growth and soil processes—are used as examples of how these factors may affect C conservation and sequestration rates (Klein Goldewijk *et al.*, 1994; also see Chapter 25 for more details on IMAGE 2.0). A discussion of the effects of these factors on ecosystems also is presented in Chapters 1 and A. The values in Table 24-11 are derived from the IMAGE 2.0 model to indicate how much the net C flux from forest ecosystems (or net ecosystem production) could change (percent change from baseline conditions) by 2050; it is assumed that plantations would respond in the same manner. The percent changes in this table do not include regions where land-cover change occurred; they include only those that affect the cycling of C in regions that were forested in 1970 and still forested in 2050 (referred to as stable forested regions). Differences between simulations are governed by interactions among land cover, the biosphere, climate, and CO_2 concentrations.

Forests growing in mid- and high-latitudinal belts could potentially increase their net C uptake in response to a changed climate and atmosphere (Table 24-11, compare entries 1 and 8). In contrast, the net C uptake in low-latitude forests under the

Table 24-11: *Estimates of magnitudes of direct and indirect effects of global change on net C flux from stable forested regions (i.e., areas that were forested in 1970, the baseline, and still forested in 2050). Data were generated by the IMAGE 2.0 model (van Minnen et al., 1995).*

Effect	Latitudinal Belts (% Change)[1] Low	Mid	High
1. Baseline—all feedbacks to 1970 values	202	-2	-21
2. CO_2 fertilization and water-use efficiency	215	10	-11
3. Temperature and moisture feedback on plant growth	129	143	212
4. Temperature feedback on soil respiration	193	-46	-87
5. 2 and 4	210	-32	-75
6. 3 and 4	154	117	190
7. 2 and 3	136	153	220
8. 2, 3, and 4	174	129	202

[1] All net C fluxes are from the atmosphere to the biota; change in net flux was calculated as the difference between net C flux in 2050 and 1970, divided by the net flux in 1970 x 100.

combined effect of all factors (entry 8) could be lower than under baseline conditions. In other words, the region of the world that has the greatest potential for C conservation and sequestration (Table 24-5) under present climate conditions has the potential to lose some of this benefit under a changed climate and atmosphere. Although tropical forests have the largest potential to respond to CO_2 fertilization and water-use efficiency (Table 24-11, entry 2), this could be potentially offset by the response of plant growth and soil respiration to changed temperature and soil moisture (Table 24-11, entry 6).

In mid and high latitudes, a changed climate could have a large effect on the net C uptake rates of forests and thus rates of C sequestration due mostly to greater stimulation by increased temperatures and moisture on plant growth (Table 24-11, entry 3) than of soil respiration (Table 24-11, entry 4). Under no change in climate, the contribution by forests in these latitudes to the future global amount of C sequestered and conserved would be about 20% (Table 24-5). The results in Table 24-11 suggest that a potential exists to increase this share substantially, particularly given that the amount of land available is likely to increase or at least remain constant (Table 24-10).

In conclusion, under the conditions simulated by the IMAGE 2.0 model, which considers the entire suite of global change factors, there is a potential that C conservation and sequestration by forest management in the tropical region would become less important in the future, mainly due to loss of available land—unless policies are instituted to secure the required land areas for mitigation measures. In contrast, sequestration of C in temperate and boreal forest lands could play a larger role because available lands are likely to remain constant or increase and net rates of C uptake could increase.

24.7. Research and Data Needs

To improve our ability to estimate the mitigation potential of forestry practices, increased efforts are needed in the following areas:

- Realistic land-use modeling at national scales to determine trends in and constraints to forest cover, agricultural land needs, and land availability potentials. Variables such as present and projected population growth, agricultural productivity, forest growth rates, and energy demand should be linked with national trends in land use in these models so that assessments can be made of lands technically and actually available for C conservation and sequestration projects; possible interventions and their direct and indirect effects on future land uses; and key barriers that might be encountered in attempting to implement forestry options for mitigation.
- Improvements in the economic methodology for valuing all costs, including land, and especially benefits associated with forest management options for C conservation, storage, and substitution.
- Improved information about how different silvicultural and other management practices for major forest types and plantation species, growing under different climate/edaphic regimes, affect the dynamics, distribution, and retention of C in forests.
- Better understanding of the efficiency with which wood is converted into wood products, the life expectancy of wood products, and the energy balance of wood products versus that for alternative products that wood displaces.

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