TROPICAL FORESTS: THEIR PAST, PRESENT, AND POTENTIAL FUTURE ROLE IN THE TERRESTRIAL CARBON BUDGET

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Abstract. In this paper we review results of research to summarize the state-of-knowledge of the past, present, and potential future roles of tropical forests in the global C cycle. In the pre-industrial period (ca. 1850), the flux from changes in tropical land use amounted to a small C source of about 0.06 Pg yr^{-1}. By 1990, the C source had increased to 1.7 ± 0.5 Pg yr^{-1}. The C pools in forest vegetation and soils in 1990 was estimated to be 159 Pg and 216 Pg, respectively. No concrete evidence is available for predicting how tropical forest ecosystems are likely to respond to CO_2 enrichment and/or climate change. However, C sources from continuing deforestation are likely to overwhelm any change in C fluxes unless land management efforts become more aggressive. Future changes in land use under a "business as usual" scenario could release 41-77 Pg C over the next 60 yr. Carbon fluxes from losses in tropical forests may be lessened by aggressively pursued agricultural and forestry measures. These measures could reduce the magnitude of the tropical C source by 50 Pg by the year 2050. Policies to mitigate C losses must be multiple and concurrent, including reform of forestry, land tenure, and agricultural policies, forest protection, promotion of on-farm forestry, and establishment of plantations on non-

Water, Air, and Soil Pollution **70**: 71–94, 1993.

forested lands. Policies should support improved agricultural productivity, especially replacing non-traditional slash-and-burn agriculture with more sustainable and appropriate approaches.

1. Introduction

Atmospheric CO_2 concentrations have increased by almost 30% during the last two centuries (Houghton et al., 1992: Raynaud et al., 1993). The causes of this increase are the burning of fossil fuels and changes in land use, particularly conversion of forests to agriculture (Houghton and Skole, 1990). The relative magnitudes and contribution to atmospheric CO_2 concentrations of these activities have changed over time.

Prior to this century CO_2 emissions from changes in land use, mainly caused by agricultural expansion in temperate countries, were higher than emissions from the combustion of fossil fuels (Houghton and Skole, 1990). From the turn of the century until about the 1930s, global CO_2 emissions from changes in land use were similar in magnitude to those from fossil fuel combustion. Since then, world-wide fossil fuel use has soared, land-use change in temperate regions has diminished, and deforestation in the tropics has accelerated. Thus biotic emissions from the temperate zone declined greatly and have approached a balance as forests expanded onto abandoned agricultural lands and as logged stands regrew (Houghton et al., 1987). After about the 1940s, CO_2 emissions from the changes in land use in the tropics have dominated the flux from the biota to the atmosphere, although they remain far below global fossil-fuel produced fluxes.

Although the trends in CO_2 additions to the atmosphere from burning fossil fuels and changes in land use are relatively well known, the C budget cannot be balanced at present (Houghton et al., 1992). The balance between all known C sources and sinks results in an amount of about 2.2 ± 2.5 Pg C yr^{-1} unaccounted for or "missing". Some research suggests that mid-latitude ecosystems are the repositories of this "missing" C (Tans et al., 1990) while others suggest that the tropics are (Taylor and Lloyd, 1992). However, the magnitude of the proposed mid-latitude sink depends on the magnitude of the tropical flux to set the bounds (Tans et al., 1990). It is clear, therefore, that progress in balancing the global C budget will be made only with improved understanding of the C fluxes from the tropics.

1.1. THE CARBON BUDGET FOR TROPICAL FORESTS

The important reservoirs and fluxes of C in tropical forest ecosystems are shown in Figure 1. The main reservoirs are the C in biomass, including above and belowground components, necromass (dead organic matter), and soil, and the much smaller quantities stored in wood products off-site. The main biotic flows of C between the atmosphere and forests are net C fixation via photosynthesis (net primary productivity) and heterotrophic respiration (decomposition of detritus [fine and coarse litter and dead roots] and soil C). Some C fixed by photosynthesis is also transferred to coastal systems via export in rivers as dissolved and particulate organic C, currently estimated at 0.1 Mg C $ha^{-1}.yr^{-1}$ for the humid tropics (Meybeck, this volume; Hall et al,. 1992).

A net CO_2 flux to the atmosphere is also brought about by changes in land use from high to low C density systems (e.g., from forests to agriculture). Net releases of C to the atmosphere by land-use change depend on the amount of C stored within native

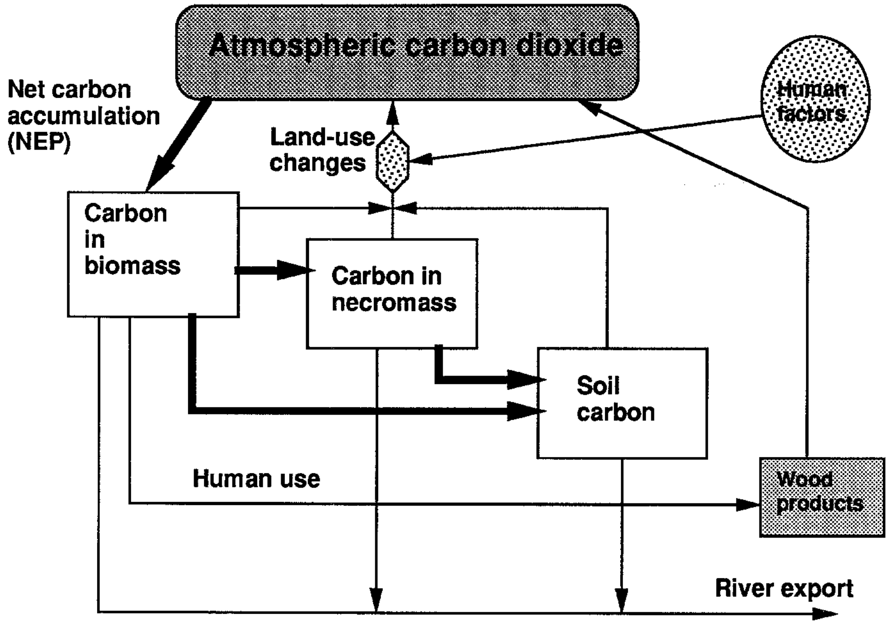

Figure 1. Basic model of the pools and flows of C within and between tropical forest ecosystems and the atmosphere caused by changes in land use or cover due to human and natural disturbances. The relative importance of the flows and stores varies over the course of time. The heavy arrows show the transfer of C from the atmosphere to the land during regrowth and recovery processes.

vegetation and soil, the rate and form of land clearing, and the intensity of soil disturbance. Rates of land-use change depend on social, economic, and political factors. A net accumulation of C occurs in forests recovering from disturbance via storage in biomass, necromass, and soil. The rate of C accumulation is a function of biotic and abiotic conditions and human activities, and can occur over decades to centuries (Lugo and Brown, 1992).

Tropical forests have undergone many changes in land use over the centuries. The changes usually follow certain pathways; the main paths of concern to the global C cycle are shown in Figure 2. The development process begins with mature tropical forests which may have once been primary forests, but most no longer are (Brown and Lugo, 1990). Mature tropical forests are converted to logged forests, permanent agriculture and pastures, or shifting cultivation. Logged forests, when managed or protected, regenerate and recover towards a mature state. However, they are also often converted to permanent or shifting cultivation because logging activities provide access to the forests (Knabe et al., 1990). Shifting cultivation and forest fallows include areas just cleared and burned for subsistence agriculture and areas in natural forest regrowth. Under long rotation periods, this system is relatively sustainable. However with ever-shortening cycles, particularly in areas with increasing population pressures, these lands often become badly degraded. Poor

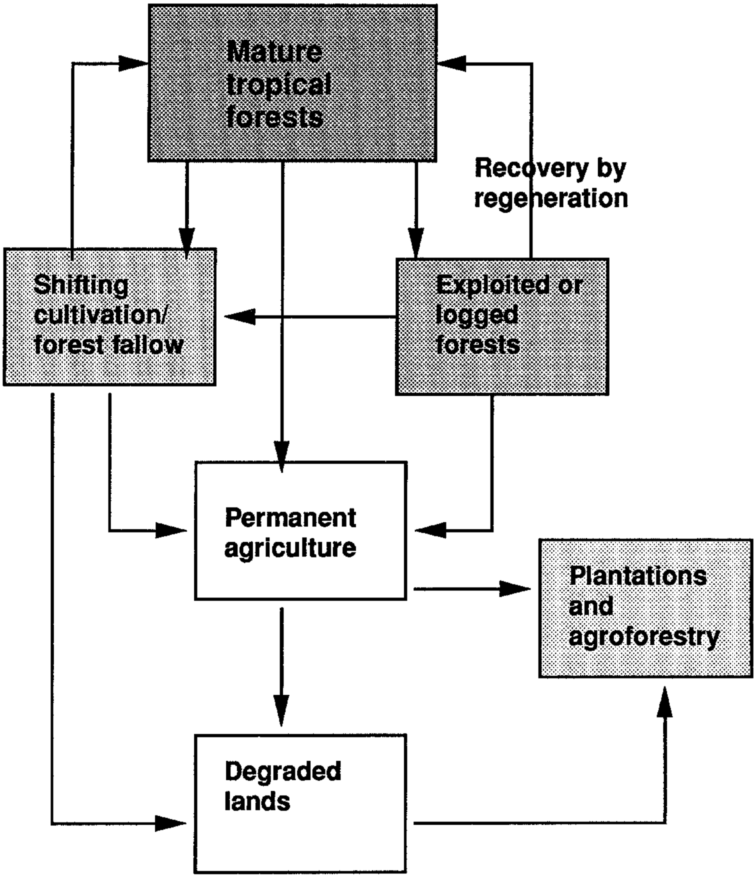

Figure 2. Land-use changes in the tropics of concern to the global C cycle.

agricultural practices or high grazing pressure also can lead to degraded lands. Re-establishment of vegetative cover through regeneration, plantations, or agroforestry or reduction in grazing would help to rehabilitate these degraded lands.

To determine the role of tropical forests in the global C budget requires that the model in Figure 1 be quantified thoroughly for all the land uses in Figure 2, from the past to the present. This has generally been done for most land uses and land-use changes in Figure 2 as far back as the 1800s as well as for recent decades (Brown et al., 1986; Detwiler and Hall, 1988; Hall and Uhlig, 1991; Houghton et al., 1983). Agroforestry systems generally have been ignored because their rates of establishment are small and exert very little influence on the global C cycle at present. Rates of C accumulation or loss in mature forests have also been ignored in C models to date on the assumption that they are in steady state with the atmosphere, an assumption that is difficult to support today (Brown and Lugo, 1990; Lugo and Brown, 1986,1992). It is now time to relax this assumption and develop complete C budgets and their changes for all land uses (Lugo and Wisniewski, 1992).

During the last two centuries the role of tropical forests in the global C budget has been complex, and many data gaps and uncertainties still exist. The main purposes of this paper are to (1) present results of research that quantify the C model in Figure 1 for the land uses and land-use changes in Figure 2 for past (about 1850), present (1990), and future (ca. 2050) conditions as a means of summarizing the present state of knowledge concerning the role of tropical forests in the global C budget and (2) assess the alternatives for tropical land management for C conservation and sequestration. We also give recommendations for future research needs to improve C budgets for the tropics and to undertake effective mitigation options.

2. Past Carbon Budgets

2.1. PAST CARBON FLUX ESTIMATES FROM DECONVOLUTION

Estimates of C fluxes between the terrestrial biota and atmosphere can be derived from simulation models of land-use change (e.g., Detwiler and Hall, 1988; Houghton et al., 1983) or from another method referred to as deconvolution (e.g., Sarmiento et al., 1992). This method uses the historic record of atmospheric CO_2 concentrations (obtained from ice cores, and then direct measurements after 1958) and ocean models to calculate annual C emissions and accumulations required to generate the historic atmospheric record. Subtraction of only the fossil fuel emissions from the total yields a residual non-fossil flux of C which is usually assumed to be a terrestrial flux.

Results from the deconvolution suggest a steady net biotic source of about 0.4-0.6 Pg C yr^{-1} to the atmosphere from 1850 to about 1935. After this time period, the flux became a net biotic sink (despite the apparent increase in C source from changes in land use in the tropics; cf. Figure 3) reaching a maximum of about 0.8 Pg C yr^{-1} in the 1970s. Then it abruptly became zero by the 1980s, where it has hovered until the present time. The cumulative net flux for the whole time period was a net release of 25 Pg. This differs markedly from the results of Houghton (1992a) who suggests that the tropics alone have been a source of about 67 Pg C.

If the deconvolution results are valid, there has been a large biotic C sink operating in the terrestrial landscape that we know little about. The total sink is not only that suggested by the deconvolution analysis itself, but also that to overcome the net source caused by changes in land use (not considered in the deconvolution analysis). Clearly we are still far from understanding the past C budget which of course influences our understanding of the present and future budgets for the tropics.

2.2. WHOLE TROPICS

Past estimates of terrestrial C pool sizes in the tropics (latitudes 23.5 N to 23.5 S) are limited to biome-specific estimates of natural vegetation types only vaguely arranged by latitude (e.g., Whittaker and Likens, 1973). Estimates of net C fluxes from the tropics have been made by extrapolating changes as far back as to about 1750, under the assumption that prior to this time, the tropical forest landscape was in steady state with respect to C exchanges to and from the atmosphere.

Humans have been active components of the tropical landscape for millennia, and their populations have fluctuated widely in specific areas (e.g., Mayans and Incas of Central and South America, and the past great civilizations of Cambodia and Sri Lanka). Despite these fluctuations, there has been an overall increase in human populations through time and a parallel increase in human-induced forest disturbance. It is likely, therefore, that the tropical landscape has not been in C steady state in recent history. Carbon losses occur in areas of increased human activities but C gains also occur on previously disturbed and now abandoned lands. The magnitude of these gains and losses are likely to be different across different geographic regions and what their balance is in time and space at this scale is largely unknown. Factors to consider are the general increase in human populations and economies, implying greater overall C losses than gains in forests, and the increased substitution of fossil fuels for wood fuels in many tropical countries implying reduced pressure on forests. These factors make clear that the relationship between population growth and forest disturbance is not linear.

Since 1850, the estimated contribution to the total biotic CO_2 emissions from land-use change in the tropics varies by region for different time periods (Figure 3). Until the early 1900s, the emissions were estimated to be greatest from tropical Asia, after which time significant increases occurred in Latin America. This region became the dominant source until about the mid 1970s. From the 1970s to the present time, emissions from Latin America and Asia have been about equal to each other. Emissions from Africa appear to have been the lowest during the whole period of record.

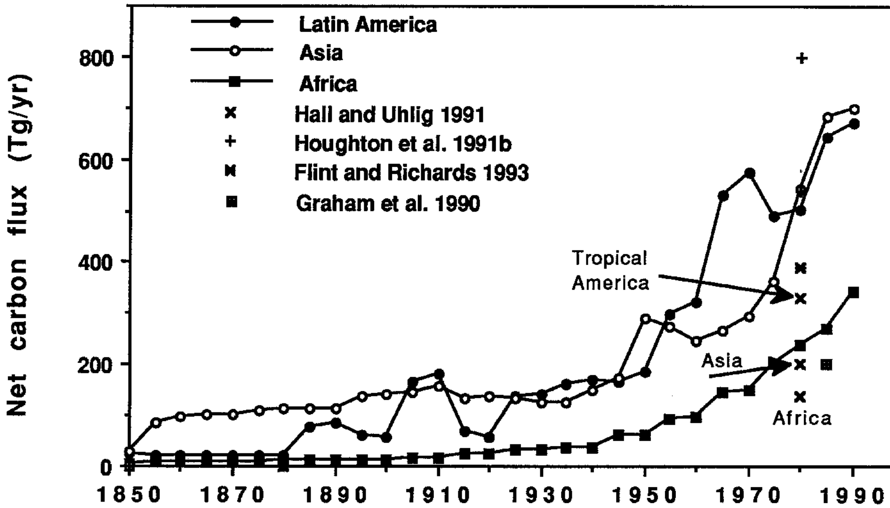

Figure 3. Net C flux from changes in tropical land use from 1850 to 1980 (data from Houghton, 1992a and indicated sources).

The high emissions from tropical Asia during the early part of the record reflect the accelerated pace of forest conversion and degradation caused by the introduction of plantations of spices, tea, rubber, and coffee after the Europeans arrived in the 19th century (Richards and Flint, 1993; Whitmore, 1984). This pace was accelerated further as mechanized logging was introduced and log extraction occurred over large areas (Whitmore, 1984). Large scale conversion of forests to croplands and pastures occurred after 1940 in Latin America (Houghton et al., 1991a) and still later in tropical Africa (Houghton, 1992a).

The total C flux from the tropics for the period 1850 to 1990 is estimated as 67.4 Pg (Houghton, 1992a). A best estimate for the annual flux for 1850 is 0.06 Pg C yr^{-1} (Houghton, 1992a), with an uncertainty range of 0.02-0.10 Pg C yr^{-1}.

2.3. REGIONAL ANALYSIS

Improvements in estimates of C emissions from the tropics are likely to be made when each region, with its unique history of land use and other ecological and socioeconomic information, is considered within the regional context rather than extrapolating a few data (e.g., forest C densities) across the whole tropics. Such improved analyses have been done to date for Latin America (tropical and non-tropical countries by Houghton et al., 1991a, b; selected countries by Hall et al., 1985), and tropical Asia (Flint and Richards, 1993; Houghton and Hackler, 1993; Iverson et al., 1993a; Richards and Flint, 1993). In addition, Hall and Uhlig (1991), using country-specific-data present results for all of the tropics. Although it is expected that these regional studies have improved estimates, it is important to realize that considerable uncertainties still remain, particularly the further back in time one goes.

2.3.1. Latin America

The analysis by Houghton et al. (1991a, b) for this region spanned the period 1850 to 1985. The major improvement in this analysis was a refinement of the data on land use and rates of land-use change in this region; data on C pools in vegetation and soils were basically the same as those used in other analyses by this group (e.g., Houghton et al. 1987). Up until about 1930, the simulated annual flux was less than 0.2 Pg C yr^{-1}, followed by a period of a slowly increasing flux to about 0.3 Pg C yr^{-1} by 1950. From 1950, the simulated flux increased rapidly to about 0.6 to 0.7 Pg yr^{-1} by 1965. By 1985, the net flux had increased to about 0.95 Pg yr^{-1}.

From a land use perspective, expansion of pasture lands and croplands was responsible for the greatest release of C (76% of total; Houghton et al., 1991a, b). From a process perspective, decay of plant material left on site at the time of harvest or clearing caused the largest release of C (43% of the total), yet this pathway is one of the most poorly understood (e.g., decomposition rates of slash, etc.). Changes in soil C contributed the least amount to the total flux (13%).

The estimated C flux from this region for the whole period was 30.7 Pg C, with an uncertainty range of 17.3 to 35.3 Pg C. An earlier analysis (Houghton et al., 1983), produced an estimate for this region of 42.5 Pg C for the period 1860 to 1980. Houghton et al. (1991b) believe that the lower estimate in their new analysis was due to improved estimates of soil C losses, more accurate assignment of lands cleared to ecosystem types, and presumably to C pools, and a more conservative approach to dealing with fuelwood. An even more recent simulation of the land-use change model by Houghton (1992a) results in an estimated flux of 25.1 Pg C for the period 1850 to 1985, a reduction from the

Houghton et al. (1991b) analysis. The work on Latin America demonstrates that more region-specific data can reduce C fluxes from the land and reduce the uncertainty range.

Table 1. Estimated carbon pools and net fluxes (by time interval; negative sign is a flux to the atmosphere; other values are a flux to the land) associated with changes in land use during different decades from 1880 to 1980 for 13 tropical Asian countries (Flint and Richards, 1993). The flux from soils is not included.

POOLS (Pg C):	1880	1920	1950	1980
Closed forests	46.39	39.18	31.16	20.63
Discontinuous forests	3.32	2.79	2.56	2.15
Grassland/shrubland	0.92	0.98	0.98	0.88
Barren/sparsely vegetated	0.06	0.06	0.06	0.05
Wetland forests	5.38	4.47	3.51	2.30
Wetland non-forests	0.24	0.18	0.14	0.10
Temporary crops	0.51	0.62	0.74	1.05
Permanent crops	0.17	0.30	0.59	0.93
Settled area, etc.	0.01	0.02	0.03	0.05
Total forest	55.08	46.44	37.24	25.09
Total non-forest	1.92	2.16	2.53	3.06
Total	57.00	48.60	39.77	28.15
FLUXES (Pg C yr^{-1}):	1880 -1920	1920 -1950	1950 -1980	1880 -1980
Closed forests	-7.21	-8.02	-10.53	-25.75
Discontinuous forests	-0.53	-0.23	-0.41	-1.16
Grassland/shrubland	0.06	0.00	-0.10	-0.04
Barren/sparsely vegetated	0.00	0.00	-0.01	-0.01
Wetland forests	-0.91	-0.96	-1.21	-3.07
Wetland non-forests	-0.06	-0.05	-0.04	-0.14
Temporary crops	0.11	0.12	0.31	0.54
Permanent crops	0.13	0.28	0.35	0.76
Settled area, etc.	0.01	0.01	0.02	0.03
Total forest	-8.64	-9.20	-12.14	-30.00
Total non-forest	0.25	0.37	0.53	1.14
Total net	-8.39	-8.84	-11.61	-28.84
Average annual	-0.21	-0.29	-0.39	-0.29

2.3.2. Tropical Asia

Flint and Richards (1993) approached their analysis for this region somewhat differently from the simulation models used for Latin America. Complete C inventories were developed for this region based on compiling data from the literature for more than 90 subnational units at different time periods (3 to 4 decade long periods) between 1880 to 1980. Differences between the C inventories through time were used to calculate the net flux. This approach accounted for conversion between land uses (forests to croplands and vice versa) and degradation of lands (mostly forests) remaining under the same use.

However, it did not account for soil C changes nor for time lags caused by decay of organic materials either left on site (e.g., slash) or at the user end (e.g., wood products).

A summary of their results of C pools and fluxes for the Asian region is given in Table 1. During the 100 yr period 1880 to 1980, the C pool in forest vegetation decreased by more than half, generating a net C flux of 28.8 Pg. Houghton and Hackler (1993), using a terrestrial C model and adding a new routine to account for forest biomass degradation, obtained a net C flux, including soils, of 19.2 to 32.6 Pg for the period 1850 to 1990. The estimate by Flint and Richards (1993) would be larger and closer to the upper limit of Houghton and Hackler's results if soil C losses (about 4.5 Pg C for the period; Houghton and Hackler, 1993) were added and the period extended to 1990.

2.3.3. Tropical Africa

To date, no specific historical analysis of this region has been done, other than the results shown in Figure 3.

3. Present (1980-90) Carbon Budgets

The C pool in living above and below ground vegetation of tropical forests (trees only, which accounts for about 95% of the total; Brown and Lugo, 1992) was estimated to be 159 Pg and that in soil (litter layer and mineral soil to 1 m depth) 216 Pg (R. Dixon and S. Brown, unpublished results from ongoing research; Eswaran et al., 1993).

Estimates of C emissions from the tropics caused by changes in land use have varied widely, from 0.4 to 2.5 Pg yr^{-1} for 1980 and from 1.5 to 3.0 Pg yr^{-1} for 1989/90 (Table 2). The range represents about 10 to 50% and 25 to 54% for 1980 and 1990, respectively, of the emissions from global fossil fuel burning. The uncertainty in these estimates has been large due to high uncertainties in rates of deforestation, rates of forest degradation, fate of deforested lands, and C pools of the forests being cleared (Brown and Iverson 1992).

Table 2. Recent estimates of the carbon flux, Pg C yr^{-1}, from the tropical landscape for 1980 and 1990.

Source	Year	Range	Average
Detwiler and Hall, 1988	1980	0.4-1.6	1.0
Hall and Uhlig, 1991	1980	0.52-0.64	0.58
Houghton et al., 1987	1980	0.9-2.5	1.7
Houghton 1992a	1980		1.3
Houghton 1991	1989	1.5-3.0	
Houghton 1992a	1990	1.2-2.2	1.7

To further compound this uncertainty, rates of tropical deforestation have increased in the last decade, from about 12 Mha yr^{-1} in 1980 to 15.4 Mha yr^{-1} in 1990 (Aldhous, 1993), and these new estimates of land-use change have not yet been incorporated into all the models. Furthermore, there is now evidence that many of the "undisturbed" forests, particularly in tropical Asia are undergoing degradation, that is their C pools are being reduced, often by illicit removals of wood for fuel or timber that does not get recorded by the usual channels (Brown et al., 1991, 1993; Iverson et al., 1993a; Richards and Flint, 1993). Attempts to incorporate such forest biomass degradation into the terrestrial C models have been made for tropical Asia (Houghton and Hackler, 1993) but not the rest of the tropics. Evidence also exists for the reverse process, that is forests assumed to be undisturbed are accumulating biomass (Brown et al., 1993; Lugo and Brown, 1992). However, to what degree the loss or gain of biomass in mature forests is pan-tropical still needs to be determined.

Our present best estimate for the net C flux to the atmosphere from tropical land-use change in 1980 is 1.0 to1.3 Pg yr^{-1} and for 1990 1.2 to 2.2 Pg yr^{-1} (Table 2). The estimate from land use change in the Brazilian Amazon alone accounts for up to 58% of the 1990 flux (Fearnside 1992). These estimates do not include fluxes associated with reduction in biomass caused by degradation nor biomass accumulation in forests classed as "undisturbed" or assumed to be in steady state.

Estimates of the 1980 C flux, for regional and total tropics, based on the work of Houghton et al. (1991b) and Houghton (1992a) are higher in all cases than estimates made by others (Figure 3 and Table 2). The lowest estimates at the regional scale are those made by Hall and Uhlig (1991). However, compared to the range of flux estimates made by the different investigators about a 5 to 10 yr ago, present estimates are substantially closer in agreement.

Although all studies use essentially the same data sets, different results are produced because of differences in preferred rates of land-use change and C densities, differences in how certain modeling routines allocate C after clearing and burning, and differences in modeling shifting cultivation, forest logging, and forest regrowth. For example, the model used by Hall and his co-workers retains a portion of the original forest C as long term storage in charcoal and soot (not considered in the other models). While this process is logical and supported by the literature, the value of the parameter is very uncertain (3-19% of the initial biomass C) and the model output is very sensitive to it. For countries with extensive shifting cultivation, a significant portion of the biomass can be converted to charcoal each cycle, and with many cycles over large areas this will substantially reduce net C emissions.

4. Potential Future Carbon Budgets

Many variables will affect future C storage in, and fluxes to and from tropical forested regions. The most important of these, certainly in the short to medium term, is continued anthropogenic alteration of the landscape. Longer term influences include increasing atmospheric CO_2 concentrations, possible changes in temperatures and precipitation, and changes in patterns and magnitudes of chemical inputs from the atmosphere. We evaluate the potential impacts of these different variables and their possible influence on net C fluxes from the tropical forest regions for the year 2050. First, we consider probable land-use changes, followed by a brief evaluation of the potential impacts of higher CO_2 concentrations (doubling pre-industrial values) on net C fluxes in the altered landscape. Then we evaluate the possible changes associated with predicted climate changes. Global climate models are consistent in predicting a mean temperature rise of 1 to 2 C throughout the year in tropical regions, but vary in their predictions of the total amounts and seasonal distribution of precipitation. Therefore, both increases or decreases in precipitation will be considered as possible scenarios.

4.1. LAND-USE CHANGE

Continuing anthropogenic impacts on tropical forests are the most immediate source of future C fluxes from the tropical landscape into the atmosphere. Predictions of anthropogenic flux are dependent upon many variables, and consequently remain speculative. Despite the many factors that are important, human population growth and the demand for agricultural lands will dominate by driving land-use changes for the foreseeable future. Other related issues that will influence the level of future deforestation, forest degradation, forest recovery, and other C gains and losses include economic and social variables such as economic growth, agricultural productivity improvements, government policies ranging from land tenure to taxation, resource constraints, level of industrialization, and international terms of trade (Deutscher Bundestag, 1990). They also include public perceptions regarding the role of forests in furthering or impeding economic development. The relationship between C fluxes and these variables will not be linear, nor will it be consistent among nations.

With continued and complete deforestation of tropical forests, the maximum amount of C that could be released to the atmosphere would be nearly equal to the present "active" forest C pool, or about 200 Pg (160 Pg in vegetation and 40 Pg C from soil; see Section 3. above and using a soil C loss rate given in Houghton et al., 1991b). This represents an average annual C source of 3.3 Pg yr^{-1} for the next 60 years. This value is approximately twice the net flux estimated for 1990 (Table 2). However, not all tropical forests will ever be cleared; even now rates of deforestation in several nations have slowed (e.g., Thailand and Brazil).

Not only are some tropical countries making efforts to curb their deforestation rates, but efforts by the international community are also being proposed and mounted to reduce rates. For example, the Enquete-Commission of the German Bundestag proposed an aggressive three-stage program to counteract deforestation (Deutscher Bundestag 1990). It first proposed a crash program within the scope of international negotiations to slow rates of deforestation and to protect undisturbed forests that are in great danger of being destroyed. Next, it proposed that deforestation be brought to a complete halt by 2010, followed by a program to restore forest cover in tropical countries to the level of 1990. Funding for such a program is to be accomplished from yearly contributions by developed, non-tropical countries. Certainly the outcome of the 1992 United Nations Conference on Environment and Development (particularly Agenda 21 and the Biodiversity and Climate Change Conventions) provides the groundwork for such a program proposed by the Enquete-Commission.

A recent study attempts to anticipate likely deforestation rates for 54 tropical countries encompassing most of the tropical forest region (Trexler and Haugen, 1993). This study starts with a 1990 baseline rate of tropical deforestation of 15 Mha yr^{-1}, with a corresponding C release of 0.95 to 18 Pg C yr^{-1} under low and high biomass scenarios. These figures correspond well with other estimates of both the areal extent of deforestation (Aldhous, 1993) and associated C release (Table 2). Future deforestation rates were estimated by Trexler and Haugen for each country on a decade by decade basis, based on a subjective consideration of many physical, social and economic variables such as those mentioned above, and upon extensive interviews with country experts. They did not include natural processes of forest recovery and growth nor reduction in forest biomass density caused by degradation. The study concluded that 660 Mha are likely to be deforested in these 54 countries through 2050 (reducing the 1990 forest area by about a third), with net C emissions of 41 to 77 Pg under low and high biomass scenarios. By 2050, emissions level off towards 0.5 to 1.0 Pg C yr^{-1}, and would probably decline thereafter.

4.2. CHANGES IN ATMOSPHERIC CO_2 CONCENTRATIONS

By the year 2050 it is estimated that the atmospheric CO_2 concentration will be approximately 2.5 times the pre-industrial level of 280 ppm under the business-as-usual scenario (Houghton et al., 1992). It has been hypothesized that this change in C availability to plants will modify C exchange rates between the tropical biota and atmosphere (i.e., CO_2 fertilization), irrespective of any changes in climate.

A principal effect of increased atmospheric CO_2 concentrations is increased C fixation rates over the short term, as documented in a variety of field and laboratory experiments (e.g., Kimball et al., 1993). Increased rates of photosynthesis and plant growth favor C assimilation by plants and would thereby diminish the net C flux from the tropical region, if short-term responses of plants are predictive of their long-term responses, which is uncertain.

Recent work with humid tropical forest mesocosms in controlled-environment growth chambers (Korner and Arnone, 1992) indicated that leaf area and plant biomass were not significantly increased under high-CO_2 conditions. Furthermore, although C stores did not increase significantly, litter production, fine root growth, rates of mineral nutrient leaching, and rates of soil respiration all increased. Thus, doubling of atmospheric CO_2 concentrations had a small effect on C storage within the mesocosms, but stimulated rates of C and nutrient cycling substantially. However, the study was of a very short duration (about 3 mo). The lack of a significant increase in C stores in the mesocosms does not imply that humid tropical forests will respond this way in the longer term. Nor does it rule out that other tropical forests will be stimulated.

Plant growth is expected to be stimulated in tropical dry forests because they tend to be water-limited rather than nutrient-limited and CO_2 enrichment increases water-use efficiency (measured as the amount of water lost per unit of C assimilated) by C3 plants. Changes in the water-use efficiency of plants may have very important impacts in seasonally dry and arid regions. Under field conditions, it is possible that rates of C assimilation throughout the growing season will increase dramatically under high-CO_2 conditions (e.g., Idso, 1988), leading to a greater potential for agriculture, agroforestry, and forestry in these regions, and concomitant increases in net C storage. Furthermore, soils of the dry tropics tend to be more nutrient rich compared to the humid tropics as they have not been intensively leached. Although difficult to predict because of the lack of research on this topic, it is in the seasonally dry and semiarid lands of the tropics that we may expect to see the greatest changes in plant productivity and C sequestering. However, changes in climate could counteract this expectation if they become more arid.

Increases in plant C:N and root:shoot ratios are also observed under high-CO_2 conditions (Norby et al,. 1986; Overdieck this volume). The consequent change in the C:N ratio (and ratio of C to other plant nutrients) of litter produced by the vegetation has the potential to increase immobilization of plant nutrients by increasing competition between soil organisms and plants, and thereby decrease plant nutrient availability and plant production. This reduction may be balanced against the opposing effect of greater (potential) root production under high-CO_2 conditions. With a greater ability to exploit soil nutrient and water resources, plants may in fact benefit from high-CO_2 conditions. It is clear that further research is needed to shed light on these potential ecosystem responses.

All in all, there is no reason now to accept or reject the hypothesis that a change in the relative availability of CO_2 and plant nutrients caused by a change in the atmospheric CO_2 concentration will impact tropical vegetation dramatically. Experiments larger and longer than any yet conceived by ecologists would be necessary to begin to give definitive answers to this persistent question.

4.3. CLIMATE CHANGE IMPACTS

Climates have changed and will change from natural and anthropogenic phenomena. These changes in the past have changed vegetation patterns dramatically in the tropics. For example, much of the Amazon basin that is now forested was savanna during the Pleistocene. Natural climate changes are relatively slow, whereas human-induced climate change is expected to occur more rapidly. With respect to modeling the effects of greenhouse gas emission, global climate models are consistent in predicting a 1 to 2 C increases in temperature throughout the tropical region by 2050 (Houghton et al. 1992). These changes will lead to higher air and soil temperatures, greater water demand by the atmosphere, and, without compensating changes in precipitation, greater aridity during dry periods. Therefore, we expect direct temperature effects on plants, other organisms, and soil, and indirect effects on water and nutrient availability.

Not only will climate change affect processes within ecosystems, but it is likely to cause shifts in present distribution of vegetation types within and between biomes as well (Cramer and Solomon, 1993; Leemans, 1992; Neilson, this volume). For example, within the tropical latitudes, the area of dry forests and savannas is projected to increase by about 11% over present values under the future climate at double CO_2, whereas the areas of tropical seasonal and moist forests are projected to decrease by about 4% or less (R. Leemans, pers. comm.; results based on the BIOME model of Prentice et al., 1992). The changes are not uniform over all continents; tropical moist forests in South America are projected to increase in area over present day extent by about 5% whereas all other continents will experience a loss of up to 20% in Asia.

Increasing temperatures are expected to increase both net photosynthesis and plant respiration rates (e.g., Larcher, 1983). If rates of net photosynthesis increase more slowly than do rates of plant respiration (for example if nighttime temperatures increase more rapidly than daytime temperatures), it may be that net productivity at the stand level will diminish. However, statistical summaries show a positive correlation between total net primary productivity (NPP) and temperature (e.g., Box, 1978) and between actual evapotranspiration (AET) and NPP (Raich et al., 1991; Rosenzweig, 1968). Temperature and AET are closely related where water is abundant. At present, there are no stand-level empirical data which support a decrease in productivity at higher temperatures within the range of 20-30 C, despite the theoretical strengths of this argument.

Increasing soil temperatures increase rates of CO_2 efflux from soils, all other factors remaining the same (Raich and Schlesinger 1992). Under the assumptions that soil temperatures in the tropics will increase 1 to 2 C by change in climate and that rates of soil-CO_2 production double for every 10 C increase in temperature, the rate of soil-CO_2 efflux in tropical dry and moist forests could increase by 8% and 16% for a 1 and 2 C temperature rise, respectively. However, this potential C loss may be negated by greater C inputs to the soil via increased rates of plant productivity and changes in the chemical characteristics of plant litter (see Section 4.2). For example, an increased lignin:N ratio increases the proportion of litter inputs that become stabilized soil organic matter (Parton et al., 1987). Thus, C cycling rates could be stimulated with minimal impacts on mean net C pool sizes. Again, the actual effects of climate warming are not readily predicted from existing information.

Predicted changes in magnitudes and distribution of rainfall in the tropical forest regions of the world vary among the models from decreases to increases in different places. Plant production tends to increase with increasing precipitation in the tropics (Brown and Lugo, 1982; Raich et al., 1991). Decreasing precipitation and/or increased aridity due to increased evapotranspiration demands can be expected to decrease net C uptake. Furthermore, potential changes in water budgets will affect streamflow and export of C from the land by rivers. Without better information it is impossible to predict what the net effects of changes in precipitation will have on net C fluxes in tropical forests in 2050.

4.4. EFFECTS OF ALTERED PATTERNS OF CHEMICAL INPUTS TO THE ATMOSPHERE

Human activities stimulate the biogeochemical cycling rates of many materials, including the plant nutrients N, P, and S (Peterson and Melillo, 1985). This eutrophication of the biosphere could increase the forest C sink by about 0.25% of the annual forest net primary production only, and mostly in the temperate zone (Peterson and Melillo 1985).

Not only do human activities simulate the cycling of plant nutrients, but they also produce other gases and air pollutants that adversely affect forests. For example, the increase in tropical fires and biomass burning produces (1) methane and CO which interfere with stratospheric ozone, and (2) hydrocarbons, NOx, and SO_2 which are precursors of phytotoxic photo-oxidants (Andreae et al., 1988; Crutzen et al., 1989). These gases can affect forests by reducing photosynthesis and causing adverse effects on soils and root systems (Knabe 1983). Thus, there is the potential to damage tropical forests, but so far to an unknown degree.

4.5. INTERACTIVE EFFECTS OF CHANGES IN LAND USE, CLIMATE AND ATMOSPHERIC CO_2 ON NET CARBON FLUXES

The interactive effects of all future processes impacting tropical forests are extremely complex and are poorly understood as the forgoing single-effect discussions have illustrated. It is likely under current land management practices, however, that anthropogenic land-use change will overwhelm any future changes in C fluxes (sources or sinks) from CO_2-fertilization and climate change as less forest vegetation is left to respond. Even if C pools of forests increase due to CO_2-fertilization and/or climate change, then those forests being cleared in the future will have larger C pools and thus release larger quantities when they are deforested. Further increases in C fluxes from changes in land use could be slowed or reversed with different land management practices as will be discussed in Section 5.

Comprehensive models are needed to integrate all of the effects due to CO_2-fertilization, climate change, and other atmospheric chemical inputs within the next 5 to 10 yr. Information and sub models are now available to start this process. These models could give more accurate estimates of future C storage and fluxes, although the accuracy of the predictions would still be constrained by the broad uncertainties of social and political activities.

5. Potential for Management of Tropical Lands for Carbon Conservation and Sequestration

The "business-as-usual" scenario is seen above (Section 4.1) to result in the ongoing loss of tropical forests at a rapid rate. Anthropogenic deforestation will likely continue to be rooted in the same complex set of demographic, institutional, and policy variables that are operative today. This magnitude of forest loss and other forms of land degradation will impose tremendous economic, social, and environmental costs on the people and resource bases of many tropical countries. Past attempts to reduce global deforestation rates have met with limited success, partially caused by severe resource constraints for the types of programs that have been called for repeatedly, including forest protection, agricultural intensification, and natural forest management. The expanding interest in climate change mitigation may both be a lever to encourage policy reform in tropical forest nations, and to encourage international funding of measures to protect existing forests and to expand reforestation efforts (see Section 4.1 and Deutscher Bundestag, 1990). Such programs will be successful only if they are integrated with the social and economic needs of the local people.

Observation of the biotic C cycle suggests several techniques that would help slow the accumulation of C in the atmosphere. These are:

1. Slowing the loss and degradation of existing forests. This can be furthered through establishing protected areas, forest reserves and parks, managing natural forests for multiple use, improving the practices and efficiency of exploitative activities such as logging, and in particular working with shifting cultivators to implement different agricultural practices, thus decreasing pressure on remaining forests.

2. Expanding the size of existing C reservoirs in vegetation and in products. Over 1 Gha of previously forested land have been converted to agricultural, pastoral, and other uses in the tropics. In many cases this land has proved incapable of sustaining long-term uses, is continuously degrading, and may even be abandoned. Very large areas of land would be more productive and economic over time if returned to tree cover. This can be promoted by encouraging the regeneration or reforestation of previously forested areas, promoting sustainable agricultural practices to reduce slash-and-burn pressures, and assisting in the recovery of severely degraded forests. Such measures would often be ecologically and socially beneficial. Hundreds of millions of additional hectares could support in principle both higher agricultural yields and additional tree cover through agroforestry systems.

3. Conserving and expanding the size of soil C reservoirs. Forest clearing and continuous cropping has resulted in near universal declines of soil organic C. This C is lost directly into the atmosphere or transported via runoff and soil erosion. Present soil conservation measures are a start in the maintenance of existing soil C pools, but the

ability of degraded soils to re-accumulate C as a result of reforestation or other land management practices has significant long-term potential.

4. Substituting biomass for present and future fossil fuel use in energy production. Either waste products from other industrial processes may be used (e.g. sugar, rice, and timber production residues), or biomass can be grown specifically for energy production (see Sampson et al., this volume). Biomass could be grown in large-scale plantations on presently non-forested land or rely on a dispersed supply system using small-scale growers. Biomass could displace both the small-scale use of kerosene and gas-use in cities and the need for fossil-fuel electric plants.

The potential of these options to slow CO_2 accumulation in the atmosphere depends on previous experiences, costs, the response of the local population, and the will of governments and the international community to conserve forests and stabilize global climate (Deutscher Bundestag, 1990).

Several studies have assessed the availability of land on which additional C could be stored (Brown et al., 1992; Grainger, 1988, 1990; Houghton et al., 1991c; Iverson et al., 1993b). A summary of the literature concluded that land technically suitable in the tropics for expanded management and agroforestry is somewhere between 0.62 to more than 1 G ha (Dixon et al., 1991). These studies of land availability tend to define land potential differently, resulting in an inability to compare estimates and methodologies. In addition, almost all of the work has focused strictly on the physical availability of land, which is not likely to have much relationship to how much land can actually be made available for forestry interventions. Land regarded as degraded is often a vital base of subsistence for somebody and would be defended against any attempt to reforest without advantage to the traditional user. That is, very little of what might be considered degraded tropical lands is in practice likely to be abandoned land.

These estimates of land suitability must be viewed with care in that they generally omit consideration of the political, social, and economic forces influencing true land availability. Furthermore, very few projections exist of the potential for slowing deforestation or exploiting biomass resources in place of fossil fuels. An attempt to take these various variables into account for more than 50 tropical countries is presented by Trexler and Haugen (1993). Based on country-specific information and experts, the study estimates by decade how much deforestation could plausibly be reduced, how much land could be assisted to regenerate, how much land could be converted to agroforestry systems, and how much land could reasonably be converted to plantations in light of infrastructural and supply and demand variables (Table 3). The end-use of several hundred million hectares could probably be changed through concerted policy interventions between now and 2050.

Trexler and Haugen (1993) conclude that as much as 50 Pg C could be kept from or removed from the atmosphere by 2050 through the aggressive pursuit of the practices discussed in Table 3. Figure 4 illustrates continent by continent the gradual reduction in emissions resulting from the implementation of these practices. Slowing deforestation and natural forest regeneration account for the largest C gain (78%), followed by plantation establishment (19%), and agroforestry (3%) (Figure 5). This trend in C gains confirms previous experience and analysis that showed forest conservation and natural regeneration is cheaper, easier, and less likely to be resisted by the local population than reforestation (Deutscher Bundestag, 1990).

Table 3. Estimates of areas of tropical lands in 54 countries potentially and actually available for C sequestration options (Trexler and Haugen, 1993).

Sequestration option	Potential area (Mha)	Actual area (Mha)
Slowing deforestation	647.3	509.2
Natural regeneration	314.8	216.7
Agroforestry	156.5	66.1
Plantation establishment	72.8	66.8

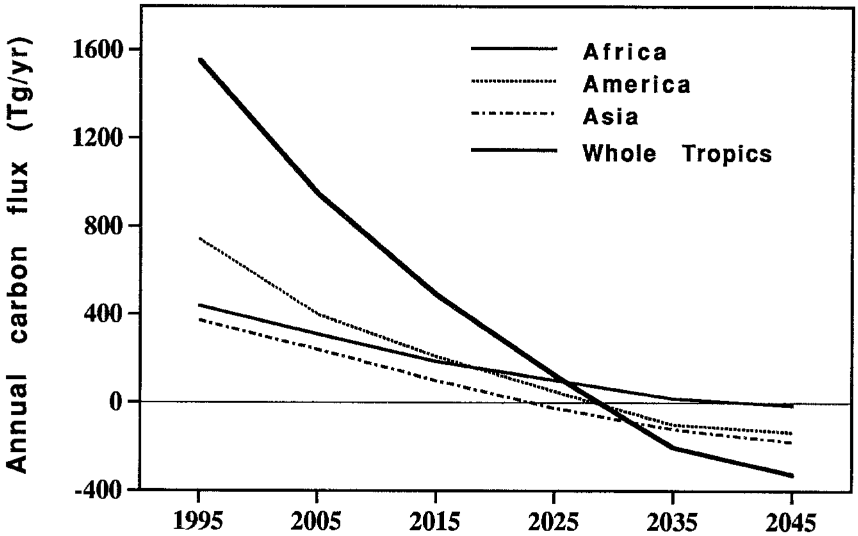

Figure 4. Gradual reduction in C emissions, continent by continent, resulting from implementation of the C conservation/sequestration practices given in Table 3 (from Trexler and Haugen, 1993).

Land availability per se is not the primary constraint to using forestry for climate change mitigation in the near to mid-term (Trexler and Haugen, 1993). Social, political, and infrastructural barriers are likely to keep possible reforestation rates modest for at least a decade or so. Even then, the rate at which reforestation and other measures can be accomplished realistically is modest compared to the plausible availability of land in many countries of the tropics. Given the magnitude of ongoing deforestation, the continuing pressures associated with rising human populations, and the necessarily incremental impacts of measures to slow deforestation, Trexler and Haugen conclude that, even if such a plan could be implemented, it would not be until 2030 before the 54 countries as a group become a net sink for biotic C (Figure 4). It will be considerably longer, if ever, before biotic C levels in these countries could return to the levels present today. With population and other pressures building throughout the tropics, the scenarios presented by Trexler and Haugen (1993) would represent dramatic increases in the effectiveness and magnitude of forestry programs.

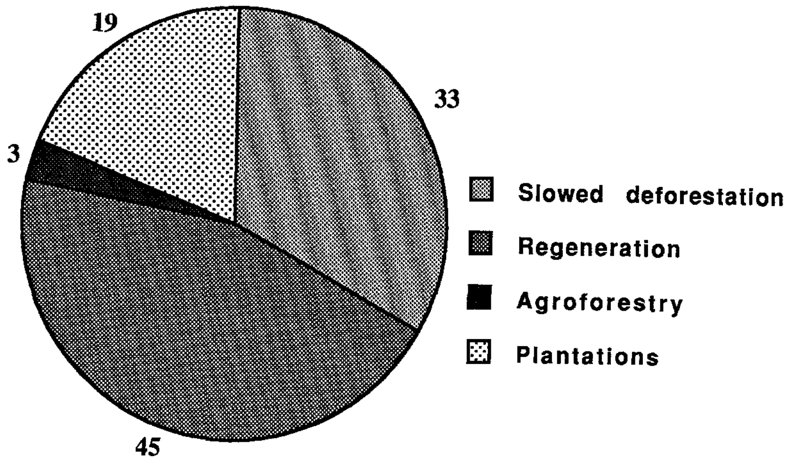

Figure 5. Relative contribution of each policy given in Table 3 to reduce C emissions to the cumulative effect for 1990-2050 (from Trexler and Haugen, 1993).

The analysis of Trexler and Haugen (1993) focuses on the ability to prevent deforestatation and to return tree cover in some form to already deforested lands. It does not include C losses or gains associated with further degradation or recovery of existing forests, the potential recovery of biomass on land deforested between now and 2050, the potential for increased forest management, or the land-use and C fluxes associated with potential climate change itself. Neither do they include the potential for changes in soil organic C (losses and gains) in their analysis. Activities that promote increases in C sequestration in vegetation also cause increases in soil organic C (Lugo and Brown, 1993). Judicious selection of plantation and agroforestry species can cause soil organic C to accumulate faster than under secondary forests. The accumulation rate of soil C therefore, need not be slow and there are alternatives for managers to increase or conserve the pool (Lugo and Brown, 1993).

Storage of additional C in soils will be an important mechanism for long term C offset objectives. Soil organic C can be separated into different functional pools, active, slow, and passive fractions, based on their residence times within soils (Parton et al., 1987; Swift and Woomer, 1993). The potential to replenish different soil C pools is related to the formation and turnover times of these pools. The passive pool is stable for hundreds to thousands of years and is not subject to management. On the other hand, the active pool is highly subject to recent organic additions to soils and subject to rapid loss when these inputs are not longer available. The slow pool, derived from litter inputs, can form rapidly depending upon the quantity and quality of the inputs, and is lost over decades. Because this pool turns over slowly, it is likely to be a more secure C sequestering mechanism than plant biomass (Lugo and Brown, 1993).

Trexler and Haugen (1993) did not include in their analysis the potential for large-scale commercial biomass utilization in the tropics. There are major impediments to the use of commercial biomass in the tropics, even on a more localized scale. Developing countries may not wish to be seen relying upon "primitive" biomass sources, preferring instead to emulate the energy technologies of more industrialized countries. Furthermore, the history of commercial plantations in the tropics is checkered at best, and indeed there is little precedent for the scale of planting that would be involved. Other important issues that would be faced include technology transfer barriers, the danger that natural forests would be cleared or relied upon for biomass supplies, and the sustainability of intensive biomass production on tropical soils. Nevertheless, the theoretical potential of biomass technologies to affect net C fluxes in the tropics is so large as to merit much more investigation.

Assessing the potential costs of measures such as those discussed here is difficult. Work by Dixon et al. (1991) is a first step in identifying ranges of potential costs, but the cost picture is complex. Some of the land-use changes proposed are likely to be cost-effective in their own right, requiring no "C subsidy". Others are not, and will require such a subsidy. It is also difficult to prepare a proper economic analysis as C storage is just one of the implications of many tropical forestry programs, and the many other costs and benefits (e.g. watershed protection, conservation of biological diversity, income generation) are equally difficult to quantify.

Overall, our ability to predict accurately future management opportunities in tropical forest areas is not well developed. Much more intensive country-specific assessments are called for. Shifting cultivators in particular will present very difficult problems calling for intensive extension and other services. Tropical forestry programs undertaken with global change mitigation in mind will need to be integrated into the social, environmental, and economic contexts and needs of the countries in which they are undertaken. Failure to understand this has brought about the failure of many tropical forestry efforts intended to solve fuelwood and other problems. The same could easily occur with forestry efforts intended to mitigate global climate change.

6. Research Needs

6.1. NEEDS FOR IMPROVING PAST, PRESENT AND FUTURE CARBON BUDGETS

1. The most effective way to reduce a large amount of the uncertainty in C flux and pool estimates in the tropics is to improve the mapping of area and area-change of land cover/land use using remote sensing technology, including the identification of all classes of disturbed forests (highly disturbed to mature). As the analysis requires several points in time, equal effort should be spent on earlier remote sensing imagery (1970s) as well as more recent imagery.

2. Efforts should be made to improve the estimates of C pool sizes in different types of tropical vegetation and soils. Recent work by Iverson et al. (1993a) and Brown and Iverson (research in progress) have demonstrated that producing maps of forest biomass (the tree component only) and soil C densities using a modeling approach in a geographic information system (GIS) is feasible. This approach needs to be expanded to the whole tropics, and improved to include C in other forest components (e.g., understory, woody debris, etc.). If coupled in a GIS with improved information and maps of land use over

time, a spatially detailed analysis of both magnitudes of C pools and fluxes will be possible. Thus changes in land use can then be matched with the appropriate C stocks, and present uncertainties in C pool and flux estimates can be reduced. This type of analysis could be coupled to other ecosystem or climate models to investigate future potential changes.

3. Establishment of a network of permanent, continuous forest inventory plots is needed to allow for detection of change in C densities of tropical forest lands. This should be coupled with remote sensing imagery to place the network of plots into a regional monitoring context. Such a network is the only way to determine rates of C accumulation or loss by different types of forests (i.e., mature and young, moist and dry, protected and unprotected). Until progress is made in establishing a continuous forest inventory network in conjunction with monitoring by remote sensing, our ability to balance the C budget in the tropics will remain elusive.

4. A more comprehensive analysis of the fate of burned or otherwise disturbed biomass-C such as charcoal is needed. This is particularly important in models of shifting cultivation as shown by Detwiler and Hall (1988) and Hall and Uhlig (1991); their simulated C flux is very sensitive to the proportion of the biomass that remains as charcoal.

5. Efforts should be made on developing relationships/models between changes in land use, forest degradation, and C densities and other variables such as population density, transportation network densities, logging, hardwood trade, agricultural production, etc. These empirical models are needed for reliably projecting future trends in land use and C fluxes in the tropics.

6. Comprehensive models need to be developed, using the spatially-oriented data bases generated by the above research items, to allow the synthesis and simulation of the complex interactions, including possible management scenarios, that are likely to influence tropical forests into the future.

7. Because past patterns of land use strongly influence the present C budget (pools and fluxes) by generating lands of different C pools and fluxes, it is imperative that the history of land use and corresponding C densities be well documented. The approach discussed above for tropical Asia (cf. Section 2.3.2) is a step in the right direction, however, the analysis needs to be expanded to the whole tropics.

8. Ecosystem-level studies to measure the effects of CO_2-enrichment and climate change on mature and secondary dry and humid tropical forests need to be established. These need to extend for several years as the effects may take this length of time to become fully apparent.

6.2. NEEDS FOR IMPROVING ESTIMATES OF CARBON SEQUESTRATION AND CONSERVATION FOR CLIMATE CHANGE MITIGATION

1. Improve research efforts to produce better estimates of areas and location of lands technically and actually available for C conservation and sequestration projects, and the likely quantities and rates of C that could be sequestered or conserved on these lands.

2. The management of soil organic C formation as a tool for C sequestration is poorly understood. Additional research on C allocation patterns (to aboveground litter or fine roots) in different plant species and how organic C enters into the different soil C pools could be particularly useful in selecting appropriate strategies for soil C management.

3. Develop and implement management schemes to learn which ones do and do not work for C conservation and sequestration over the long term. Emphasis should be placed on developing sustainable alternatives to the non-traditional forms of shifting cultivation to reduce deforestation.

7. References

Aldhous, P.: 1993, tropical deforestation: not just a problem in Amazonia, *Science* 259,1390.

Andreae, M. O., E. V. Browell, M. Garstang, G. L. Gregory, R. C. Harriss, G. F. Hill, D. J. Jacob, M. C. Periera, G. W. Sachse, A. W. Setzer, P. L. Silva Dias, R. W. Talbot, A. L. Torres, S. C. Wofsy.: 1988, Biomass-burning emissions and associated haze layers over Amazonia, *Journal of Geophysical Research* 93, 1509-1527.

Box, E.: 1978, Geographical dimensions of terrestrial net and gross primary productivity, *Radiation and Environmental Biophysics* 15, 305-322.

Brown, S., L. R. Iverson.: 1992, Biomass estimates for tropical forests, *World Resource Review* 4, 366-384.

Brown, S., A. E. Lugo.: 1982, Storage and production of organic matter in tropical forests and their role in the global carbon cycle, *Biotropica* 14, 161-187.

Brown, S., A. E. Lugo.: 1990, Tropical secondary forests, *Journal of Tropical Ecology* 6, 1-32.

Brown, S., A. E. Lugo.: 1992, Aboveground biomass estimates for tropical moist forests of the Brazilian Amazon, *Interciencia* 17, 8-18.

Brown, S., A. J. R. Gillespie, A. E. Lugo.: 1991, Biomass of tropical forests of south and southeast Asia, *Canadian Journal of Forest Research* 21, 111-117.

Brown, S., L. R. Iverson, A. E. Lugo.: 1993, Land use and biomass changes in Peninsular Malaysia during 1972-82: a GIS approach, in V. Dale (ed), *Effects of Land Use Change in Atmospheric CO_2 Concentrations: Southeast Asia as a Case Study*, Springer-Verlag, in press.

Brown, S., A. E. Lugo, J. Chapman.: 1986, Biomass of tropical tree plantations and its implications for the global carbon budget, *Canadian Journal of Forest Research* 16, 390-394.

Brown, S., A. E. Lugo, L. R. Iverson.: 1992, Processes and lands for sequestering carbon in the tropical forest landscape, *Water, Air and Soil Pollution* 64, 139-155.

Cramer, W. P., A. M. Solomon.: 1993, Climatic classification and future global redistribution of agricultural land, *Climate Research*, in press.

Crutzen, P. J., W. M. Hao, M. H. Liu.: 1989, Estimates of annual and regional releases of CO_2 and other trace gases to the atmosphere from fires in the tropics based on FAO statistics for the period 1975 to 1980, *Proceedings of the Third International Symposium on Fire Ecology*, Freiburg University, 16-20 May, 1989, Berlin.

Detwiler, R. P., C. A. S. Hall.: 1988, Tropical forests and the global carbon cycle, *Science* 239, 42-47.

Dixon, R. K., P. E. Schroeder, J. K. Winjum (eds).: 1991. *Assessment of Promising Forest Management Practices and Technologies for Enhancing the Conservation and Sequestration of Atmospheric Carbon and Their Costs at the Site Level*, EPA/600/3-91/067, US. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, Oregon, USA.

Deutscher Bundestag (ed).: 1990, *Protecting the Tropical Forests a High-Priority International Task, 2nd Report of the Enquete-Commission*, Bonn, Germany.

Eswaran, H., E. Van Den Berg, P. Reich.: 1993, Organic carbon in soils of the world, *Soil Science Society of America Journal* 57, 192-194.

Fearnside, P. M.: 1992, *Carbon Emissions and Sequestration in Forests: Case Studies from Seven Developing Countries, Volume 2: Greenhouse Gas Emissions from Deforestation in the Brazilian Amazon*, LBL-32758 UC-402, Energy and Environment Division, Lawrence Berkeley Laboratory, Berkeley, CA, USA.

Flint, E. P., J. F. Richards.: 1993, Trends in carbon content of vegetation in South and Southeast Asia associated with changes in land use, in V. Dale (ed), *Effects of Land Use Change in Atmospheric CO_2 Concentrations: Southeast Asia as a Case Study*, Springer-Verlag, in press.

Graham, R. L., R. D. Perlack, A. M. G. Prasad, J. W. Ranney, D. B. Waddle.: 1990, *Greenhouse Gas Emissions in Sub-Saharan Africa*, ORNL-6640, National Technical Information Service, Springfield, VA, USA.

Grainger, A.: 1988, Estimating areas of degraded tropical lands requiring replenishment of forest cover, *International Tree Crops Journal* 5, 31-61.

Grainger, A.: 1990, Modelling the impact of alternative afforestation strategies to reduce carbon dioxide emissions, in *Proceedings of the Conference on Tropical Forestry Response Options to Global Climate Change*, IPCC, Sao Paulo, Brazil, pp. 93-104.

Hall, C. A. S., R. P. Detwiler, P. Bogdonoff, P. S. Underhill.: 1985, Land use change and carbon exchange in the tropics: I. Detailed estimates for Costa Rica, Panama, Peru, and Bolivia, *Environmental Management* 9, 313-334.

Hall, C. A. S., M. R. Taylor, E. Everham.: 1992, A geographically-based ecosystem model and its application to the carbon balance of the Luquillo Forest, Puerto Rico, *Water, Air, and Soil Pollution* 64, 385-404.

Hall, C. A. S., Uhlig, J.: 1991, Refining estimates of carbon released from tropical land-use change, *Canadian Journal of Forest Research* 21, 118-131.

Houghton, J. T., B. A. Callander, S. K. Varney (eds).: 1992, *Climate Change 1992, The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press.

Houghton, R. A.: 1991, Tropical deforestation and atmospheric carbon dioxide, *Climatic Change* 19, 99-118.

Houghton, R. A.: 1992a, Tropical forests and climate, Paper presented at the International Workshop Ecology, Conservation, and Management of Southeast Asian Rainforests, October 12-14, 1992, Kuching, Sarawak.

Houghton , R. A.: 1992b, Effects of land-use change, surface temperature, and CO_2 concentration on terrestrial stores of C, Paper presented at IPCC meeting, October 1992, Woods Hole Research Center, MA, USA.

Houghton, R. A., J. L. Hackler.: 1993, The net flux of carbon from deforestation and degradation in South and Southeast Asia, in V. Dale (ed), *Effects of Land Use Change in Atmospheric CO_2 Concentrations: Southeast Asia as a Case Study*, Springer-Verlag, in press.

Houghton, R. A., D. L. Skole. 1990.: Carbon, in: B. L. Turner, W. C. Clark, R. W. Kates, J. F. Richards, J. T. Matthews, and W. B. Meyer (eds), *The Earth as Transformed by Human Action*, Cambridge University Press, pp. 393-408.

Houghton, R. A., R. D. Boone, J. R. Fruci, J. E. Hobbie, J. M. Melillo, C. A. Palm, B. J. Peterson, G. R. Shaver, G. M. Woodwell, B. Moore, D. L. Skole, N. Myers.: 1987, The flux of carbon from terrestrial ecosystems to the atmosphere in 1980 due to changes in land use: geographic distribution of the global flux, *Tellus* 39B, 122-139.

Houghton, R. A., J. E. Hobbie, J. M. Melillo, B. Moore, B. J. Peterson, G. A. Shaver, G. M. Woodwell.: 1983, Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere, *Ecological Monographs* 53, 235-262.

Houghton, R. A., D. S. Lefkowitz, D. L. Skole.: 1991a, Changes in the landscape of Latin America between 1850 and 1985, I. Progressive loss of forests, *Forest Ecology and Management* 38, 143-172.

Houghton, R. A., D. L. Skole, D. S. Lefkowitz.: 1991b, Changes in the landscape of Latin America between 1850 and 1985, II. Net release of CO_2 to the atmosphere, *Forest Ecology and Management* 38, 173-199.

Houghton, R. A., J. Unruh, P. A. Lefebvre.: 1991c, Current land use in the tropics and its potential for sequestering C, in *Proceedings: Technical Workshop to Explore Options for Global Forestry Management*, International Institute for Environment and Development, Bangkok, Thailand, pp. 297-310.

Idso, S. B.: 1988, Three phases of plant response to atmospheric CO_2 enrichment, *Plant Physiology* 87, 5-7.

Iverson, L. R., S. Brown, A. Prasad, H. Mitasova, A. J. R. Gillespie, A. E. Lugo.: 1993a, Use of GIS for estimating potential and actual biomass for continental South and Southeast Asia, in V. Dale (ed), *Effects of Land Use Change in Atmospheric CO_2 Concentrations: Southeast Asia as a Case Study*, Springer-Verlag, in press.

Iverson, L. R., S. Brown, A. Grainger, A. Prasad, D. Liu.: 1993b, Carbon sequestration in tropical Asia: an assessment of technically suitable forest lands using geographic information systems analysis, *Climate Research*, in press.

Kimball, B. A., J. R. Mauney, F. S. Nakayama, S. B. Idso.: 1993, Effects of increasing atmospheric CO_2 on vegetation, *Vegetatio* 104/105, 65-75.

Knabe, W.: 1985, Effects of chemical air pollution on forests and other vegetation, in G. B. Marini Bettolo (ed), *Chemical Events in the Atmosphere and their Impacts on the Environment, Pontificiae Academiae Scientiarum Scipta Varia* 56, Rome.

Knabe, W., P. Hennicke, W. Bach, M. Ganseforth, L. Hartenstein, V. Jung, M. Muller.: 1990, Supplementary opinion of the Enquete-Commission members on Part G, chapters 1-4, the causes of the destruction of tropical forests, in Deutscher Bundestag (ed), *Protecting the Tropical Forests a High-Priority International Task, 2nd Report of the Enquete-Commission*, Bonn, Germany, pp.393-407.

Korner, C., J. A. Arnone III.: 1992, Response of elevated carbon dioxide in artificial tropical ecosystems, *Science* 257,1672-1675.

Larcher, W.: 1980, *Physiological Plant Ecology, 2nd Edition*, Springer-Verlag.

Leemans, R.: 1992, Modelling ecological and agricultural impacts of global change on a global scale, *Journal of Scientific and Industrial Research* 51, 709-724.

Lugo, A. E., S. Brown.: 1986, Steady state terrestrial ecosystems and the global carbon cycle, *Vegetatio* 68, 83-90.

Lugo, A. E., S. Brown.: 1992, Tropical forests as sinks of atmospheric carbon, *Forest Ecology and Management* 54, 239-255.
Lugo, A. E., S. Brown.: 1993, Management of tropical soils as sinks of atmospheric carbon, *Plant and Soil*, in press.
Lugo, A. E., J. Wisniewski.: 1992, Natural sinks of CO_2, conclusions, key findings and research recommendations from the Palmas del Mar workshop, *Water, Air, and Soil Pollution* 64, 455-459.
Norby, R. J., J. Pastor, J. M. Melillo.: 1986, Carbon-nitrogen interactions in CO_2-enriched white oak: physiological and long-term perspectives, *Tree Physiology* 2, 233-241.
Parton, W. J., D. S. Schimel, C. V. Cole, D. S. Ojima.: 1987, Analysis of factors controlling soil organic matter levels in Great Plains grasslands, *Soil Science Society of America Journal* 51, 1173-1179.
Peterson, B. J., J. M. Melillo.: 1985, The potential storage of carbon caused by eutrophication of the biosphere, *Tellus* 37B, 117-127.
Prentice, I. C., W. Cramer, S. P. Harrison, R. Leemans, R. A. Monserud, A. M. Solomon.: 1992, A global biome model based on plant physiology and dominance, soil properties and climate, *Journal of Biogeography* 19, 117-134.
Raich, J. W., W. H. Schlesinger.: 1992, The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate, *Tellus* 44B, 81-99.
Raich, J. W., E. B. Rastetter, J. M. Melillo, D. W. Kicklighter, P. A. Steudler, B. J. Peterson, A. L. Grace, B. Moore III, C. J. Vorosmarty.: 1991, Potential net primary production in South America, *Ecological Applications* 1, 399-429.
Raynaud, D., J. Jouzel, J. M. Barnola, J. Chappellaz, R. J. Delmas, C. Lorius.: 1993, The ice record of greenhouse gases, *Science* 259, 926-934.
Richards, J. F., E. P. Flint.: 1993, A century of land use change in South and Southeast Asia, in V. Dale (ed), *Effects of Land Use Change in Atmospheric* CO_2 *Concentrations: Southeast Asia as a Case Study*, Springer-Verlag, in press.
Rosenzweig, M. L.: 1968, Net primary productivity of terrestrial communities: prediction from climatological data, *American Naturalist* 102, 67-74.
Sarmiento, J. L., J. C. Orr, U. Siegenthaler.: 1992, A perturbation simulation of CO_2 uptake in an ocean general circulation model. *Journal of Geophysical Research* 97, 3621-3645.
Swift, M. J., P. Woomer.: 1993, Organic matter and the sustainability of agricultural systems: definition and measurement, in K. Mulongoy and R. Merckx (ed), *Dynamics of Organic Matter in Relation to Sustainability of Agricultural Systems*, J. Wiley and Sons, pp. 3-18.
Tans, P. P., I. Y. Fung, T. Takahashi.: 1990, Observational constraints on the global atmospheric carbon dioxide budget, *Science* 247, 1431-1438.
Taylor, J. A., J. Lloyd.: 1992, Sources and sinks of atmospheric CO_2, *Australian Journal of Botany* 40, 407-418.
Trexler, M. C., C. Haugen.: 1993, *Keeping it Green: Evaluating Tropical Forestry Strategies to Mitigate Global Warming*, World Resources Institute, Washington, DC, USA, in press.
Whitmore, T. C.: 1984, *Tropical Rain Forests of the Far East*, 2nd Edition, Oxford Science Publication, Clarendon Press.
Whittaker, R. H., G. E. Likens.: 1973, Carbon in the biota, in G. M. Woodwell and E. V. Pecan (eds), *Carbon and the Biosphere*, US Atomic Energy Commission, CONF-720510, National Technical Information Service, Springfield, VA, USA, pp. 281-302.