CARBON SEQUESTRATION AND STORAGE IN TROPICAL FORESTS

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KATRINA BROWN

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KATRINA BROWN

Centre for Social and Economic Research

on the Global Environment

University of East Anglia

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ABSTRACT

Tropical deforestation is a major contributor of carbon dioxide to the atmosphere. CO_2 is released as a result of forest clearance, and in addition, a significant carbon sink is destroyed. However, estimates of global CO_2 emissions from tropical deforestation differ due to the range of estimates of the extent of deforestation, differing definitions of forests, and other factors. Most data are aggregated, so not enough is known about the assumptions made in previous studies. This study attempts to disaggregate such data, and presents a simplified matrix of the carbon fluxes due to land use change from forestry in the tropics. In this way it quantifies just one of the many benefits of tropical forests.

1. Introduction

In recent years worldwide attention has focused on the destruction of tropical forests. Although tropical forests remain almost entirely in developing countries, they are viewed by many as a global resource, and much of the concern on their destruction has been voiced by those in the developed countries. The North sees forests as providing a global source of biological diversity and as a sink for carbon dioxide (hence they have been dubbed "the green lungs of the world"). The South (in some cases) argues that developing countries need to exploit natural resources such as forest as part of the process of economic development, as the developed countries have in the past.

Tropical forests therefore have many values and provide benefits on a global, national and local level, where they provide livelihood, and food and economic security for many millions of people. This paper examines specifically the role of tropical forest in carbon sequestration and storage, and the changes in these properties with land use conversion. This represents one aspect of the value of forests. Pearce (1990) reviews the total economic value of tropical forests. This includes direct value of timber and non-timber products, recreation, medicine, plant genetics, education and as human habitat; indirect value of nutrient cycling, watershed protection, air pollution reduction, micro-climate effects; option value, the future uses; and existence value (non-use values).

Current international concern on global warming resulting from the build up of greenhouse gases in the atmosphere highlights the carbon fixing properties of tropical forests, and the emissions caused by large scale biomass destruction. These properties may form the basis for international funding of forest conservation and afforestation projects. For such resource transfers to take place, it is essential to understand carbon fluxes in tropical forest systems. This paper reviews current literature on carbon dynamics in tropical forests, and puts forward a simplified matrix of carbon fluxes under different land use change scenarios.

Land use change, and most particularly deforestation in the tropics, has a significant effect on the global carbon flux. Forests and their soils may store as much as 2000 billion tonnes (Bt) of carbon (C), or 1500 BtC for soils alone (Gribbin, 1990). Deforestation and land use conversion to agriculture are also sources of a number of other gases with a potential warming effect, including methane, nitrous oxide, carbon monoxide, and ozone. This paper concentrates on emissions of CO_2. However, estimates of aggregate emissions from deforestation differ, as shown in the Table 1 below, due to different estimates of area of forest cleared, and assumptions as to carbon stored per hectare. The estimates range from 0.4 BtC to 2.9 BtC.

Table 1:ESTIMATES OF GLOBAL CO_2 EMISSIONS FROM TROPICAL DEFORESTATION, 1980

Source		Billion tonnes C
Andrasko, 1990	(+0.32 as CH_4)	0.4-2.8
WRI,1990		2.8
Myers, 1989	(mean 1.8)	0.9-2.5
Detwiler and Hall, 1988		0.4-1.6
Sedjo, 1989		2.9
Houghton, 1990		0.4-2.6

Note : It is not always clear if estimates are net of carbon sequestrated by subsequent land use.

As many authors, including Houghton (1990) point out, rates of deforestation are believed to have increased in the decade since 1980 (they probably reached a peak between 1987-89, and are now in decline). The figure is more likely to now be in the region of 2-3 BtC/yr. This would be roughly equivalent to 35 - 50% of current emissions of CO_2 from fossil fuels. Using satellite images, Setzer and Pereira (1991) calculated that biomass burning in Brazilian Legal Amazon in 1987 contributed 0.52 BtC. It was possible to detect about 20 million hectares of different types of vegetation burned, of which 8 millions were associated with recent deforestation. CO_2 accounted for 0.47 Bt of carbon emitted (other carbon compounds accounted for remaining 0.05 Bt).

In previously published studies much of the data is aggregated to give the total amount of carbon released as a result of deforestation, but this is of little use if the calculations are not presented. In the same way, many writers have concentrated on the potential effects of climate change on land use and deforestation, rather than *vice versa*, for example, Shunkla *et al.* (1990).

CO_2 emissions from tropical deforestation are usually calculated by one of two methods: the ecological method and the geochemical balance method. The ecological method calculates net CO_2 emissions from tropical deforestation on the basis of CO_2 sources and sinks in the tropical biosphere. The geochemical method regards the total net emissions of CO_2 from land use change as the upper limit for CO_2 emissions from tropical deforestation, and employs mathematical models to calculate the flux of CO_2 between the biosphere and the atmosphere, and between the oceans and the atmosphere. These models are calibrated by studying the ratio of carbon-13 to carbon-12 and radioactive carbon-14 over a period of time. The results can be used to deduce biospheric carbon fluxes.

This paper concentrates on the direct measurement of CO_2 sources (the ecological method) and reviews estimates by various authors using this method. The ecological method calculates the *net* quantity of CO_2 emissions, ie: net of subsequent vegetation, on the basis of cleared forest and of secondary vegetation; the density of the biomass of the burned tropical forest, the type of secondary vegetation; the release of CO_2 from the cleared biomass over time and from the soil after deforestation; and the fixation of atmospheric CO_2 in secondary vegetation.

Data are required on the following parameters in order to estimate the quantity of CO_2 emissions attributable to tropical deforestation :

a)information on type of forests being cleared, and the subsequent land use;

b)estimates of biomass density, and carbon storage in the various types of forest, and in the secondary vegetation;

c)proportion of biomass which is burned;

d)proportion of biomass which, though burned, is kept in long term storage;

e)the rate of CO_2 release in biomass which is neither burned, nor in long term storage.

However, major areas of uncertainty and scientific dispute concern the following:

i.the extent of deforestation in tropics;

ii.estimates of C sequestration and storage in vegetation and soils;

iii.definitions of vegetation types;

iv.subsequent land use and extent;

v.end uses of timber and products.

Following sections review the current state of knowledge concerning these issues and seek to clarify some of these areas of uncertainty. Each of these areas is explored and some estimates of the effects of land use change in the tropics put forward.

2.Estimates of the rate of deforestation in tropical regions

The first problem is in defining the different types of forest and vegetation cover;

the second is in quantifying the extent of deforestation and land use conversion; a third is in identifying subsequent land use.

i.Classification of Tropical Forests

Myers (1990:373) defines tropical forests as *"evergreen or partly evergreen forests, in areas receiving not less than 100mm of precipitation in any 6 months for two out of three years, with mean annual temperature of 24 plus degrees Celsius, and essentially frost-free; in these forests some trees may be deciduous; the forests usually occur below 1300m (though often in Amazonia up to 1800m, and generally in SE Asia up to only 750m); and in mature examples of these forests there are several more or less distinctive strata."* Such moist forests exist in more than 70 countries of the tropics, but 34 countries account for 7.8 million km square, or 97.5 percent of the present biome. Brazil contains approximately 27.5 percent of all tropical forests.

Authors distinguish between open and closed forest. The FAO (1991) defines forests as being closed when trees of the different stories and the undergrowth cover a large portion of the ground, and if no grass cover exists. Moist evergreen and deciduous forests account for most of the closed forests. The tree crowns of open forests cover at least 10% of the ground surface, which in such forests is typically covered by a continuous carpet to grass. In general, these open forests correspond to dry deciduous forests of the tropics.

The Federal Republic of Germany (1991), for example distinguishes 7 classes of tropical forest:

1. <u>Evergreen moist forest</u>: equivalent to closed evergreen forest or rainforest, 10 degrees north and south of the equator in Amazon/Orinoco basin, Congo/Guinea basin, parts of India, Thailand/Indochina, and eastern Australia.
2. <u>Predominantly deciduous moist forest</u>: seasonally leafless, monsoonal and transitional. May border the evergreen moist forest with no clear lines of demarkation. This includes all closed types of high forest which shed leaves of at least the upper layer during a clearly defined dry season, with a lower stand density than evergreen moist forest.
3. <u>Predominantly deciduous dry forests</u> Usually found on the edges of 2.
4. <u>Special sites</u>, including mangrove forests, swamps and flood plains.
5. <u>Coniferous tropical forests</u>.
6. <u>Bamboo forests</u>.
7. Others types of forest

The first three are the most important types as far as the present study is concerned; in terms of their extent, rate of destruction, and carbon fixing properties.

In addition to classification according to climatic and site related criteria, forest can also be divided into primary, secondary and logged-over forests depending on their condition. Primary forests are virgin forests whose development has been disturbed only very slightly or not at all by human intervention, so that their physiognomy has been determined exclusively by their natural environment. They are also defined as climax forests, being the final stage of ecological succession. Secondary forest includes all stages of successions which take place on naturally bare land or land that has been cleared. Virgin or natural forest in which trees are felled in a more or less systematic manner and to an extent that the stand structure has been changed, are referred to as logged-over forests. These may be included in the group of secondary forests.

Other authors distinguish between productive and unproductive forests. Brown and Lugo (1984) define unproductive forests due to physical reasons (for example, rough terrain, flooding), and legal reasons (for example, national parks or reserves). The area in national parks and reserves accounted for only 13 percent of the total unproductive category.

ii. Estimates of Deforestation

Accelerating conversion of tropical forests is occurring for a number of interlocking socio-economic and political reasons (Wood, 1990). These include inequitable land distribution, entrenched rural poverty, and growing populations which push landless and near-landless peasants onto forest lands; government-subsidised expansion into forest regions by plantations growing export crops, timber companies, and cattle ranches; and government-sponsored population relocation to frontier regions.

FAO (1991) estimates, given in Table 2, show that 17 Mha (out of total area of 1884 Mha in 1980) of tropical forest were cleared annually between 1981 and 1990, almost exclusively by burning. Preliminary estimates of the forest area and rate of deforestation in 87 countries in the tropics shows that 169.3 Mha were cleared between 1980 and 1990. Tropical Asia had the fastest relative rate of deforestation (1.2-1.3 percent per annum) among the three tropical continents, while its absolute rate was lowest, due to smallest initial forest area. Within continents, West Africa had the fastest rate of deforestation, though tropical Latin America had the largest area deforested, with *average annual deforestation* of 6.78 Mha.

FAO's results would appear to be substantiated to a degree by those of Setzer of the National Space Research Institute of Brazil (Setzer and Pereira, 1991). In 1987, Setzer used satellite imagery to determine that 8 Mha of virgin forest in the Legal Amazon were cleared in that year. However, 1987 may have been a year of unusually high deforestation, as it was the last year that tax credits were available to new landowners who cleared their Amazon holdings, and many large landowners may have wished to take advantage whilst they still could. At the same time Brazil's legislature was discussing taking 'unimproved' land as part of land reform programme, so again many landowners may have cleared large tracts to retain ownership rights. In 1988 and 1989, tax credits were suspended and later cancelled, some policing and fining of illegal fires was initiated and wet weather discouraged burning. Follow up studies by Setzer showed a decline in the area burned each year, a 40 percent drop to 4.8 Mha in 1988, and a further 40-50 percent drop in 1989 to 2.4-2.9 Mha. The methodology has been criticised as it uses space photos of smoke, and smoke may extend beyond burned area, but would not detect areas deforested but not burned (WRI, 1990). The authors apply a weighting for the amount of vegetation which is forest, and the amount as *cerrado* (savanna).

Table 2:FAO Preliminary Estimates of Tropical Deforestation (millions hectares).

	Number of countries	Forest area 1980	Annual average loss
Latin America	**32**	**922.9**	**8.30**
Central America	7	77.0	1.35
Carribean	18	48.8	0.17
Tropical South America	7	797.1	6.78
Asia	**15**	**310.8**	**3.60**
South Asia	6	70.6	0.44
Continental SE Asia	5	83.2	1.35
Insular SE Asia	4	157.0	1.81
Africa	**40**	**650.4**	**5.03**
West Sahel	8	41.9	0.39
East Sahel	6	92.3	0.70
West Africa	8	55.2	1.18
Central Africa	7	230.1	1.47

Tropical Southern Africa	10	217.7	1.14
Insular Africa	1	13.2	0.15
Total	**87**	**1884.1**	**16.93**

Source: FAO (1991)

Thus the range of annual deforestation rates for Brazil's Amazon is between 1.7-8 Mha per year (see Wood, 1990), numbers large enough to affect significantly the *global* rate. Most probably, deforestation accelerated in the early 1980's, peaked in 1987, and declined somewhat in 1988-89 because of changed policies and wetter weather. Bouwman (1990) cites a rate of 0.6 percent of total global forest area as being cleared for **permanent** use each year, and that much of this is taking place in the Amazon Basin.

In recent years, remote sensing techniques have ensured greater accuracy in estimates, although these are by no means conclusive. Houghton *et al.* (1985) review some of the earlier estimates and highlight disparities caused by different definitions of vegetation. There remains, however, a certain amount of scepticism over the true rate of deforestation.

iii. Subsequent Land Use

Tropical forests are exploited by people for a variety of purposes, including timber extraction, shifting cultivation, permanent agriculture and pasture. Leduc (1985) identifies causes as slash-and-burn agriculture; commercial timber extraction; cattle raising; fuelwood gathering; commercial agriculture; and additional causes such as large dams, and mining. These various land uses differ in their effect on vegetation and soil, and therefore in the amount of CO_2 released when a unit area of forest is converted.

Much of the clearing in tropical rainforests is for shifting cultivation. Johnson (1991) estimates that 64 percent of tropical deforestation is as a result of agriculturalists; 18 percent by commercial logging; 10 percent by fuelwood gatherers; 8 percent by ranchers. However, there are different types of shifting cultivation, which may have different effects on carbon fluxes. Davidson (1985) distinguishes two types of shifting agriculture in tropical moist forests. First, the traditional, low intensity form of shifting cultivation which has been practised for many generations, initially involving the clearing of primary forest but afterwards based on a secondary forest fallow system.

Secondly, a more destructive form, in which primary forest is cleared and the land cultivated continuously until it is degraded then it is abandoned.

According to the German Bundestag (1990), shifting cultivation in the tropics remains an appropriate means of land use under the prevailing climatic and soil conditions as long as certain conditions are met:

i)farming must be extensive, with long fallow period, of 12-20 years for most fertile soils, but 30-100 years for nutrient poor soils, for example those in much of the Amazon basin.

ii)plot size must not exceed 1-2 ha, so that it can be readily recolonised by surrounding forest vegetation;

iii)crop mixtures and mixes should ensure maximum ground cover to avoid soil erosion.

It seems likely that in many parts of the world, shifting cultivation is now posing a threat to forest resources for a number of reasons :

-population growth is exceeding the capacity of existing cropland;

-farmers are forced to settle and cultivate unsuitable and poor land;

-land scarcity is further aggravated by ownership and distribution.

Houghton *et al.* (1987) describe typical shifting cultivation as a cycle, which begins with the burning of a plot of forest. Some of the large trees are left standing. Food crops are planted in the ashes and harvested from periods of 1-10 years. The yields generally decline over time as the forest grows back and soil fertility is reduced. Some of the surface organic matter is oxidised during the burn and in the earliest years of cropping. The soil organic matter develops again as the forest regrows. The period of fallow, after which the forest may be burned and cleared again, may last from 3-80 years depending on the cultural and environmental conditions.

Based on the FAO data, clearing of forests for the different land uses can be broken down as follows: shifting cultivation accounts for 40 percent of cleared primary forest; permanent cropping and cattle ranching 50 percent; logging (removes 28 percent of above ground biomass) I0 percent. The proportions vary from region to region, with 35 percent of forest destruction in tropical America attributable to shifting cultivation, 49 percent in Asia, and 70 percent in Africa. 31 percent of forest is cleared for conversion to pasture for cattle in the Americas.

3.Carbon Dynamics in Tropical Ecosystems

It is particularly important to distinguish between the active **sequestration** of CO_2 by trees as they grow - the flow concept, and the **storage** of carbon in forest biomass *and* soils, the stock concept. Overall, forest ecosystems store 20-100 times more carbon per unit area than croplands and play a critical role in reducing ambient CO_2 levels, by sequestrating atmospheric carbon in the growth of woody biomass through the process of photosynthesis. When a forest is cut down, not only does the photosynthesis and therefore active fixing cease, but if the wood and timber is destroyed (most commonly by burning of at least a proportion), then carbon stored by the trees in the past will be released as CO_2. There are still a number of scientific uncertainties, particularly concerning carbon dynamics in "representative" natural and disturbed tropical forests, and carbon fluxes in tropical soils which may account for one third of the flux from deforestation.

i) Biomass

An undisturbed moist tropical forest exhibits net growth for about 100 years after its establishment (Kyrklund, 1990), compared with 30-40 years of *rapid* growth described by Myers (1989). After this as far as carbon is concerned the forest reaches a state of equilibrium where emission at night equals daytime absorption, and dieback equals growth. Grayson (1989) maintains that existing unmanaged forests contribute no *net* carbon since standing biomass remains the same, and carbon fixed by growth is balanced by carbon released to the atmosphere through death and subsequent rotting.

The CO_2 absorption rate is directly proportional to the growth rate. In commercial, even aged stands of forest it is simpler to estimate incremental growth and for example in Britain, the Forestry Commission produces yield tables, showing growth rates for most common commercial species (coniferous and deciduous) under a range of different conditions per year. Forest growth can be modelled with an S-shaped logistic curve (see Dewar, 1990). However estimating the *average growth rate per hectare* for natural tropical forest where a wide variety of species may be present (for example, as reported by Pearce (1989) one hectare of the Yanomano Forest in Peru was found to contain 283 species of tree; there were only twice as many individuals as there were species) clearly this is much more complex. Table 3 shows estimates of growth in tropical forests compiled from various sources, and from different sample sites within the categories. Again there are problems with definition, and in finding a mean rate which can be applied to a range of forests and conditions.

Table 3:BIOMASS PRODUCTION IN TROPICAL FORESTS: SOME ESTIMATES

	Dry Matter (t/ha/year)	**Carbon (t/ha/year)**
Bolin et al. (1986) (various sites)		
Tropical rainforest	7.75 - 10.19	3.88 - 5.10
Seasonal tropical forest	5.50 - 7.20	2.75 - 3.60
Cannell (1982)		
Rainforest (Manaus)	15.00	7.50
Rainforest (Ivory Coast)	12.73 - 24.60	6.36 - 12.30
Jordan (1989)		
Amazonian rainforest (mean)	12.66	6.33
Slash and burn (after 3 years)	5.26	2.62

Note: Assumes carbon is 50 percent of dry matter (DM)

Myers (1990) assumes a working mean figure of 20 t biomass/ha/yr for growth in tropical forest *plantation*. As Myers notes, there is much variability in figures adduced for growth rates and yields, according to climatic conditions, soil types, and a number of other factors. Myers then assumes that one half of plant growth is made up of carbon, and that therefore such a plantation can assimilate 10 tC/ha/yr. However, it is not made clear what the nature of the plantation is, and one assumes that such a figure would not apply to an uneven, natural stand. Indeed, eucalyptus plantations in southern Brazil have been found to have an average growth rate of over 30 t/ha/yr, with occasional top yields of 70 t/ha/yr. Sedjo (1989) applies a universal mean rate of 6.24 tC/ha/yr, which appears to be closer to the expected rate according to data presented in Table 3. The Federal Republic of Germany (1991) estimate annual production of dry wood mass in more or less natural tropical forests as between 8 t/ha (evergreen moist forest) and 3 t/ha (moist deciduous forests).

The estimation of standing biomass can be made by two methods: destructive sampling, and from timber volume estimates. Brown and Lugo (1984) have calculated the carbon content of tropical vegetation using these two methods. In 1982 they calculated tropical forest biomass density by means of destructive sampling, based on the selection of small areas, less than 30 ha, which were clear-felled in order to directly measure the biomass. In 1984 they produced new estimates of the biomass of tropical forest, this time based on volumes. The results summarised in Table 4 show that there is a significant difference between the results from the two methods. Brown and Lugo point out that the database for estimating the biomass or carbon pool in tropical forests is poor at best, and that very few destructive sampling studies have been carried out, and it seems unlikely that those which have been are representative. In contrast, much more information on standing timber volumes in tropical forest from a broader geographical area and from more and larger plots is available. In 1984 Brown and Lugo used data from FAO detailing stand volumes of forests surveyed in 76 countries, covering 97 percent of the area that lies in the tropical belt. These are categorised into two broad classes: **closed** forests, where the forest stories cover a high proportion of the ground and lack a continuous dense ground cover, and **open** forests in which the mixed broadleaf-grassland tree formation has a continuous dense grass layer and the tree canopy covers more than 10 percent of the ground. There were further classifications according to degree of disturbance and productivity.

Volume data, in cubic metres are converted to total biomass by assuming a mean wood density of 0.2 t/m^3 (Moore *et al.*, 1981). The ratio of total biomass to usable stem biomass was assumed by the German Bundestag to be 1.6 for closed forests and 3 for open forests. The density of wood varies over a limited range, and when averaged over a mixed forest the range becomes even smaller. Mid range is assumed by Marland (1988) as 0.52 t/m^3. Houghton *et al.* (1985) report that the fractional carbon content of wood varies between 0.47 - 0.52 of dry matter (DM).Most authors then assume that 50 percent of DM is carbon. Sedjo (1989) uses the following conversion factors for converting volume of stemwood to tC: 1 m^3 of stemwood is equivalent to 1.6 m^3 of biomass; 1 m^3 of forest biomass (stem, roots, branches etc) absorbs 0.26 t C equivalent. Sedjo applies an average figure of forest growth of 15 m^3/ha/yr of stemwood, which therefore means that 1 ha of *new* forest will sequester 6.24tC/ha/yr (15 X 1.6 X 0.26).

Brown and Lugo, cited in Detwiler and Hall (1988) show that from volume data, primary closed forest was found to contain 90 tC/ha, and primary open forest 31 tC/ha. Destructive sampling showed primary closed forests consisted of 164 tC/ha, and primary open forest 40 tC/ha. According to Brown and Lugo, the estimates derived from the volume data may be more representative of tropical forests because; i) the volume data are more numerous, ii) there appears to be a bias in selecting plots with larger vegetation for destructive sampling.

Table 4 shows a range of estimates derived by this method, again illustrating the variation between different sample sites, illustrated by the data from Bolin *et al* (1986).

Table 4:ESTIMATES OF CARBON STORAGE IN TROPICAL FORESTS tC/ha

		RAINFOREST	SEASONAL FOREST
sites	1	202.35	156
	2	187.38	113.33
	3	136.67	63.33

Source: Bolin *et al*, 1986

ii) Soils

Soil sources of carbon dioxide include respiration of living biomass, and breakdown of dead organic matter. After clearcutting of forest the first will be largely eliminated, but the second will be stimulated by the addition of fresh decomposable organic matter to the soil.

Goreau and de Mello (1988) comment that the rapid decline in carbon dioxide release from soils after deforestation suggests that respiration of live roots, and of those insects, fungi and bacteria that depend directly on living vegetation for their food make up approximately three-quarters of carbon dioxide production in soils.

Over half of the soil organic matter, and thus the carbon, is contained within the top 40 cm of soil profile. The German Bundestag (1990) calculates the average carbon content for closed forests to be 133 tC/ha in the top 100 cm, and 72 tC/ha in the top 40 cm. For open forests, the equivalent estimates are 80 tC/ha in top 100 cm, 49 tC/ha for top 40 cm.

The most useful soil carbon data are those compiled by the German Bundestag, giving the proportions of forested area in each category. These are shown in Table 5 below.

Table 5: ESTIMATES OF BIOMASS AND SOIL CARBON

Forest category	**Area** (percentage)	**Biomass** (tC/ha)	**AGB** (percentage)	**Soil** (tC/ha)
Lowland rainforest	11	172	83.3	118
Lowland moist forest	19	185	85.5	88
Dry forest	10	146	-	100
Montane rainforest	14	161	81.3	179

Montane moist forest	14	146	88.2	101
Montane dry forest	32	40	70.0	42

Note: Dry forests correspond to open forest; all others to closed forest
AGB Above ground biomass; the percentage of biomass which is above ground ie: not including roots
Source: Adapted from German Budestag (1990)

This table shows that in tropical forests the carbon in soil is roughly equivalent, or less, than the above ground biomass. This contrasts with the temperate case, where soil may contain more carbon per hectare than vegetation.

iii) Carbon Changes with Land Use Conversion

Carbon will be released at different rates according to the method of clearance and subsequent land use. With burning there will be an immediate release of CO_2 into the atmosphere, and some of the remaining carbon will be locked in ash and charcoal which is resistant to decay. The slash not converted by fire into CO_2 or charcoal and ash decays over time, releasing most of its carbon to the atmosphere within 10-20 years.

Studies of tropical forests indicate that significant amounts of cleared vegetation become lumber, slash, charcoal and ash; the proportion differs for closed and open forests; the smaller stature and drier climate of open forests result in the combustion of higher proportion of the vegetation.

Houghton *et al.* (1987) maintain that over the long term, a constant rate of deforestation for shifting cultivation will not contribute a net flux of carbon to the atmosphere. Carbon released to the atmosphere during burning balances the carbon accumulating in regrowth. However, this is probably no longer the case, as in recent years the area cleared annually for shifting cultivation has increased, the rotation length has been reduced, and the area of fallow forests may also have decreased as fallow lands are cleared for permanent use. All these trends have increased the net release of carbon from the tropics.

This is illustrated by Uhl's studies (1987) of succession following slash and burn agriculture in Amazonia. Due to burning and decomposition of forest wood and root residues, there is a dramatic decline in carbon stocks during slash and burn agriculture. After 5 years of succession, 86% of the plant mass from the pre-existing forest had disappeared. Biomass accumulation during this time added only 38 t/ha. Total carbon stocks at five years were well below half that of the pre-burn forest stocks. Based on measurement of tree growth and litter production, total above ground production averaged 12.58 t/ha/yr over the five year study period, a value almost identical to that measured for mature forest. Pioneer trees grew faster than primary trees.

Soil carbon declines when soil is cultivated as a result of erosion, mechanical removal of topsoil, and increased oxidation. Oxidisation is probably responsible for greatest loss and is the only process which directly affects the CO_2 content of the atmosphere. Again the scale and timing depends on the use after clearing. Detwiler and Hall estimate that conversion of forest soils to permanent agriculture will decrease the carbon content by 40 percent; conversion to pasture decreases content by 20 percent; shifting cultivation causes a decrease of 18-27 percent; and selective logging seems to have little effect on soil carbon. This assumes that losses caused by permanent agriculture occur over 5 years; those caused by shifting cultivation occur over 2 years; and losses due to conversion to pasture occur within a short time. Approximately 35 years of fallow are required to return to level found under undisturbed forests.

v) Carbon in Subsequent Land Use

If tropical forestland is converted to pasture or permanent agriculture, then the amount of carbon stored in secondary vegetation is equivalent to the carbon content of the biomass of crops planted, or the grass grown on the pasture. If a secondary forest is allowed to grow, then carbon will accumulate, and maximum biomass density is attained after a relatively short time (45 years according to German Bundestag, 1990). Table 6, below summarises the carbon content of soils and biomass in the relevant land uses.

Table 6:CARBON STORAGE IN DIFFERENT TROPICAL LAND USES

	Biomass (tC/ha)	**Soils** (tC/ha)	**Total** (tC/ha)
Closed primary forest	167	116	283
Closed secondary forest	85-135	67-102	152-237
Open forest	68	47	115
Forest fallow (closed)	28-43	93	121-136
Forest fallow (open)	12-18	38	50-56
Shifting cultivation (year 1)	10-16	31-76	41-92
Shifting cultivation (year 2)	16-35	31-76	47-111

Permanent cultivation	5-10	51-60	56-70
Pasture	5	41-75	46-80

Source: compiled from German Bundestag (1990), Houghton *et al.* (1987).
Assumes carbon will reach minimum after 5 years in cropland, after 2 years in pasture.

These data can be used to calculate the total changes in biomass and soil carbon as a result of land use changes, as shown in Table 7, below. This table illustrates the net carbon storage effects of land use conversion from tropical forests; closed primary, closed secondary, or open forests; to shifting cultivation, permanent agriculture, or pasture. The negative figures represent emissions of carbon; for example, conversion from closed primary forest to shifting agriculture results in a net loss of 194 tC/ha. The greatest loss of carbon involves change of land use from primary closed forest to permanent agriculture. These figures represent the **once and for all change** that will occur in carbon storage as a result of the various land use conversions.

Table 7:CHANGES IN CARBON WITH LAND USE CONVERSION tC/ha

	Original C t/ha	Shifting agriculture	Permanent agriculture	Pasture
Original C t/ha		79	63	63
Closed primary	283	-204	-220	-220
Closed secondary	194	-106	-152	-122
Open forest	115	-36	-52	-52

Note: Where range was given in Table 6, a mid point is used here.
Shifting agriculture represents carbon in biomass and soils in second year of shifting cultivation cycle.

4.End Use Issues

The above estimates show emissions of carbon if all the biomass is lost. This may be true if burnt, but not if used for timber. When calculating the *net* effects of deforestation on carbon flux, it is important to also consider the end uses of timber cleared from the forest. This may contain the bulk of biomass carbon, and although removed from the growing site, the carbon may not be released to the atmosphere as CO_2; it may remain stored for some time depending on the use, and the life of timber products produced. A model developed by Dewar (1990) describes carbon storage in vegetation (especially forests) and in products removed from vegetation (timber, grain, etc). This illustrates the relation between carbon storage, vegetative growth, rotation length, and the *carbon retention properties* of products. This enables management strategies to be examined with respect to their effect on carbon storage (see also Thompson and Matthews, 1989). This has not been examined by the present study which concentrates solely on effects of land use strategies on vegetation and soil carbon.

5. Conclusions

The calculations show that the largest loss of carbon from both biomass and soils occurs with a change of land use from tropical forest to permanent agriculture. This change also degrades the environment in many other ways, including loss of soil fertility and erosion. Conversion to pasture involves changes of a similar magnitude, though if the emissions of methane from cattle grazing this pasture were included, this conversion may have more serious consequences in terms of greenhouse gas emissions. The conversion of tropical forests to shifting agriculture produces considerable emissions of CO_2, and soil and biomass take many years to recover their carbon store. These results are necessarily generalised, and it must be stressed that empirical evidence from individual experimental sites may provide different data. In particular, different practices of shifting agriculture will affect the carbon flux in differing ways. Some methods of shifting agriculture may be less damaging to the environment than others.

More research is now being conducted into less damaging cultivation practices. For example, Southworth *et al.* (1991) have developed a model which simulates tenant farmer colonisation and its effects on deforestation and associated carbon losses. The model is used to contrast the typical pattern of colonist land use in Rondonia, Brazil, with a system of sustainable agriculture. Sustainable agriculture is simulated to resemble the activities of a group of immigrant Japanese farmers who have settled in eastern Brazil. In this system, farmers clear plots of 10 ha each in the first two years of settlement. Annual crops are planted in the first and second years; annual and perennial crops intercropped in the third year so that carbon recovery is initiated. After 10 years of intercropping, the land is left fallow for eight years. The intercropping acts to increase the rate of succession, and no significant carbon loss or gain is assumed to take place during this period.

The dual role of forests both as a source of greenhouse gases and as a sink for

CO_2 gives rise to a number of forest-related options aimed to ameliorate greenhouse gas concentrations in the atmosphere; curb deforestation; reforestation; and sink enhancement. Of these the first should be given priority, given the range of services provided by tropical forests.

What are the possibilities then for a development policy based on "sustainable" management to benefit local populations? Wood (1990:41) highlights the political character of such policy: *"Tropical forests...must provide both an immediate source of livelihood for those dependent on them and a sustainable resource for future generations. If that goal is to be accomplished, key actors - government agencies, NGOs, leading institutions, timber industries, scientists, and most of all peasants - will have to fulfil new and expanded roles within the ecopolitical hierarchy".* At present less than 1 percent of the worlds tropical forests are managed in a sustainable way (as defined by Barnett, 1992). Leduc (1985) observes that in developing countries, the people harmed most acutely by deforestation are usually poor and rural. He contends that this in part explains why the process is continuing. The most acutely affected contemporary losers from tropical deforestation (ie: the rural poor) tend not to be of primary political significance to national policy makers. In the extreme case, indigenous people are not even part of a cash economy, and often encounter antipathy from government officials and the general public.

This paper has quantified the effects of changes in land use in tropical forests on the carbon sequestration and storage properties of vegetation and soils. However many other benefits provided by tropical forests are at least equally important. Their role in supporting livelihoods of millions of forest dwellers, and millions more people who live at their edges should not be undermined. The carbon sequestrating and storing properties only add strength to arguments for conservation, and the role of northern governments in facilitating policies whereby developing countries are able to ensure protection of their own resources.

Bibliography

Andrasko, K., 1990, Global Warming and Forests : An overview of Current Knowledge. *Unasylva* 163:3-1.

Barnett, A., 1992. *Deserts of Trees: The Environmental and Social Impacts of Large-scale Tropical Reforestation in Response to Global Climate Change*. London:FOE.

Bolin, B., 1977. Changes of Land Biota and Their Importance for the Carbon Cycle. *Science* 196: 613-615.

Bolin, B., B.R.Doos, J.Jager and R.Warrick, (eds) 1986. *The Greenhouse Effect, Climate Change and Ecosystems*. Scope 29 John Wiley:Chichester.

Bouwman, A. F., 1990. Land Use Related Sources of Greenhouse Gases *Land Use Policy 7*: 154-164.

Brown, S., and A.E. Lugo, 1984. Biomass of Tropical Forest: A New Estimate based on Forest Volumes. *Science* 223: 1290-1293.

Cannell, M.G.R., 1982. World Forest Biomass and Primary Production Data, London; Academic Press.

Davidson, J., 1985 Economic Use of Tropical Moist Forests *The Environmentalist* Supplement 9.

Detwiler, R.P., and C A Hall, 1988. Tropical Forest and the Global Carbon Cycle, *Science* 239: 42-47.

Dewar, R.C., 1990. A Model of Carbon Storage in Forests and Forest Products. *Tree Physiology* 6: 417-428.

Fearnside, P.M., 1985. Brazil's Amazon Forest and the Global Carbon Problem. *Intercienca*, 10.4.

Federal Republic of Germany, 1991. FRG Tropical Forest Report, FRG, Bonn, March 1991.

FAO, 1991. Unpublished Deforestation Data, October 1991, FAO: Rome.

German Bundestag (Ed), 1990. Protecting the Tropical Forests: A High Priority International Task. Bonner Universitats-Buchdruckerei: Bonn.

Goreau, T.J., and W.Z. de Mello, 1988. Tropical Deforestation: Some Effects on Atmospheric Chemistry, *Ambio* 17.4:275-281.

Grayson, A.J. 1989. Carbon Dioxide, Global Warming and Forestry. *Forestry Commission Research Information Note 146* Forestry Commission: Alice Holt.

Gribbin, J., 1990. *Hothouse Earth, The Greenhouse Effect and Gaia*, London; Transworld Publishers Ltd.

Hall, D.O., H.E. Mynick, R.H. Williams, 1990. Carbon Sequestration versus Fossil Fuel Substitution, Princeton University/Centre for Energy and Environmental Studies Report No. 255. November 1990.

Houghton, R.A., 1990. The Future Role of Tropical Forests in Affecting Carbon Dioxide Concentration of the Atmosphere. *Ambio* 19.4:204-209.

Houghton, R.A., R.D. Boone, J.M. Melillo, C.A. Palm, G.M. Woodwell, N. Myers, B.Moore III, D.L. Stole, 1985, Net Flux of carbon dioxide from Tropical Forests in

1980. *Nature* 316: 617-620.

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, and N. Myers, 1987. The Flux of Carbon from Terrestrial Ecosystems to the Atmosphere in 1980 due to Changes in Land Use : Geographical Distribution of the Global Flux. *Tellus* 39B: 122-139.

Johnson, B., 1991. *Responding to Tropical Deforestation*. WWF UK: Godalming.

Jordan, C.F. (ed) 1989. An Amazonian Rainforest: The Structure and Function of a Nutrient Stressed Ecosystem an the Impact of Slash and Burn Agriculture. *UNESCO Man and Biosphere Series Volume 2* Paris: UNESCO.

Kaul, O.N., 1991. Forest Biomass burning in India. *TISGLOW: TERI Information Service on Global Warming* 2.2:2-17.

Kyrklund, B., 1990. The Potential of Trees and the Forestry Industry in Reducing Excess Carbon Dioxide, *Unasylva* 163: 12-14.

Leduc, G., 1985. The Political Economy of Tropical Deforestation. In Leonard, H.J. (ed) *Divesting Nature's Capital: The Political Economy of Environmental Abuse in the Third World*. Chapter 5: 179-226, New York: Holmes and Meier.

Mann, L.K., 1986. Changes in Soil Carbon Storage after Cultivation, *Soil Science* 142.5:279-288.

Marland, G., 1988. The Prospect of Solving the CO_2 Problem Through Global Reforestation. US Department of Energy Carbon Dioxide Research Division Report TR039, Feb 1988.

Molofsky, J., CAS Hall, N Myers, 1986. A Comparison of Tropical Forest Surveys. US Department of Energy Carbon Dioxide Research Division Report TR032, June 1986.

Moore, B., R D Boone, U.E, Hobbie, R.A. Houghton, J.M. Melillo, B.J. Peterson, G.R. Shaver, C.J. Vorosmarty, and G.M. Woodwell, 1981. A Simple Model for Analysis of the Role of Terrestrial Ecosystems in The Global Carbon Budget. In Bolin, Bert (Ed), *Carbon Cycle Modelling*, Scope 16, Chichester; John Wiley, 367-385.

Myers, N., 1990. Tropical Forests. In Leggett, J., *Global warming, The Greenpeace Report* 372-399, Oxford: OUP.

Myers, N., 1989. The Greenhouse Effect: A Tropical Forestry Response, *Biomass* 18,1: 73-78.

Myers, M., 1988. Tropical Deforestation and Climatic Change. *Environmental Conservation* 15.4: 293-298.

Myers, N. and T.J. Goreau, 1990. Tropical Forests and the Greenhouse Effect : A Management Response, *Climatic Change*.

Olson, J.S., J.A. Watts, L.J.Allison, 1983. Carbon in Live Vegetation of Major World Ecosystems. US Department of Energy Carbon Dioxide Research Division Report TR004, June 1983.

Pearce, D.W., 1990. An Economic Approach to Saving the Tropical Forests. *LEEC Paper 90-06.* IIED/UCL.

Pearce, F., 1989. Turning up the Heat: Our Perilous Future in the Global Greenhouse. London:Palladin.

Salati, E., R.L.Victoria, L.A.Martinelli, J.E.Richey, 1991. Forests: Their Role in Global Change, with Special Reference to the Brazilian Amazon. In Jager, J., and H.L.Ferguson (eds), Climate Change: Science, Impacts and Policy. Proceedings of the 2nd World Climate Conference 391-396. Cambridge:CUP.

Sedjo, R.A., 1989. Forests to Offset the Greenhouse Effect. *Journal of Forestry* 87.7: 12-15.

Setzer, A.W., and M.C. Pereira, 1991. Amazonia Biomass Burnings in 1987 and an Estimate of Their Tropospheric Emissions, *Ambio* 20.1: 19-22.

Shunkla, J., C. Nobre, P. Sellers, 1990. Amazon Deforestation and Climate Change, *Science* 247:1322-1325.

Southworth, F., V.H.Dale, and R.V.O'Neill, 1991. Contrasting Patterns of Land Use in Rondonia, Brazil: Simulating the Effects on Carbon Release. *International Social Science Journal* Nov 1991, 681-698.

Thompson, D.A. and R.W. Matthews, 1989. The Storage of Carbon in Trees and Timber. *Forestry Commission Research Information Note 160*.

Uhl, C., 1987. Factors Controlling Succession Following Slash and Burn Agriculture in Amazonia. *Journal of Ecology* 75: 377-407.

Wood, W.B., 1990. Tropical Deforestation: Balancing Regional Development Demands and Global Environmental Concerns. *Global Environmental Change* 1.1 23-41.

Woodwell, G.M., R.H. Whittaker, W.A. Reiners, G.E. Likens, C.C. Delwiche, D.B. Botkin, 1987. The Biota and the World Carbon Budget. *Science* 199: 141-146.

World Resources Institute, 1990. *World Resources 1990-91*. Oxford:OUP.