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ESTIMATION OF CARBON DIOXIDE FLUX FROM TROPICAL DEFORESTATION

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Abstract

This study estimates the carbon dioxide flux arising from conversion of tropical forests to other forms of land-use. Based on the assumption that population change is a major factor in deforestation, it infers parameters and functions of the relationship using recent research on tropical forests. With three scenarios for population change, this study estimates carbon dioxide flux during the 120 year period from 1980 to 2100 in three regions - Latin America, Africa, and Asia. The results are 61.1 billion metric tonne of carbon (tC), 91.6 billion tC, and 134.5 billion tC respectively as medium-low, medium, and medium-high estimates of carbon dioxide release.

KEYWORDS: *Climate change, Deforestation, Carbon dioxide emission*

1. Overview

Carbon dioxide has been released into the atmosphere since humans began altering natural vegetation long ago, and until the beginning of the twentieth century, the main sources of carbon flux were in the middle latitudes of the northern hemisphere. However it is believed that almost all of the carbon flux released from land-use change since 1950 is from deforestation in the tropics. The amount of carbon stored in both soil and vegetation in the tropics is estimated at 200 billion tC each, which is equal to more than 50 % of the amount in the atmosphere. Accordingly, predicting carbon behavior is a crucial task for forecasting climate change. In addition to tropical deforestation, carbon sinks in middle and higher latitudes are important considerations regarding carbon exchange between terrestrial ecosystems and the atmosphere, but this paper does not deal with them. The affects of climate change on tropical forests are also not considered here.

The definition of forest in this paper includes forests with at least 10% crown cover of trees and bamboos including close and open forests, and which are not subject to agricultural practices. Further, since plantations are only about 2.5 % the size of natural forests in all tropical regions (FAO, 1993), they are not considered here. In addition, this paper does not differentiate between closed forests and open forests, or coniferous forests and hardwood forests, instead grouping forest types together for each country: these details are not particularly significant here, because of the complexity of changes in land use and the irregularity of their carbon content, among other things.

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This paper takes population increase as the sole driver of tropical deforestation. In reality, many factors combine in an intricate way to cause deforestation, but for all tropical regions and a time span of over one hundred years, we judged that it would not be a serious error to base our estimates on population. Using this working assumption, we analyzed the speed of deforestation and population increase in tropical countries in the 1980s, and tropical Asian countries in particular over one hundred years from 1880 to 1980. The analysis revealed a relationship between population density and percentage of forest area in a given region. Next, using cohort component analysis to predict population change on a country by country basis, plus data about the relationship between population density and forest area, we forecast future changes in forest area. For calculations of population, we used medium, high, and low estimates for fertility, and a medium level for mortality rates. For this reason, this paper uses the terms medium, medium-high, and medium-low for population estimates. Finally, we coupled the future area changes with a method recommended by the OECD(1992) in order to estimate carbon dioxide flux from tropical deforestation, and calculated the global carbon budgets from tropical land-use until the year 2100 AD.

2. Estimates of deforestation

Many studies about changes in tropical land-use have been conducted since the last century (Marsh, 1874). Studies which tried to quantify social and economic causes include Houghton (1988), Palo *et al.*(1987, 1990), Rotmans (1990), Parks (1994), and IMAGE2 (Alcamo *et al.*, 1994). Houghton (1988) predicted deforestation rates from 1981 to 2100, postulating that the decline in forest area is a function of population increase. Palo *et al.* (1987) attempted to analyze the dynamics of deforestation by taking into account population growth, impoverishment of rural communities, soil erosion, and other factors. In addition, the United Nations Research Institute for Social Development (UNRISD, 1990) developed a varied approach to the socioeconomic structure of deforestation in Nepal, Tanzania, the Amazon, and Central America.

Among these many approaches, the parameter with the strongest correlation to forest area is population density. Lugo *et al.* (1981) found a correlation between the two of -0.8 for the Caribbean region. Palo (1987) used data from 72 tropical countries to obtain a correlation coefficient of -0.334 on a country basis, and -0.80 to -0.90 on a regional basis. Seeing these results, FAO in its 1990 tropical forest resource assessment developed and used a method of interpolating forest area over time using population density (Scotti, 1990). There are a number of conjectures about the relationship between the increase in population density, and the decrease of forest area. Among them, the main cause of deforestation is thought to be the expansion of cultivated land in response to increasing population. Based on an analysis of FAO's Production Yearbook, Allen *et al.* (1985) asserted that there is a statistically significant correlation between population increase, expansion of cultivated land, and a decline in forest area, and that this is particularly noticeable in Asia and Africa. From FAO's 1980 tropical forest assessment, Lanly (1982) found that the increase in land area under shifting cultivation resulting from the increase in population pressure was the reason for 70 % of deforestation in Africa, 50 % in Asia, and 35 % in Latin America.

There are three problems with using population change to describe trends in forest area. First, there are various cause-and-effect processes by which population growth leads to deforestation, and the degree of their effects on forests varies widely. For example, depending on whether an increase in food production comes about from an increase in shifting cultivation, or from an increase in settled cultivation, the impact on forests is vastly different. Second, results will depend on the extent to which factors other than population are considered, such as national development policies, land use rights, commercial logging, and the demand for timber. Third, current trends show a decrease of forest area due to population increase, but a halt or reversal of these trends would affect forecasts. For example, in the middle latitudes, many countries have experienced periods of rapid exploitation of national forests and land resources. Mediterranean countries and England did not see a drop in deforestation until almost all forests had disappeared. However the trend reversed in Japan and the United States when the amount of surviving forest cover was still high.

IMAGE2 (Alcamo *et al.*, 1994), TROPOFORM (Grainger, 1988, 1990) or LUCS (Faeth *et al.*, 1994) and other models which express deforestation as the result of social processes attempt to either internalize or externalize these causes and effects. Houghton (1988) and IS92 (Pepper *et al.*, 1992) abandoned this approach and attempted to base macro trends on population changes alone. The present study uses this latter method of forecasting, for two reasons. First, no logical model yet exists to explain forest use and disappearance on the scale of all tropical regions; at the same time it is doubtful that a good estimate over a long time period (the object of this study) could be made even, if a detailed socio-economic model were constructed on current incomplete information about the state of tropical regions. Second, as mentioned below, trends in tropical forests now and over the past one hundred years are indeed considered to have a close relationship to population trends. There is a great possibility that this relationship may change, but at present we believe that an extrapolation of current trends also has a certain validity.

3. The relationship between population density and forest area

We assume a relationship between the ratio of forest area w and population density p in a given region.

$$w = f(p) \tag{1}$$

The regional rate of population change r_P and rate of forest loss r_f are defined as a functions of time t, with the area A of a given region, forest area A_f, and population P.

$$r_P = \frac{1}{P} \cdot \frac{dP}{dt} \tag{2}$$

$$r_f = -\frac{1}{A_f} \cdot \frac{dA_f}{dt} \tag{3}$$

The population elasticity of deforestation E_P is r_f divided by r_P.

$$E_P = \frac{r_f}{r_P} = -\frac{p \cdot f'(p)}{f(p)} \tag{4}$$

Fig.1 shows the relationship between E_P and p, the former being calculated from the average rate of deforestation over the 10 years from 1981 to 1990 based on the 1990 FAO tropical forest resources assessment (FAO, 1993), and the average rate of population increase over the 25 years from 1955 to 1980. White circles ○ indicate Asian countries, squares □ indicate Latin American countries, and black circles ● indicate African tropical countries. E_p

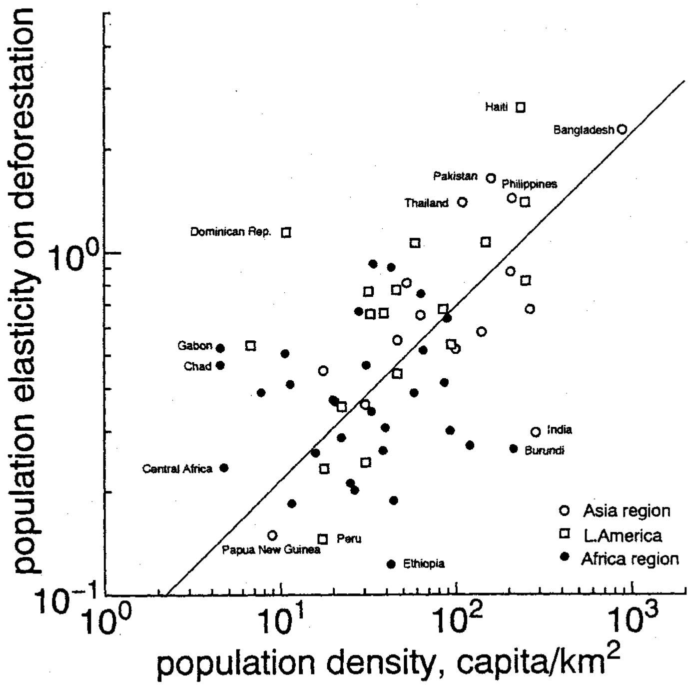

Figure 1. Population elasticity of deforestation, all tropical countries relation between rate of forest area decline 1981 - 1990 and rate of population increase 1955 - 1980

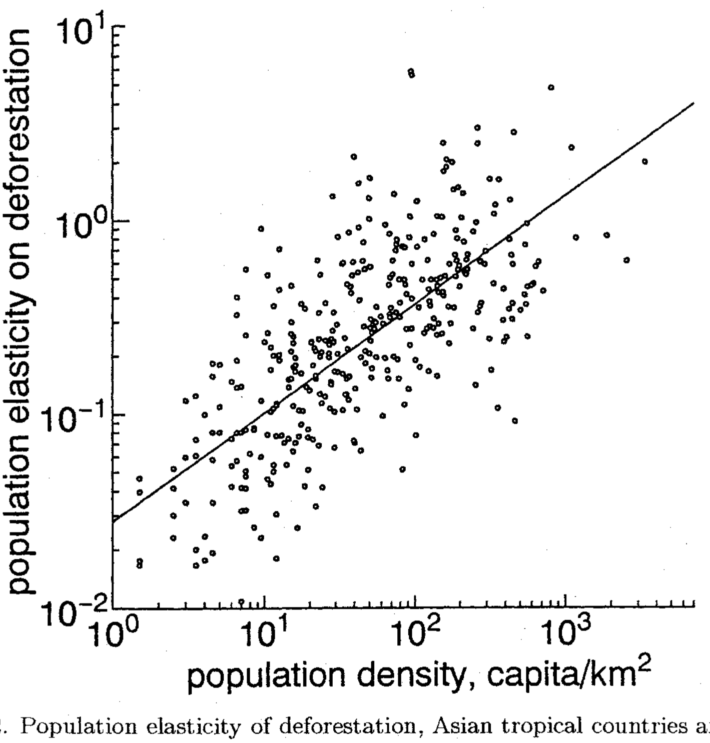

Figure 2. Population elasticity of deforestation, Asian tropical countries analyzed by state

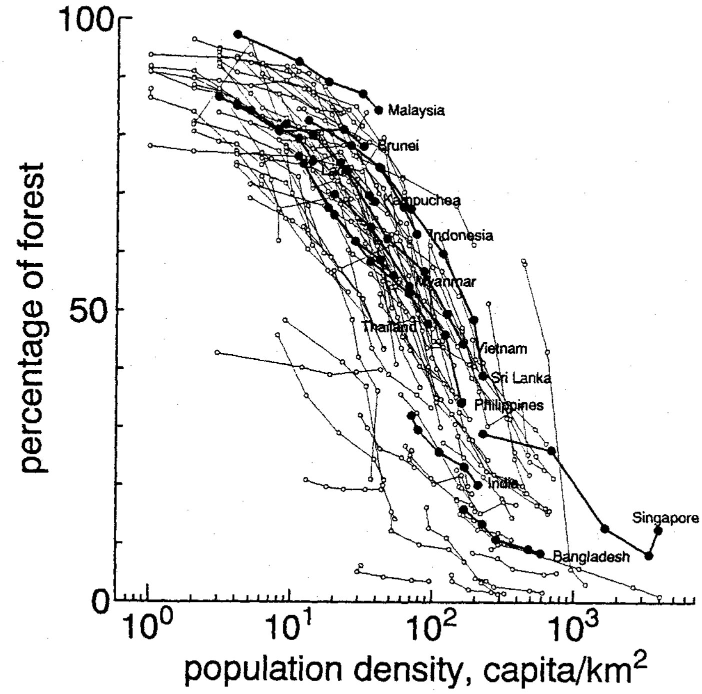

Figure 3. Percentage of forest area vs. population density, tropical Asian countries by state

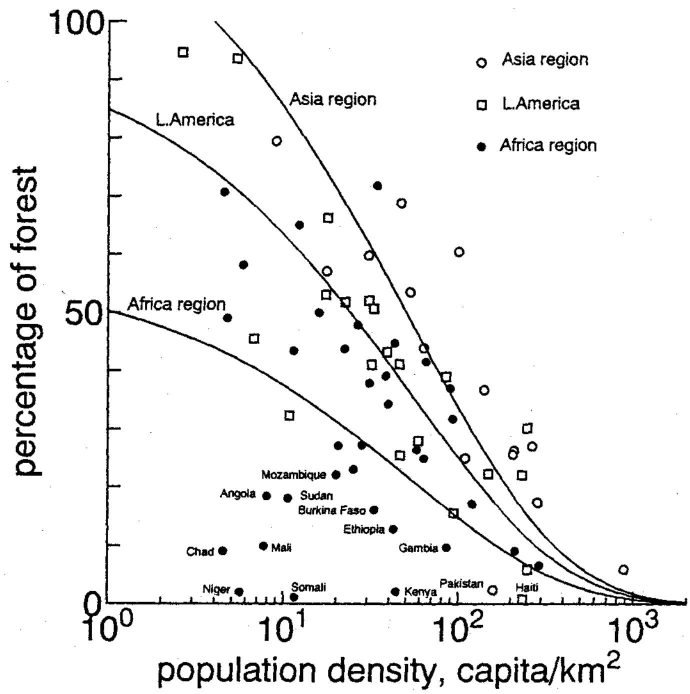

Figure 4. Regression curve for percentage of forest area vs. population density, all tropical countries

Table 1. Regression coefficients of equation (6)

Region	p_0	a_0'	a_1	w_0	n	R	e	Figure
Africa	53.4	-2.69	0.504	57.6	35	0.61	19.7	4
Asia	53.4	-2.69	0.504	130.9	15	0.86	12.4	4
L.Amer.	53.4	-2.69	0.504	97.4	21	0.84	12.9	4
Asia	141.1	-	0.500	108.7	65	0.92	10.1	5
Asia	210.7	-3.58	0.560	-	374	0.66	0.94	2

n : number of data, R : multiple correlation coefficient,
e : residual standard deviation

tends to increase with population density, in a certain convergent range, except in the case of India, Ethiopia, and the Dominican Republic etc.

Next, we assume that this trend is expressed as a linear relationship by the next equation.

$$\ln E_P = a_0' + a_1 \ln p \tag{5}$$

This relationship can be observed clearly over the long term as a phenomenon of Asian tropical deforestation, which is shown in Fig.2. Also, using the same data, Fig.3 displays a plot based on forest area and population data (Richards *et al*, 1993) from 105 states of 13 tropical Asian countries from 1880, 1920, 1950, 1970, and 1980.

The elasticity (Fig.2) is calculated using the average rate of deforestation over the previous ten years at four points in time from 1920 to 1980, and average population growth rates over the previous 35 years. The lines in Fig.1 and 2 are regression lines based on eq. (5). Based on eq. (5), the right side of eq. (1) : $f(p)$ becomes:

$$w = w_0 \exp\left[-\left(\frac{p}{p_0}\right)^{a_1}\right] \tag{6}$$

Here, p_0 is:

$$p_0 = \left[\frac{\exp(a_0')}{a_1}\right]^{-\frac{1}{a_1}} \tag{7}$$

and w_0 is the ratio of forest area to population density at time 0. Figures 4 and 5 exhibit the fit of eq. (6).

Fig.4 shows a regression line from eq. (6) for the 3 regions, Asia, Latin America, and Africa based on data from the 1990 FAO tropical forest resource assessment. However, parameters p_0 and a_1 are values from the regression in Fig.1, and only w_0 is calculated with the regression. Asia and Latin America show a relatively good fit, but Africa's fit is poor. Countries for which the fit is poor are mostly those with savanna-type climates such as Niger, Chad, Mali, Somalia or Pakistan.

Fig.5 uses country data, aggregated those in Fig.3, to produce a regression curve. Here, we calculated the three parameters a_1 , p_0 and w_0 simultaneously. In this example, we see that

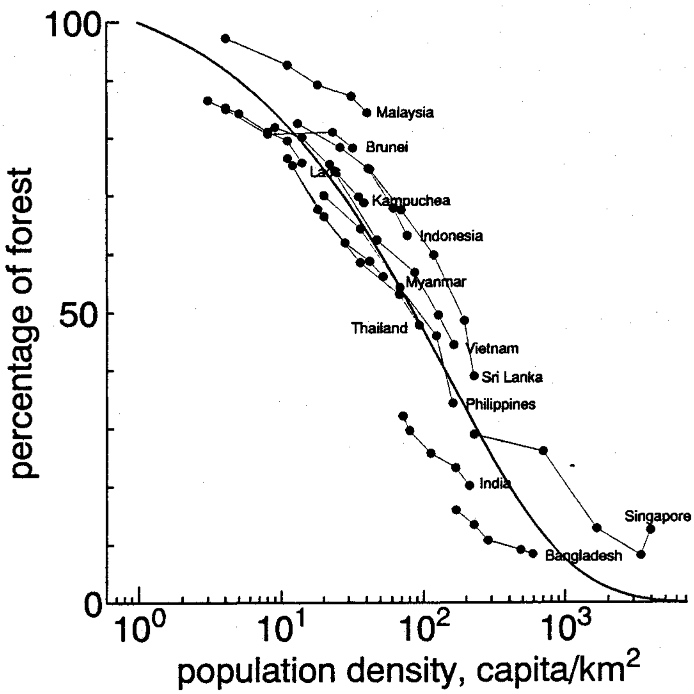

Figure 5. Regression curve for percentage of forest area vs. population density, tropical Asian countries

Table 2. Land-use change matrix for the Africa region 1981 - 1990

	Classes at year 1990 (area in 1000ha)									
Classes at 1980	Closed forest	Open forest	Frag. forest	Long fallows	Short fallows	Shrubs	Others	Water	Plantations	Total in 1980
Closed forest	16781	382.1	291.8	82.6	524.3	9.5	247.5			18318.8
Open forest	23.6	10049	371.2	48.3	117.8	12.7	397.3	0.1	1.4	11021.4
Frag. forest	24.1	40	8088.8	1	5.8	7.7	293.5			8460.9
Long fallows	7.7	14.6	1.6	556.8	51.7	4.4	28.5			665.3
Short fallows	7.6	10.9	2.1	9.6	2254.8		53.3	0.4		2338.7
Shrubs	0.8	10.8			1.1	3877.9	154.3	0.1		4045
Others	16.9	38.2	11	34.3	63.1	86.6	26452	51.2		26753.3
Water	0.5			3.2	0.5	0.1	81.5	2960.1		3045.9
Plantations					0.4		0.4		4.6	5.4
Total in 1990	16862.2	10545.6	709.3	8820.2	2991.9	3998.9	27707.9	3011.9	1.4	74649.3

time series data from a one hundred year and cross-sectional data of all tropical Asia regions produce one regression of good fit with eq. (6).

Table 1 shows regression coefficients. w_0 and p_0 have large regional differences, but a_1 is relatively consistent for all regions. p_0 is a population density scale parameter. As one can see from eq. (6), w_0 and p_0 values have a high mutual dependency in the process of estimation, so it is difficult at present to estimate them precisely and separately by region. For the above reasons, this paper uses 0.504 and 53.4 capita/km^2 for a_1 and p_0 values, based on the analysis of all tropical areas and w_0 is assumed to be a specific coefficient to target regions.

4. The fate of cleared forests

Cleared forest areas are converted for permanent cultivation, pasture land, or shifting cultivation; fallow forest, which leads eventually to those uses; or to other land uses. The 1980 FAO tropical forest resource assessment estimated that of 11.3 million ha deforested annually, 5.1 million ha (45 %) became fallow forest after a phase of shifting cultivation, and the remaining 6.2 million ha (55 %) were convert to other than forest (Lanly, 1982). The 1990 assessment (FAO, 1993) estimated that 24 % of forest land cleared was converted to fallow or scrub, 44 % to non-forest uses, 16 % was fragmented for cultivation, while the remaining 16 % became degraded. The question of whether fallow forest became permanently cultivated land or reverted to woodland is a major issue for calculating carbon dioxide flux. Myers (1980) assumes that almost all fallow forest is eventually cleared and tends to decrease in area. However, FAO's 1980 study (FAO/UNEP, 1981) found that from 1980 to 1985, fallow forest area actually increased. According to FAO's 1990 study (1993) of land-use changes in the Africa region (Table 2), the 3 million ha of long-term and short-term fallows in 1980 increased by 8 million ha owing to the conversion of closed and open forests. During the same period, less than 100,000 ha of forest were permanently converted to other land-uses by clearing. Further, sources of other land-use include many classes such as closed forests, open forests or scrub, and few pass through a period of fallows. Using this information, this paper assumes that there are only two classes of land resulting from tropical forest conversion: fallows and permanent cultivation. It also assumes that fallow forests remain in that state, and that no other changes occur to them that release carbon. Finally, this study assumes the figures for permanent conversion to cultivation of 50 % of forest cleared in Asia, 30 % in Africa, and 65 % in Latin America. These figures were taken from the 1980 FAO tropical forest study (Lanly, 1982), and are presumed not to change over time or within regions.

5. Amounts of carbon flux and time lag after deforestation

In this study, we assume two kinds of land-use changes.

The first is permanent conversion to cultivated land or pasture. Carbon is assumed to be released in the following process. First, country by country values for the amount of carbon stored in above-ground biomass (vegetation) are taken from data based on the 1990 FAO tropical forest study (FAO, 1993). 45 % of this value is assumed to be burned the year the forest is cleared, but 9 % is assumed to be carbonized, and not released into the atmosphere. The remaining 55 % is assumed to be released steadily over ten years. Accordingly the amount of carbon dioxide flux in the same year an area is cleared is $45\times0.91+55\times0.1 = 46.45$ %, and thereafter 55×0.1 = 5.5 % per year over the next 9 years. Eventually, according to this process, there is a possibility that 95.95 % of the carbon dioxide in vegetation is released into the atmosphere, but we deduct the amount of carbon kept in the ground for shifting cultivation and pasture land from the first year. This study uses 5 tC/ha from Houghton (1991) for the above-ground biomass of cultivated land. The carbon flux released from the soil as a result of deforestation is considered to be 25 to 38 % of the original amount (Houghton, 1991, Fearnside, 1990). The release of carbon is considered to continue over a long period of time, but this study assumes a constant rate of release over 25 years totaling 30 %; this estimate is in the middle of the above range. Incidentally, IS92 assumes the highest value for this parameter – 38 % of the total.

The second type of land-use change is from forest to fallows after a phase of shifting cultivation. The carbon release changes over a period of around ten years along with the changes in land-use. However, shifting cultivation and fallow forest area are treated as one type in this study because this study deals with a longer time scale. It is estimated that, from this second type of landuse change, carbon in vegetation decreases by about 50 % (OECD, 1991), and carbon in soil decreases by about 10 % (Houghton *et al.*, 1985); this study assumes that these decreases are carbon released into the atmosphere. Also, for convenience, this study uses the same time-lag function as described in the previous paragraph.

For carbon stored in vegetation per unit of forest area, we use a biomass value for each country based on FAO's 1990 tropical forest study. This amount of carbon is calculated from biomass estimates using the factor 0.45 (Whittaker, 1975). The estimation of the biomass density of forests was based on wood volume measurement. Houghton (1991) pointed out that recently reported values for the amount of carbon stored in forests are about half of older values, and that there is a rather large gap between estimates calculated from wood volume, as opposed to destructive sampling. From Table 3, it is clear that the values used in this study are relatively low . The IS92 values in the table are aggregated ones used in IPCC's update in 1992 (Pepper *et al.*, 1992). They are based on the OECD's method(1991), and are almost equal to those used in this study. Table 3 also indicates amounts of carbon in the soil used in this study.

6. Population estimates for tropical forest regions

Forecasting population is a major issue for this study, since it is taken as the major driving force of deforestation. Populations of tropical countries continue to change, and their total fertility rates are high at 3 to 6 % per year. The rate of population growth for all tropical regions is 2.7 %, arid their 1985 population of 1.86 billion people is estimated to rise to 4.67 billion in 2025 (United Nations, 1991).

There is considerable variation in population growth rates between countries, with Kenya set to increase 3.3 times, India and Brazil 1.7 times, and Thailand 1.5 times over the next forty years. Country-by-country calculations were necessary to give this study the degree of precision needed for the differences within regions. Cohort component method is used to calculate values from 1985 to 2100. Treating changes in life expectancy and fertility as external variables, the age distribution of a population in any year is calculated from age distribution of the starting year, a model life table, a model age pattern of fertility, and a sex ratio. This study does not include immigration and emigration between countries. It uses model life tables and age patterns of fertility compiled by the United Nations Population Division (United Nations, 1992). For the lengthening of average life spans, this study uses a model with a medium growth

Table 3. Carbon flux from tropical forests

Region	this study (1994)	IS92 (1992)	Dixon *et al.* (1994)	Houghton(1991) closed	open
		Vegetation (tC/hectare)			
Africa	59.9	47.3	99	136/111†	90/15‡
Asia	81.5	86.7	153±21	112/ 60†	60/40‡
L. Amer.	76.1	65.4	130	89/ 73†	27/27‡
		Soils (in undisturbed forest, tC/hectare)			
Africa	81.7	78.7	120		
Asia	88.6	91.2	139	90–100	50
L. Amer.	91.6	93.1	120		

†The first value is for undisturbed forests and the second value is for logged forests.
‡The first value is based on destructive sampling of biomass and the second value is calculated from wood volumes.

patterns used by the United Nations.

This study presumes three fertility scenarios as used by the long term population estimates of the United Nations Population Division - medium, high, and low. These scenarios are different in the way fertilities are established, and for the medium estimate, the total fertility rate is presumed to stabilize at a replacement value of 2.06. The high estimate presumes stabilization set 5 % higher at 2.17, and the low estimate 5 % lower at 1.96. The speed at which each country approaches these levels varies greatly. The United Nations Population Division released adjusted values up to the year 2025 for the total fertility rate by country in its 1990 world population estimate report. This study uses these values until the year 2025, and extrapolates for subsequent years. Using the methodology described, this study forecasts population for 71 tropical countries.

According to the forecasts, the population of 2.1 billion in tropical regions in 1990 becomes 5.2 to 7.8 billion in 2050, and 6.5 to 11.7 billion 2100. In other words, the population is forecasted to increase between 3 and 5.6 times by 2100.

7. Estimates of forest area and carbon dioxide flux

Forest area can be predicted by substituting the population values obtained in Section 6 into eq. (6) which relates forest area to population density. The increase in average population density over the previous 25 years is assumed to be the driving force of deforestation. Accordingly, average values and time lags must both be calculated for the population variable. Parameter w_0 in eq. (6) is determined from the percentage of forest area, and population densities by country, in the base year (1980). When forests are cleared, they are converted at a certain rate depending on the region, to permanently cultivated land and pasture, or else shifting cultivation and fallows. A corresponding amount of carbon is presumed to be released over a maximum of 25 years. This study uses one sum for the amount of carbon flux in the atmosphere from forest clearing before the base year (1980) for the three tropical regions. The estimates of Houghton *et al.* (1983) are used for the speed of deforestation in the three regions for that time period.

Fig.6 shows the changes in forest area for the medium range estimate. The rate of deforestation reaches a maximum in 2010 of 13.8 million ha, and declines thereafter. Tropical forests decrease by 990 million ha, and 53 % of the forests remaining in 1980 disappear during the 120 years from 1980 to 2100. The actual forest area cleared in Latin America is the largest, but Africa (62 %) shows the largest percentage decrease, followed by Latin America (50 %), and the Asian region (45 %). Asia and Latin America experience their peak rate of forest loss during the 1980s and 1990s, but for Africa this occurs in the decade following the year 2010.

Fig.7 displays the area deforested annually for the three scenarios. It shows the total percentage of forest cleared by the year 2100 — 53 % for the medium scenario, 78 % for the medium-high scenario, and 35 % for the medium-low scenario. The slow pace of deforestation for the medium-low scenario from 1980 onward illustrates the high sensitivity of deforestation to population change.

Fig.8 shows the carbon dioxide flux under three scenarios. Our medium scenario results in a forecast that tropical deforestation causes the carbon dioxide flux of 1.1 billion tC in 1980 to peak at 1.3 billion tC in the beginning of the next century and then decline. Thus, 91.6 tC is released during the 120 years from 1980 to 2100. The medium-high scenario peaks at 1.6 billion tC per year and produces 134.5 billion tC, while the medium-low scenario peaks at 1.2 billion tons per year, and releases 61.1 tC over 120 years.

8. Discussion

A number of other studies have attempted to estimate carbon flux resulting from future tropical deforestation, assuming no aggressive reforestation occurs, including Houghton (1988), IS92 (Pepper *et al.*, 1992), Trexler (1993) and IMAGE2 (Alcamo *et al.*, 1994).

Houghton's (1988) results were used by the United States Environmental Protection Agency (Lashof and Tirpack, 1990) and the 1990 IPCC assessment. The Houghton study made four estimates: it combined two cases of deforestation rates, one with forest clearing continuing steadily at a rate measured in the first half of the 1980s and a second in which the rate grows with population; and two other cases, one with a high level, and one with a low level of carbon per hectare. In the steady-rate case, forests available for conversion will be exhausted in 2097, and the peak value for the deforestation rate is 14.9 million ha/y. The high carbon estimate predicts 281 billion tC of net carbon flux over the 120 years from 1980 to 2100, while the low carbon estimate predicts 118 billion tC over the same period. In the scenario with deforestation linked to population, closed forests in the Asian region will disappear in the year 2046, and tropical forests available for conversion will disappear worldwide in the year 2078. Depending on the assumption of carbon per hectare, the net carbon dioxide flux will reach 324 billion tC and 138 billion tC for the high and low estimates respectively, over the 120 years.

The IPCC prepared independent estimates for an update in 1992 (Pepper *et al.*, 1992). It assumed that population growth results in a decrease of forest area with a 25-year time delay, and investigated deforestation in four areas: Brazil, other countries of South and Central America, Asia, and Africa. Then it employed the method proposed by OECD for calculating

carbon conversion from deforestation. It considered three cases for population growth: IS92a,b,e

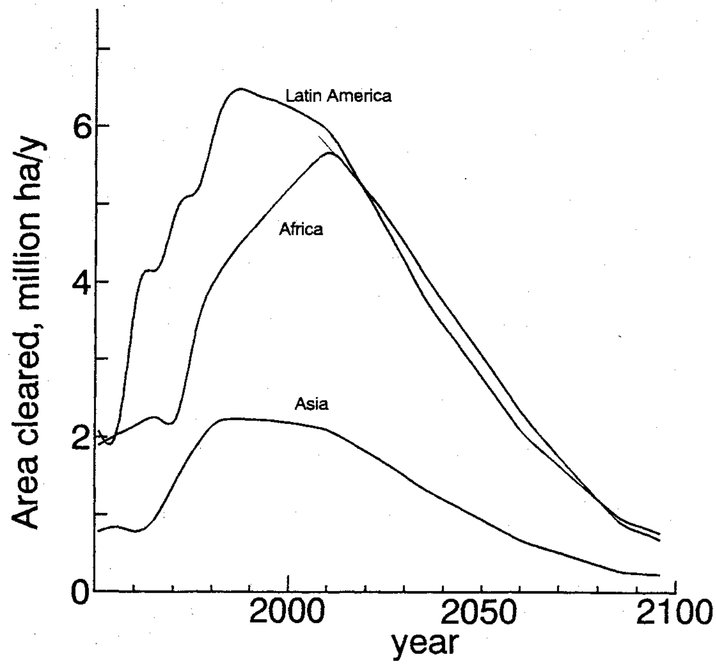

Figure 6. Regional comparison for medium scenario of deforestation rate

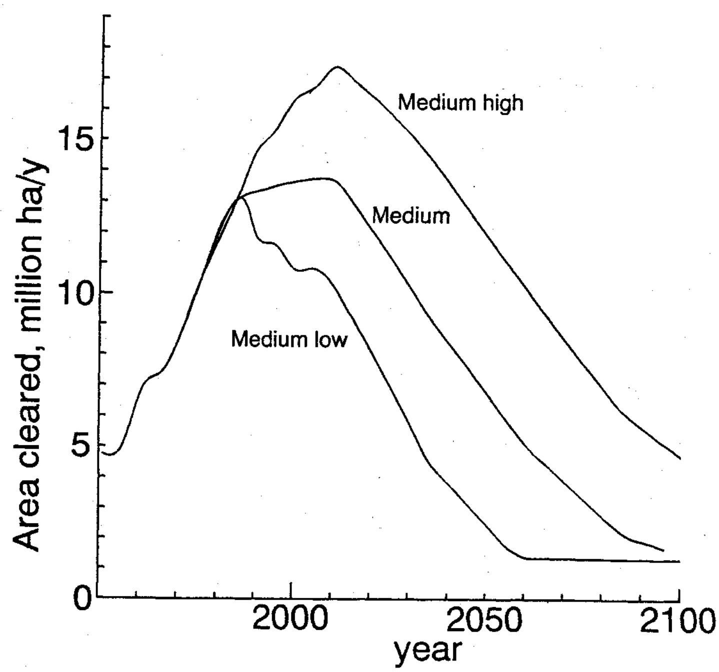

Figure 7. Comparison of deforestation rates for three scenarios

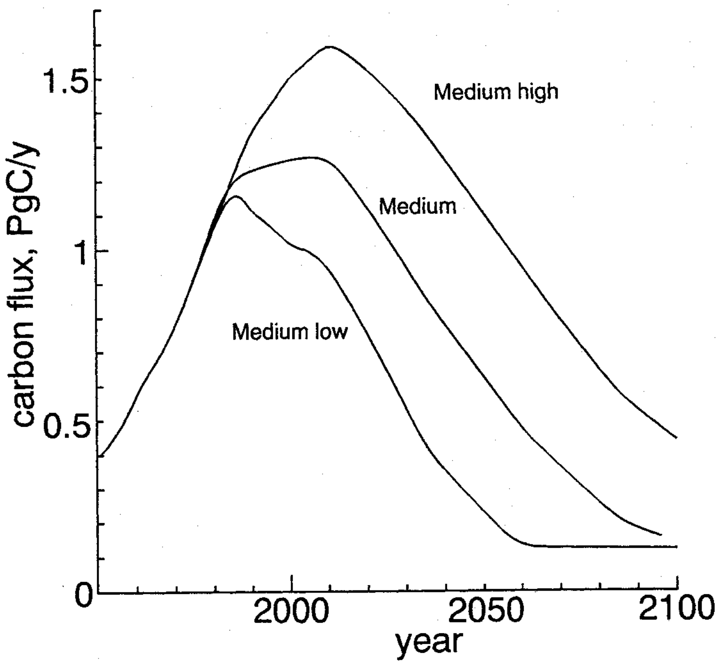

Figure 8. Comparison of carbon dioxide flux for three scenarios

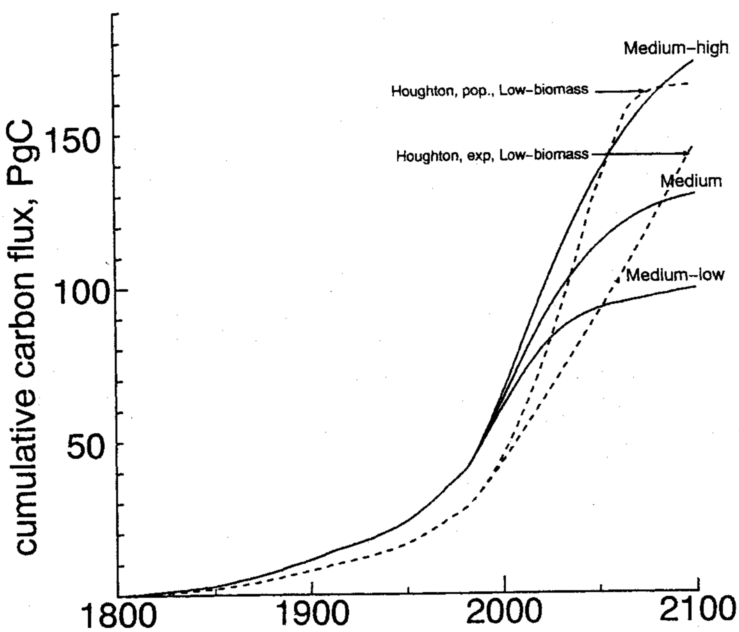

Figure 9. Cumulative carbon dioxide flux

used World Bank 1989-90 figures (11.3 billion people in the year 2100); IS92f used the United Nations' medium-high estimate (17.6 billion people in the year 2100); and IS92c used United Nations' medium-low estimates (6.4 billion people in the year 2100). Finally, IS92d assumed an annual decrease of over 2.5 % in the rate of deforestation measured in the first half of the 1980s. These estimates resulted in the following predictions for carbon flux during the 110 years from 1990 to 2100: IS92a,b,e, 86 billion tC; IS92f, 97 billion tC; IS92c, 80 billion tC; and IS92d, 30 billion tC.

Trexler *et al.* (1993) estimated deforestation in 54 countries, taking into account natural, social and economic conditions, as well as specialist opinions in each country. They predict deforestation between 1990 and 2050 to be 660 million ha, and the total carbon dioxide flux to range from 41 billion tC to 77 billion tC.

IMAGE2 (Alcamo *et al.*, 1994) adopted a complicated estimation procedure. It estimates land productivity as determined by a number of factors including demand for land for eight types of grain cultivation, four types of livestock raising, fuel wood demand, and biomass energy farms, climate, and soil. It goes on to link these elements with climate, vegetation, and various energy and industrial models. This model starts with a rate of tropical deforestation of 13.7 million ha/y in the 1980s, and the CW scenario predicts carbon flux until the year 2100 of 80 billion tC.

Based on current trends, estimates of net carbon dioxide flux from 1980 or 1990 until the year 2100 range from 80 billion tC to 320 billion tC. Houghton's (1988) estimate which uses the highest values for carbon per hectare is rather large compared to the other recently advocated ranges. If this high estimate is excluded, the range of Houghton's estimate for carbon flux for the next 110 or 120 years becomes 80 to 138 billion tC, which corresponds with the 91.0 billion tC medium value or 134.5 billion tC high value estimate of this study. However, the low estimate of 61.0 billion tC of this study is out of Houghton's range. This is because of the nature of eq. (6) in which the land area converted per unit of population increase rapidly decreases with decrease in the percentage of forested land.

Houghton (1988) estimates 78 billion tC of carbon dioxide flux from tropical forest clearing from 1800 to i980 for the high biomass case, and 28 billion tC for the low biomass case. Another study estimates 135 to 228 billion tC of carbon dioxide flux from land-use change for all regions of the world from 1860 to 1980 (Houghton *et al.*, 1983). The present study calculates 61 to 134.5 billion tC of flux from 1980 to 2100; for tropical regions alone, these figures are 1 to 3 times the carbon dioxide emissions up to the present, and 30 to 100 % forecast of carbon flux predicted for the whole world.

Fig.9 shows the future carbon dioxide flux estimated in our study, and a historical carbon dioxide flux assumed similar to Houghton's pattern (1988) and smoothly joined with our estimates. Also, in the figure, Houghton's low carbon estimates are given. In the figure both studies show a steep increase from the end of the twentieth century until the beginning of the twenty-first century, which levels off towards the end of the twenty-first century with a cumulative carbon flux ranging from 100 to 180 billion tC.

Recent forecasts about tropical forests, this one included, predict that between fifty and one hundred percent of remaining forests will be cleared by the end of the next century. This alarming scenario has been restated many times since the 1970s. Myers (1983) estimated tropical forest loss at the beginning of the 1980s as 24.5 million ha/y, and predicted that at that rate tropical forests would disappear within 38 years. Guppy (1984) used Lanly's (1982) data to predict the end of tropical forests in 2057. These estimates as well as Houghton (1988), IS92, which are extensions of previous ones, and this study use simplifying assumptions to extrapolate the rate of deforestation into the future. Although tropical deforestation is admittedly a result of many complex factors, it is indeed closely correlated to population pressure as shown in Figures 4 and 5. Certainly there are arguments to the contrary, but in this complex world, the fact that that population has been strongly connected to tropical deforestation in the past and present cannot be denied. The results of this study, which are an extrapolation of trends up to the present day, do have a valid basis. The implications should be addressed as real issues.

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