Continental Scale Estimates of the Biotic Carbon Flux from Land Cover Change: 1850 to 1980

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CONTINENTAL SCALE ESTIMATES OF THE BIOTIC CARBON FLUX FROM LAND COVER CHANGE: 1850 TO 1980

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ABSTRACT

Houghton, R. A. and J. L. Hackler. 1995. Continental Scale Estimates of the Biotic Carbon Flux from Land Cover Change: 1850 to 1980. ORNL/CDIAC-79, NDP-050, Oak Ridge National Laboratory, Oak Ridge, Tennessee. 144 pp.

This document describes a Numeric Data Package (NDP) that contains annual carbon flux estimates from land cover change for nine regions of the world (i.e., North America, Europe, the Former Soviet Union, Pacific Developed Region, China, South and Central America, North Africa—Middle East, Tropical Africa, and South and Southeast Asia). Annual rates of land cover change and vegetation—soil response curves for each region and ecosystem are included in the database. The vegetation—soil curves are used in a bookkeeping carbon model to estimate the carbon flux with the atmosphere from the clearing or degradation of vegetation, cultivation of soils, decay of dead vegetation, and the recovery of abandoned lands. The model calculates the net flux of carbon in each region based on land cover change rates and vegetation—soil response curves for the period 1850 to 1980 (a few regions have land cover records beginning in 1700 and carbon flux estimates ending in 1990). These data were collected and modeled in an attempt to reduce the uncertainty associated with the magnitude and time course of the flux of carbon from terrestrial vegetation to the atmosphere.

Analysis of the land cover data found that about 58×10^6 ha of land were converted to agricultural use in 1980 alone. About 40% of this total involved lands previously cleared or degraded by shifting cultivators. These land cover changes resulted in a net flux to the atmosphere of 1.4×10^9 Mg of Carbon. This clearing, and the degradation of other ecosystems, is a result of increased demand for agricultural and wood products by the world's growing population. These demands have resulted in a significant decline in the amount of carbon sequestered per hectare of forest. For example, in South and Southeast Asia the mean carbon content of forestland has decreased from 137 Mg C/ha in 1880 to 109 Mg C/ha in 1980, a 20% decrease in 100 years.

The data in this NDP were developed in three phases. The first phase was the collection of land cover change data from international and national data sources and the conversion of these data into annual rates of clearing, logging, or abandonment for each major ecosystem in a region. Secondly, regional— and ecosystem—specific vegetation—soil response curves were developed for each region. In the final phase, the land cover change rates and response curves were entered into a sequential bookkeeping model and the annual flux of carbon from land cover change was calculated. The resulting NDP contains: annual deforestation/afforestation rates, vegetation—soil response curves for each natural ecosystem in each region, and the net annual flux of carbon to or from the atmosphere for each region.

These data are available from the Carbon Dioxide Information Analysis Center (CDIAC). The NDP consists of this document and a set of 20 Lotus 1-2-3™ files, 3 flat ASCII data files, and 2 FORTRAN and 2 SAS™ data retrieval programs. This document contains information on the methods and model used in obtaining each variable; descriptions of file contents and formats; and discusses the sources, restrictions, and limitations of the data. These data are available free of charge from CDIAC on a variety of media as well as through the Internet.

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PART 1: INFORMATION ABOUT THE DATA PACKAGE

1. NAME OF THE NUMERIC DATA PACKAGE

CONTINENTAL SCALE ESTIMATES OF THE BIOTIC CARBON FLUX FROM LAND COVER CHANGE: 1850 TO 1980

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3. KEYWORDS

Afforestation, biomass, carbon flux, decay pool, deforestation, terrestrial ecosystems, slash, soil carbon, China, Europe, Former Soviet Union, North Africa–Middle East, North America, Pacific Developed Region, South and Central America, South and Southeast Asia, Tropical Africa

4. BACKGROUND INFORMATION

Measurements taken since 1958 at Mauna Loa Observatory, Hawaii, have shown a continued increase in the atmospheric concentration of CO₂ (Keeling and Whorf 1994). This increase has been related to the release of carbon into the atmosphere from the burning of fossil fuels. However, estimates made in 1980 found that the net release of CO₂ from land cover change in the tropics was 0.4×10^9 to 2.5×10^9 Mg of Carbon, 10 to 50% of the carbon released from the burning of fossil fuels in that year (Houghton et al. 1987, Houghton et al. 1991b, Marland and Rotty 1984). Recognition by the climate change research community that changes in the type, concentration, and health of terrestrial biota had a significant influence on the abundance of CO₂ in the atmosphere resulted in the U.S. Department of Energy's (DOE's) component of the U.S. Global Change Research Program (GCRP) funding several research projects to examine the terrestrial sources and sinks of atmospheric CO₂.

The mission of DOE's portion of the GCRP is to predict the future atmospheric concentration of CO₂ and other energy-related greenhouse gases and the impacts that these could have on climate; to understand and predict the impact of emissions and climate change on biota; and to understand the economic costs or benefits of climate change and the costs that would be associated with policies aimed at mitigating the impacts of global warming (Patrinos 1993). Thus, one of the primary missions of DOE's GCRP is to measure and model the physical, chemical, and biological sources and sinks of CO₂. This information is needed to determine the cycling rates and direction of carbon transport through the global carbon cycle, and to allow for the prediction of atmospheric concentrations of CO₂ in relation to its release from the burning of fossil fuels and deforestation, and its uptake from afforestation and deep ocean transport.

To this end, the Global Carbon Cycle component of DOE's GCRP provided approximately \$670 thousand from 1983 to 1994 for the construction of a global database of land cover change and a bookkeeping-type model that would track the flux of carbon in the atmosphere caused by the degradation of forests and changes in land cover (e.g., land clearing, shifting cultivation,

afforestation).

This database contains annual estimates of the rate of land cover change for up to 18 different ecosystems in nine regions of the world (i.e., North America, Europe, the Former Soviet Union, Pacific Developed Region, China, South and Central America, North Africa—Middle East, Tropical Africa, and South and Southeast Asia) as well as regional and ecosystem specific soil and vegetation response curves. A bookkeeping model was utilized to calculate the net flux of carbon in each region based on the land cover and response curve data. These carbon flux and land cover data have been estimated for the period 1850 to 1980 for all nine regions, with some regions having land cover records beginning in 1700 and carbon flux estimates ending in 1990. Results and conclusions derived from the model may be found in Houghton et al. (1983, 1985, 1987, 1991a, 1991b), Melillo et al. (1988), Houghton (1991a, 1991b, 1993), and Houghton and Hackler (1994). (A reprint of Houghton et al. 1983 is contained in Appendix C.)

Funding for this project was secured from FY 1983 through FY 1993 from the following agencies: the National Science Foundation (DEB-79-23329, BSR-8110477, BSR-8704749); the National Aeronautics and Space Administration (NAGW 970); the DOE Office of Health and Environmental Research (DE-FG02-90ER61079); and the Global Carbon Cycle component of DOE's GCRP (a fully integrated part of the U.S. Global Change Research Program), under subcontract 19X-SB830C from Oak Ridge National Laboratory, Oak Ridge, Tennessee, managed by Martin Marietta Energy Systems, Inc., for DOE under subcontract DE-AC05-84OR21400.

5. APPLICATIONS FOR THE DATA

This database provides a continuous history of land cover change and carbon flux for nine regions of the world from 1850 through 1980, with some regions having land cover records beginning in 1700 and carbon flux data ending in 1990, as well as a set of regional and ecosystem specific vegetation—soil response curves. The land cover and response curve data, along with the carbon flux data derived from the model, may be utilized by climate modelers as inputs to general circulation models, by historians in regional and global scale studies of land cover change, or by any researcher interested in the interrelationships between anthropogenic activities and land cover change, land degradation, or atmospheric carbon concentrations.

6. COMPILATION OF LAND COVER CHANGE RATES

Historical land cover data were collected at the global, regional, and country level (e.g., Zon and Sparhawk 1923, Richards and Flint 1994, and Gifford 1992) and used to derive rates of land cover change for natural ecosystems in the nine regions shown in Fig. 1. These regions cover a majority of the vegetated land on Earth, with only small undeveloped islands and large unvegetated regions being excluded from the database (i.e., Antarctica and Greenland). Table 1 provides a list of the countries that occur within each of the nine regions.

Figure 1. Map of the nine regions covered in this database.

Geographic location determines the ecosystems contained within a region. Thus, data were collected on and divided among the several different natural ecosystems occurring in each region. Availability of information on the type and extent of the ecosystems within each region determined the number of ecosystems utilized. Table 2 lists the natural ecosystems for which data were collected within each region. A listing of the primary data sources used during the compilation of this database are shown in Section 11.2. Due to the large number of secondary sources utilized, they have not been cited in this document. A majority of these secondary sources are cited in Hall et al. (1988), *Bibliography on Tropical Rain Forests and the Global Carbon Cycle: An Introduction to the Literature*.

Table 1. Countries comprising the nine regions in the terrestrial carbon model

North America		North Africa-Middle East	
Canada	United States	Afghanistan	Libya
		Algeria	Morocco
South and Central America		Bahrain	Oman
Argentina	Guyana	Cyprus	Qatar
Bahamas	Haiti	Egypt	Saudi Arabia
Belize	Honduras	Iran	Syria
Bolivia	Jamaica	Iraq	Tunisia
Brazil	Martinique	Israel	Turkey
Chile	Mexico	Jordan	United Arab Emirates
Colombia	Nicaragua	Kuwait	Yemen
Costa Rica	Panama	Lebanon	Yemen, Democratic
Cuba	Paraguay		
Dominican Rep.	Peru	Tropical Africa	
Ecuador	Puerto Rico	Angola	Mauritania
El Salvador	Surinam	Benin	Mauritius
Falkland Islands	Trinidad & Tobago	Botswana	Mozambique
French Guiana	Uruguay	Burundi	Nambia
Guadeloupe	Venezuela	Cabinda	Niger
Guatemala		Cameroon	Nigeria
		Central African Rep.	Rep. of Congo
Europe		Chad	Réunion
Albania	Ireland	Djibouti	Río Muni
Andorra	Italy	Equatorial Guinea	Rwanda
Austria	Liechtenstein	Ethiopia	Senegal
Belgium	Luxembourg	Gabon	Sierra Leone
Bulgaria	Malta	Gambia	Somalia
Czechoslovakia	Monaco	Ghana	South Africa
Denmark	Netherlands	Guinea	Sudan
Finland	Norway	Guinea-Bissau	Swaziland
France	Poland	Ivory Coast	Tanzania
Germany	Portugal	Kenya	Togo
Great Britain	Rumania	Lesotho	Uganda
Greece	San Marino	Liberia	Upper Volta
Hungary	Spain	Madagascar	Western Sahara
Iceland	Switzerland	Mali	Zaire
	Yugoslavia	Malawi	Zambia
			Zimbabwe

Table 1. (continued)

Former Soviet Union		South and Southeast Asia	
Armenia	Lithuania	Bangladesh	Laos
Azerbaijan	Moldavia	Bhutan	Malaysia
Byelorussia	Russia	Brunei	Nepal
Estonia	Tajik	Burma	Pakistan
Georgia	Turkmen	Cambodia	Philippines
Kazakh	Ukraine	India	Sri Lanka
Kirghiz	Uzbek	Indonesia	Thailand
Latvia			Vietnam
China		Pacific Developed Region	
Peoples Rep. of China	Mongolia	Australia	Oceania
		Japan	Papua New Guinea
		New Zealand	South Korea
		North Korea	Taiwan

Table 2. Natural ecosystems within each of the nine regions

North America		
Temperate evergreen forest		Temperate deciduous forest
Temperate grassland		Temperate woodland and shrubland
Boreal forest		
South and Central America		
Tropical equatorial forest		Tropical seasonal forest
Tropical woodland		Warm coniferous forest
Temperate broadleaf forest		Grassland
Desert scrub		
Europe		
Temperate evergreen forest		Temperate deciduous forest
Temperate grassland		Boreal forest

Table 2. (continued)

North Africa-Middle East	
Temperate evergreen forest	Tropical grassland
Tropical moist forest	Tropical woodland and shrubland
Desert scrub	
Tropical Africa	
Closed forest	Open forest
(includes Bamboo forests)	
Former Soviet Union	
Temperate deciduous forest	Temperate grassland
Boreal forest	
China	
Temperate evergreen forest	Temperate grassland
Temperate deciduous forest	Tropical moist forest
South and Southeast Asia	
Degraded:	
Tropical moist forest	Tropical open forest
Tropical seasonal forest	
Undisturbed:	
Tropical moist forest	Tropical open forest
Tropical seasonal forest	Tropical grassland
Pacific Developed Region	
Temperate evergreen forest	Temperate deciduous forest
Tropical moist forest	Tropical grassland
Tropical woodland and shrubland	Desert scrub

(Note: See Appendix A for regional ecosystem definitions.)

The ecosystems in each region (Table 2) were obtained by distributing the world vegetation types of Whittaker and Likens (1973) on Küchler's map of natural vegetation (Espenshade 1986). The area of each ecosystem within each region was then proportionally reduced by the land in agriculture in 1700. Due to the lack of data prior to the 1800's, the total area of each ecosystem in each region for 1700 was extrapolated based on the regional ratio between population and land in agriculture (McEvedy and Jones 1978). Estimates of the amount of land in each ecosystem type, within each region, were then used as the seeds, or initial values, for the analysis. The rates of land cover change derived for the years following 1700 may be applied to this seed value to obtain the "actual" land area in each ecosystem.

Because the model calculating the flux of carbon does not include ecosystems in an

undisturbed state (i.e., it is assumed that they have no net changes in their carbon content), the actual area in a given ecosystem is not relevant to the carbon model. Errors in the initial allocation of land to each ecosystems would affect the model only if the rates of land clearing exceeded the available land.

Data on the area in cropland for 1700 to 1980 were compiled by country from historical documents. In most cases, records are incomplete for the earlier years. In such cases it was necessary to extrapolate from a few countries to an entire region based on regional ratios between population and land in agriculture. For the years prior to 1950 in South and Central America, for example, Argentina, Brazil, and Mexico have the most complete historical land use records. These three countries currently contain over 75% of the region's cropland (Food and Agriculture Organization 1985). Assuming that this pattern was similar in the past, the total area cleared for cropland prior to 1950 may be approximated for the South and Central America region. This was done by constructing a annual ratio between the amount of cropland and population in Argentina, Brazil, and Mexico in relation to the regional population (Houghton et al. 1991a). For years after 1950, cropland areas were generally obtained from individual country handbooks and the annual production yearbooks of the Food and Agriculture Organization (FAO).

The annual record of land cover change (i.e., rates of change) within each ecosystem were developed from noncontinuous data. The beginning rate of change for 1700–1701 was calculated from population, as discussed in the preceding paragraphs. Estimates of the rates of land cover change were made using data for individual years, or groups of years, with data. The rates for intervening years were then estimated using a stepwise or a linear function, depending on the region and ecosystem in question. Thus, the actual number of data points used to calculate the rates of change may be quite small before 1946 (the FAO began publication of their annual *Production Yearbook* in 1946). For example, in the Pacific Developed Region the annual conversion of the tropical moist forest ecosystem to cropland contains only four rates of change during the entire period of record (1700–1980). The first rate covers 1700–1869 and is population based; the second rate covers 1870–1949 and is based on Zon and Sparhawk (1923) and the first two FAO *Production Yearbooks*; the third (1950–1969) and fourth (1970–1980) rates were derived almost exclusively from FAO publications (e.g., FAO 1963).

In the Pacific Developed Region a stepwise function was used for the conversion of tropical moist forest to cropland. This means that a constant rate of change was used for each of the four periods, with the rate increasing in a stepwise fashion in 1870, 1950, and 1970. If a linear function had been used in the preceding case, as is the situation for the logging of tropical moist forest, a "zero" rate would have been calculated for 1700. A linear equation would have been developed that viewed the zero and first rate as points on a line, and the first rate would be reached by the end of the first period. This process would be repeated for the first and second rates, second and third rates, and third and fourth rates. Figure 2 provides a graphic comparison of these two methods, based on the conversion curve for tropical moist forest to cropland.

Figure 2. Comparison of the stepwise function and linear function using the tropical moist forest-to-cropland conversion curve in the Pacific Developed Region.

Land cover conversion curves similar to the one shown in Fig. 2 were developed for each ecosystem within each region. Each ecosystem may have up to seven conversion curves: (1) clearing for cropland, (2) clearing for pasture, (3) industrial logging, (4) nonindustrial logging, (5) shifting cultivation, (6) degradation, and (7) afforestation. However, in most cases only two or three conversion curves are needed for a given ecosystem within a region.

7. MODELING OF CARBON FLUX FROM LAND COVER CHANGE

A reduction in the size of a given ecosystem, and changes in the total biomass within disturbed or cleared areas are readily observable. For example, the clearing of tropical moist forest for cropland will reduce the amount of biomass contained within vegetation. Not so obvious, though well documented (e.g., Schlesinger 1986), is the decline in soil carbon that follows clearing. Like the biomass of live vegetation, the carbon content of soils may recover to their predisturbance levels if the area is abandoned and allowed to recover. Thus, when modeling the flux of carbon within the atmosphere, information must be collected on land cover change (provided by the land cover change rates), the carbon content of vegetation and soils in each ecosystem, and recovery times associated with the regrowth of vegetation after abandonment.

7.1 Vegetation-Soil Response Curves

Each ecosystem, in each region, has a vegetation-soil response curve that contains information on the mean regional carbon content (per hectare) for undisturbed vegetation and soils, as well as information on the expected change in biomass that will occur due to disturbance. These values were first computed as dry matter and multiplied by 0.45 to obtain the carbon values shown in the response curves. The estimates of organic soil carbon used in this study were made for the top 1 m of soil by Schlesinger (1984), Palm et al. (1986), and Zinke et al. (1986). Estimates for vegetation were made based on Whittaker and Likens (1973), Olson et al. (1983), Lanly (1982), and Houghton et al. (1983). The data contained in these response curves include information on the minimum carbon content reached after clearing, time (in years) to reach this minimum, carbon in live vegetation (e.g., crops) left on site, time for carbon levels to recover after abandonment, time for recovered area to reach initial carbon levels, and the fraction of cleared vegetation assigned to decay pools (the carbon in harvested vegetation decays at different rates based on the use to which the vegetation is put).

In this model, five decay pools are used. The first contains slash and dead vegetation left on-site at the time of clearing. Biomass in this pool is released to the atmosphere based on an ecosystem and region specific on-site decay rate. The second is the 1-year decay pool. Biomass assigned to this pool is assumed to be burned and released to the atmosphere in the year following clearing. The third, fourth, and fifth pools are the 10-year, 100-year, and 1000-year decay pools. The biomass assigned to these pools are released to the atmosphere using 0.1, 0.01, and 0.001 decay constants, respectively.

Response curve data contained in this database are for 1 ha of land. One of the response curve spreadsheets used for the clearing of forestland for crops and pasture in Tropical Africa is shown in Table 3. This table provides an example of the information contained in each response curve spreadsheet. Printouts of the response curves for all ecosystems and regions are contained in Appendix B.

Table 3. Vegetation-Soil Response curve data showing changes in the amount of carbon sequestered in live vegetation and soils caused by the clearing of natural ecosystems in Tropical Africa for cropland or pasture

	Natural ecosystems	
	Closed forest	Open forest
Carbon in vegetation of undisturbed ecosystem	136	30
Carbon in vegetation of "recovered" ecosystem	136	30
Carbon in crops	15	15
Time for abandoned system to "recover"	29	29
Time for vegetation to recover to primary state from "recovered" state	1	1
Carbon in soils of undisturbed ecosystems	100	50
Carbon in soils of "recovered" ecosystems	100	50
Carbon content of soil after initial rapid change following clearing	80	40
Minimum carbon content of soil in cultivated system	75	37
Time to initial rapid change	1	1
Time to soil minimum	5	5
Time for soil to reach "recovered" state	29	29
Time for soil to recover to primary state from "recovered" state	1	1
Fraction of original vegetation assigned to decay pools at time of clearing		
1-year	0.4	0.4
10-year	0.27	0.27
100-year	0.0	0.0
1000-year	0.0	0.0
Fraction left to decay on site	0.33	0.33
Rate constant for on-site decay	0.5	0.3

(Note: Carbon measurements in 10^6 g/ha; time in years.)

The data in Table 3 can be shown graphically with two curves that describe the changing amounts of carbon in soil and live vegetation following disturbance. Figure 3 shows a reduction in the amount of carbon in live vegetation following clearing. Some of the carbon removed is placed in long-term storage in buildings, crates, etc.; some is burned as fuel wood and released immediately to the atmosphere; and some is left on the ground as slash or live underbrush. The carbon in the soil declines over several years following clearing until it reaches a new equilibrium. Abandonment of the area allows the regrowth of vegetation and a reaccumulation of carbon in the soil. Accumulation of carbon will continue until initial levels are reestablished.

Figure 3. Changes in the carbon content of living vegetation and soils: clearing, abandonment, and regrowth.

7.2 The Carbon Flux Model

The rates of land cover change and the response curves described in Section 7.1 are used in the carbon flux model to calculate the net transfer of carbon between the atmosphere and terrestrial ecosystems in each region. Ecosystems and regions with no net transfer of carbon to or from the atmosphere would be described by a line with a slope of zero. Because of this, only areas in states of transition need to be modeled. Those areas that have been harvested or cleared are modeled on an annual basis as the land moves along the appropriate response curve. These areas either remove carbon from the atmosphere as vegetation and soil accumulate organic matter, or release carbon as the soils are tilled and their organic matter oxidized. These response curves are defined for 1 ha of land; thus, the response curve is multiplied by the total land in each ecosystem in each region that is in transition. To this sum is added the carbon released from the oxidation of biomass contained in five decay pools.

For each ecosystem and region, the response curves describe the changes that occur to the carbon content of vegetation and soil for seven different forms of land cover change (i.e., clearing for cropland, pasture, shifting cultivation, industrial logging, nonindustrial logging, degradation, and afforestation). Figure 4 schematically describes the partitioning of biomass and carbon that occurs when forestland is cleared. The specific allocation of carbon is determined from the appropriate vegetation-soil response curve.

Figure 4. Schematic representation of the transfer of carbon and biomass that occurs when forested lands are cleared.

The carbon transfer shown in Fig. 4 is calculated using a bookkeeping model. The model tracks the annual transfer of carbon between soils, terrestrial ecosystems, and the atmosphere caused by changes in land cover. The model calculates the flux of carbon separately for each natural ecosystem and land cover change (disturbance) type in a region. These ecosystem fluxes are then summed to obtain the annual flux of carbon to or from the atmosphere for each region (Moore et al. 1981). These regional carbon flux totals are listed in Appendix C.

The model is designed to track the transfer of forested lands to land uses with lower carbon contents (e.g., from tropical forest to pasture). During initial human habitation of a region, only undisturbed, high-carbon-content, primary forests are available for clearing. Once the minimum amount of land required for subsistence agriculture is obtained, more forests are cleared to obtain wood products. The primary forests harvested for wood products, unlike those cleared for agriculture, may be allowed to revert to forest and, with time, will recover to their previous high-carbon levels.

In modern agroforestry, trees are planted on previously cleared forestland and are allowed to grow for a few decades. These managed forests have a carbon content very close to that of the original primary forest when they have reached maturity (i.e., recovered) and are ready to be harvested (in 20 to 30-years) and will have the same carbon content as primary forests in 30 to 100 years.

In the bookkeeping carbon model, forestlands that have *just recovered* in a given year will be cleared before a similar undisturbed primary forest will be cleared. For example, the land cover rate curve for North America shows that 0.905×10^6 ha of temperate evergreen forest were logged in 1969, and the model has determined (based on the North America response curve) that 0.895×10^6 ha of forest has "just recovered" from being logged in 1919, thus the 0.895×10^6 ha of recovered forest will be recleared along with 0.01×10^6 ha of primary forest. This distinction is important because the recovered forest contains 25% less carbon than that of primary forest.

In the South and Southeast Asia region a differentiation has been made between undisturbed and degraded ecosystems. In South and Southeast Asia each forest ecosystem is represented by two pools of land (e.g., Degraded moist forest and Undisturbed moist forest). Similarly, separate land cover change rates and vegetation-soil response curves are provided. When a given amount of undisturbed forest is degraded (per the land cover change rate file for South and Southeast Asia) it is transferred to the degraded pool. The amount of carbon released is determined by subtracting the amount of "carbon in vegetation of undisturbed ecosystem" for the undisturbed forest from that of the disturbed forest. This carbon is then released based on the five decay pool definitions given in the undisturbed forest response curve. Note that during the conversion from undisturbed to disturbed land that the "carbon in soils of undisturbed ecosystems" does not change.

7.3 Carbon Flux Equations

The equations shown below were derived by CDIAC and are *approximations* of the formulas used to determine the carbon flux from land cover change in the computerized bookkeeping model. These equations are provided to assist users of this numeric data package in understanding how the carbon flux data were calculated.

The flux of carbon for an ecosystem is calculated separately for each given response curve and the carbon fluxes are aggregated to obtain the total carbon flux. These ecosystem totals are summed to obtain the regional carbon flux for each year. In general, Eq. 1 shows how the annual carbon flux (CF) with the atmosphere for a given ecosystem is calculated.

$$CF = Soil_t + Slash_t + P1_t + P10_t + P100_t + P1000_t - C_t \quad (1)$$

where $Soil_t$ is the carbon released from disturbed soil, $Slash_t$ is the carbon released from dead

vegetation left on-site after clearing, P1 through P1000 contain the amount of carbon released from the 1, 10, 100, and 1000-year decay pools, and C_a is the amount of carbon removed from the atmosphere from the regrowth and recover of vegetation and soils. The contribution of each term varies as a function of pool size or time since disturbance.

In most types of land use change (e.g., clearing for cropland, pasture, shifting cultivation) $Soil_t$ is calculated as follows:

$$Soil_t \text{ in } X = \sum_{X - T_{RC} \text{ to } X - 1} LC \cdot ((C_{US} - C_{RC}) / T_{RC}) + \sum_{X - T_{RC} \text{ to } X - T_{SM}} LC \cdot ((C_{RC} - C_{SM}) / (T_{SM} - T_{RC})) \quad (2)$$

where LC_X is the amount of land cleared in year X, C_{US} is the amount of carbon per hectare in undisturbed soils, C_{RC} is the amount of carbon per hectare remaining in the soil after the initial rapid change following clearing, T_{RC} is the time for the rapid change in soil carbon to occur, T_{SM} is the time to reach the minimum soil carbon content, and C_{SM} is the minimum soil carbon content. Some forms of logging (nonindustrial) and in the special case of forest degradation $Soil_t$ was assumed to have a value of zero.

The release of carbon to the atmosphere from $Slash_t$ in year X is calculated based on a running total of the slash pool. The rate of decay for slash is constant for each response curve, unlike the release for soil, which has an initial rapid decay rate that is used for 1 to 10 years followed by a much lower rate that may be used for several decades. Use of a constant rate greatly simplifies the equation needed to calculate the carbon emissions from slash. Equations 3a and 3b show how the annual amount of carbon released to the atmosphere from slash is calculated:

$$Slash \text{ Pool} = LC_X \cdot C_{UV} \cdot F_{CS} + (Slash \text{ Pool}_{X-1} - Slash_t \text{ in } X - 1) \quad (3a)$$

$$Slash_t \text{ in } X = Slash \text{ Pool} \cdot (1 - e^{-DR}) \quad (3b)$$

where LC_X is the amount of land cleared in year X, C_{UV} is the amount of carbon per hectare in an undisturbed ecosystem, F_{CS} is the fraction of C_{UV} that became slash following clearing, and DR is the on-site decay rate for slash.

The equation for the release of carbon from the 1-year decay pool (P1) is based on the assumption that all carbon assigned to this pool will be used as fuel or burned on-site in the year following clearing. The equation for this pool is as follows:

$$P1 \text{ in } X = LC_{X-1} \cdot C_{UV} \cdot F_{C1} \quad (4)$$

where F_{C1} is the fraction of C_{UV} that is assigned to the 1-year decay pool following clearing.

The equations for the 10-, 100-, and 1000-year decay pools (P10, P100, P 1000) are similar to those shown in Eqs. 3a and 3b. The primary difference between the equations for P10, P100, and P1000 and Eq. 3b is that the exponent in Eq. 3b is not used. Equations 5a and 5b show the formula used for calculating P10 in year X.

$$\text{P10 Pool} = \text{LC}_X \cdot \text{C}_{UV} \cdot \text{F}_{\text{CP10}} + (\text{P10 Pool}_{X-1} - \text{P10}_r \text{ in } X - 1) \quad (5a)$$

$$\text{P10}_r \text{ in } X = \text{P10 Pool} \cdot \text{DR} \quad (5b)$$

where F_{CP10} is the fraction of C_{UV} assigned to the 10-year decay pool and DR is the decay rate constant for P10 (in this case DR equals 0.1). Modification of this equation for the 100- and 1000-year decay pools only requires that the appropriate fraction and decay constant be inserted (i.e., 0.01 or 0.001 for DR) in Eqs. 5a and 5b, respectively.

The five equations shown above are used to determine the release of carbon to the atmosphere from the clearing of an ecosystem. There may also be an accumulation of carbon in live vegetation and in the soil from the abandonment of crop or pasture lands, and the regrowth of forests after logging. When land is abandoned, a linear function is used that transfers carbon from the atmosphere to live vegetation and into the soil. In some cases, the regrowth of forests after logging affected only the amount of carbon sequestered in live vegetation as the carbon content of soils was assumed to be unaffected by short-term disruptions caused by nonindustrial logging.

Removal of carbon from the atmosphere from the regrowth of vegetation on previously cleared land is calculated in this model using the following equation:

$$\text{C}_a \text{ in } X = \text{Crop}_a + \text{Soil}_a + \text{Veg}_a \quad (6)$$

where Crop_a is the amount of carbon removed by the growth of annual or perennial species on previously cleared forestland (or the amount of live vegetation left on-site after logging), Soil_a is the amount of carbon sequestered in the soil, and Veg_a is the amount of carbon removed by the regrowth of woody vegetation on previously cleared land.

The amount of carbon removed by Crop_a is a one-time removal, because the amount removed/released during the planting/harvesting/grazing cycle will be relatively constant from year to year. The equation for Crop_a is as follows:

$$\text{Crop}_a \text{ in } X = \text{LC}_X \cdot \text{C}_{\text{crop}} \quad (7)$$

where LC is the amount of land cleared for cropland or pasture in year X and C_{crop} is the amount of carbon per hectare associated with the major crop or fodder grown in the given region in the given ecosystem.

The Soil_a and Veg_a functions are used only if a previously cleared area is abandoned and allowed to return to its previous vegetation cover (if an area is logged and immediately abandoned sometimes only the Veg_a equation is used). The Soil_a and Veg_a equations, shown below, are used to calculate the transfer of carbon from the atmosphere into the soil and vegetation that occurs during the recovery of a natural ecosystem:

$$\text{Soil}_a \text{ in } X = \sum_{X \text{ to } X - (T_{\text{SR}} - 1)} [\text{LA} \cdot ((\text{C}_{\text{RS}} - \text{C}_{\text{SM}}) / T_{\text{SR}})] \quad (8)$$

$$\text{Veg}_a \text{ in } X = \sum_{X \text{ to } X - (T_{\text{VR}} - 1)} [\text{LA} \cdot ((\text{C}_{\text{RV}} - \text{C}_{\text{crop}}) / T_{\text{VR}})] \quad (9)$$

where LA is the amount of land abandoned in a given year, C_{RS} is the soil carbon content of a recovered ecosystem, C_{SM} is the minimum soil carbon content of a disturbed ecosystem, T_{SR} is the time required for an abandoned system to recover, C_{RV} is the vegetation carbon content of a recovered ecosystem, and T_{VR} is the time required for the vegetation in an abandoned system to recover. In some regions a distinction is made between a "recovered" ecosystem and an undisturbed system. In those cases equations similar to Eqs. 8 and 9 are used to bring the carbon content up from C_{RV} to C_{UV} over a period T_{UR} (i.e., time for vegetation to recover to the undisturbed state from "recovered").

7.4 Advantages of this Model

Time lags associated with the decay and regrowth of vegetation and with the decay and recovery of soils make the annual flux of carbon calculated with this model more realistic than a flux derived by simple direct transfer methods that work on the assumption that all carbon in cleared vegetation is immediately released. There are several advantages of this carbon flux model over the more complicated process-type models. First, complex physiological and ecological processes do not have to be modeled since these processes are implicitly included in the shape of the response curves. Second, the information needed to construct the response curves is readily available in the literature. Third, the shape of the response curve for any ecosystem may be directly measured in the field. Once the response curve is constructed, the flux of carbon to the atmosphere can be determined based on the type of ecosystem cleared, the amount of land cleared, and the allocation of biomass to the five decay pools (Houghton et al. 1983, Moore et al. 1981).

8. LIMITATIONS AND RESTRICTIONS OF THE DATA

The following list shows the caveats that should be considered when these data are used. Failure to consider these limitations may result in erroneous interpretation of the data.

- (1) The large number of data sources used in determining the rates of land cover change precluded the checking of all data values.
- (2) In 1700 (or 1850 in some regions), the initial land area in each natural ecosystem was approximated and then was reduced based on regional ratios of agricultural land to population (McEvedy and Jones 1978).
- (3) Area estimates for each ecosystem, in each region, have been used to construct the annual land cover change curves that were entered into the carbon flux model. Data for years with missing data were derived by assuming constant rates of land clearing or by using a linear regression function between years with data. Thus, over the 120 years covered in this database, as few as four actual data values have been used to reconstruct rates of land cover change for a region.
- (4) The amount of carbon in an undisturbed ecosystem was assumed to be constant. Thus, the total land area in a natural ecosystem within a region is not important, only the amount of land that changed status (e.g., from tropical evergreen forest to cropland).
- (5) The steady state assumption means that the estimates of carbon flux apply only to deliberately changed ecosystems and not to all ecosystems. For example, recently glaciated areas may still be accumulating carbon (Billings et al. 1982), or terrestrial respiration rates may have increased as a result of the higher concentration of CO₂ in the atmosphere. These carbon sinks have been ignored by the model and are not reflected in the carbon flux estimates provided with this NDP.
- (6) The equations contained in this document are approximations of those used in the computerized carbon flux model. As such, carbon flux values calculated using these equations may vary by $\pm 10\%$ from those produced by the computer model. This error range, however, is within the inherent error of the land cover change and response curve data used in the computer model.

9. DATA CHECKS PERFORMED BY CDIAC

An important part of the data packaging process at the Carbon Dioxide Information Analysis Center (CDIAC) is the quality assurance (QA) of the data. The QA process is an important component in the value-added concept of assuring accurate, usable information for researchers. The complete QA of a data set can be a time consuming process because data received by CDIAC are rarely in condition for immediate distribution, regardless of source. The following summarizes the QA checks performed on the various data groups presented in this document.

- (1) The rates of land cover change for all forested ecosystem types in each region were combined for the periods 1958–1963 and 1979–1989 and compared to rates independently derived by the Food and Agriculture Organization (FAO 1960, 1966, 1980, 1990).
- (2) Rates of land cover change were applied to the initial area in each ecosystem in 1850 (or 1700 when available) to produce ecosystem areas for the period 1850–1980. The estimated areas of each ecosystem were then compared for the years 1950 and 1980 with Paterson (1956), Lanly (1982), and FAO (1980).
- (3) The data values in the soil and biomass response curves were compared with the original literature sources used in their compilation.
- (4) The carbon fluxes from each ecosystem in Tropical Africa and the Former Soviet Union were recalculated using the equations contained in this document. These fluxes were then summed and compared to those provided by the principal investigators.

QA tasks 1 and 2 were conducted to check for errors in the land cover change data. All discrepancies between the FAO land cover values and those provided by the data contributors (QA task 2) were resolved. Task 3 was conducted to ensure that data entry errors had not occurred while transferring data from the original data sources cited in this document. The last task was conducted to ensure the carbon flux equations shown in this document approximated the values obtained by the more complicated carbon flux model used by the principal investigators. (The carbon flux data distributed with this database were produced by the their carbon flux model.)

10. HOW TO OBTAIN THESE DATA AND ITS DOCUMENTATION

This document describes the historical land cover and carbon flux data collected by Dr. Richard A. Houghton and Joseph L. Hackler for the U.S. Department of Energy's Global Climate Change Research Program. Their computerized data are available on 9-track magnetic tape, Exabyte 8-mm tape, QIC 0.25" tape cartridges, IBM DOS-compatible floppy diskettes (3.5" or 5.25" diskettes), and through an anonymous file transfer protocol (FTP) service from CDIAC. Requests for magnetic media should include any specific instructions required by the user and/or the user's local computer system. Requests for this data package should be addressed to

Carbon Dioxide Information Analysis Center
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, Tennessee 37831-6335
U.S.A.

Telephone: (615) 574-0390 or 574-3645
FAX: (615) 574-2232

BITNET: CDIAC@ORNLSTC
INTERNET: CDIAC@ORNL.GOV

The data files may be acquired via the Internet from CDIAC's anonymous FTP server as follows:

- FTP to CDIAC.ESD.ORNL.GOV (128.219.24.36).
- Enter "anonymous" as the user id.
- Enter your electronic mail address as the password (e.g., BIRDWELL@ORNL.GOV).
- Change the directory using "cd pub/ndp050".
- Set FTP to get ASCII files by using the FTP "ascii" command.
- Acquire the ASCII descriptive file by using the FTP "mget ndp050.des" command.
- Change the directory using "cd ascii".
- Acquire the ASCII data files and I/O files by using the FTP "mget *" command.
- Change the directory using "cd ../wk1".
- Set FTP to get the binary LotusTM files by using the FTP "binary" command.
- Acquire the binary Lotus 1-2-3TM data files using the FTP "mget *.wk1" command.
- Exit the system by using the FTP "quit" command.
- Contact CDIAC by phone, fax, or electronic mail to order a hard copy of this documentation.

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PART 2: INFORMATION ABOUT THE COMPUTERIZED DATA FILES

12. CONTENTS OF THE COMPUTERIZED DATA FILES

The following table lists the 27 files included in this database and distributed by the Carbon Dioxide Information Analysis Center (CDIAC) along with this documentation. These files are available on 9-track magnetic tape, 8-mm tape, 0.25" tape cartridge, IBM-formatted floppy diskettes, and through the Internet using the file transfer protocol (FTP) from CDIAC's anonymous FTP server.

Table 4. List and description of the digital files

File number	Name, type, and description	Logical records	Record length	Block size	File size (bytes)
1.	NDP-050.DOC (ASCII) General descriptive information file that contains the information contained in Part 2 of the documentation.	883	80	8000	70640
2.	AREAS.FOR (ASCII) FORTRAN retrieval program to read and print file 4.	36	80	8000	2880
3.	AREAS.SAS (ASCII) SAS TM retrieval program to read and print file 4.	16	80	8000	1280
4.	AREAS.ASC (ASCII) Land area data for 1700 (most regions), 1850, and 1980 for the nine regions used in this data package.	58	80	8000	4640
5.	AREAS.WK1 (Binary) Lotus 1-2-3 TM file with land area data for 1700 (most regions), 1850, and 1980 for the nine regions used in this data package.	72	100	1000	7200
6.	NETFLUX.FOR (ASCII) FORTRAN retrieval program to read and print file 8.	32	80	8000	2560
7.	NETFLUX.SAS (ASCII) SAS TM retrieval program to read and print file 8.	12	80	8000	960

Table 4. (continued)

File number	Name, type, and description	Logical records	Record length	Block size	File size (bytes)
8.	NETFLUX.ASC (ASCII) Net carbon emissions to the atmosphere from 1850 to 1980 for the nine regions used in this data package.	141	132	6600	18612
9.	NETFLUX.WK1 (Binary) Lotus 1-2-3™ file with net carbon emissions to the atmosphere from 1850 to 1980 for the nine regions used in this data package.	297	100	1000	29700
Lotus 1-2-3™ files with annual land cover change rates for each region					
10.	ASIA-RAT.WK1 (Binary) South and Southeast Asia	106	100	1000	10600
11.	CHIN-RAT.WK1 (Binary) China	54	100	1000	5400
12.	EURO-RAT.WK1 (Binary) Europe	55	100	1000	5500
13.	FSU-RAT.WK1 (Binary) Former Soviet Union	57	100	1000	5700
14.	NAFM-RAT.WK1 (Binary) North Africa—Middle East	48	100	1000	4800
15.	NAM-RAT.WK1 (Binary) North America	109	100	1000	10900
16.	PCDV-RAT.WK1 (Binary) Pacific Developed Region	53	100	1000	5300
17.	SCAM-RAT.WK1 (Binary) South and Central America	107	100	1000	10700
18.	TAF-RAT.WK1 (Binary) Tropical Africa	35	100	1000	3500

Table 4. (continued)

File number	Name, type, and description	Logical records	Record length	Block size	File size (bytes)
Lotus 1-2-3™ files with the vegetation response curves for each region					
19.	ASIA-RE.WK1 (Binary) South and Southeast Asia	53	100	1000	5300
20.	ASIA-SH.WK1 (Binary) Shifting cultivation response curves for South and Southeast Asia	45	100	1000	4500
21.	FSU-RE.WK1 (Binary) Former Soviet Union	64	100	1000	6400
22.	SCAM-RE.WK1 (Binary) South and Central America	135	100	1000	13500
23.	TAF-RE.WK1 (Binary) Tropical Africa	39	100	1000	3900
24.	TEM-RE.WK1 China, Europe, North Africa— Middle East, North America, and the Pacific Developed Region	88	100	1000	8800
Lotus 1-2-3™ files with carbon partition data. Files are provided only for the six regions whose decay pool partitioning, in the response curves, changes over time.					
25.	FSULOGPT.WK1 (Binary) Former Soviet Union	46	100	1000	4600
26.	TEMLOGPT.WK1 (Binary) China, Europe, North Africa— Middle East, North America, and the Pacific Developed Region	49	100	1000	4900

Table 4. (continued)

File number	Name, type, and description	Logical records	Record length	Block size	File size (bytes)
Lotus 1-2-3™ file with the equations described in Part 1 of this documentation implemented for one ecosystem in Tropical Africa.					
27.	MODEL-EX.WK1 (Binary) Model for the closed forest ecosystem in Tropical Africa.	1805	100	1000	180500
Total Records		4495	Total Size		433272

1. All files are stored in a fixed-block record format.
2. SAS™ is a registered trademark of the SAS Institute, Inc., Cary, North Carolina 27511-8000.
3. Lotus 1-2-3™ is a registered trademark of Lotus Development Corp., 55 Cambridge Parkway, Cambridge, Massachusetts 02142.

13. DESCRIPTIVE FILE ON THE MAGNETIC MEDIA

The following is a listing of the first file provided on the magnetic media distributed by CDIAC. This file provides variable descriptions, formats, units, and other pertinent information about each file associated with this database.

Title Of The Database

Continental Scale Estimates of the Biotic Carbon Flux from Land Cover Change: 1850 to 1980

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Scope Of The Data

The land cover, response curve, and carbon flux data contained within this database were initially intended to be used by climate modelers as inputs to general circulation models. However, these data may also be used by historians in regional and global scale studies of land cover change, or by any researcher interested in the interrelationships between anthropogenic activities and land cover change, land degradation, or atmospheric carbon concentrations.

This database contains annual estimates of the rate of land cover change for up to 18 different natural ecosystems in nine regions of the world (i.e., North America, Europe, Former Soviet Union, Pacific Developed Region, China, South and Central America, North Africa–Middle East, Tropical Africa, and South and Southeast Asia). Each ecosystem that occurs within a region has a regional and ecosystem specific vegetation–soil response curve. A bookkeeping model was designed that utilized the land cover change rates and the vegetation–soil response curves to calculate the net flux of carbon to and from the atmosphere in each region. These estimates of carbon flux and the land cover change rates have been estimated for the period 1850 to 1980, with some regions having land cover records beginning in 1700 and carbon flux estimates ending in 1990.

Twenty-seven digital files are distributed with this database. Files are included for each region and contain: (1) initial and intermediate land areas for each ecosystem–land cover type (in AREAS.WK1), (2) land cover change rates, (3) vegetation–soil response curves, (4) logging partitioning tables for regions whose logging methods have changed significantly over the last

century, and (5) annual carbon flux values (in NETFLUX.WK1). The last file included with this database (MODEL-EX.WK1) implements the equations described in Part 1 of this documentation for one ecosystem in Tropical Africa.

Figure 5 provides a schematic that may be used to determine which files were used for calculating the annual carbon flux values for a given region. For example, data from files TAF-RAT.WK1 and TAF-RE.WK1 were used in MODEL-EX.WK1 to calculate the carbon flux for one ecosystem in Tropical Africa. The abbreviations used in Figure 5 and in all the filenames used in this database are NAM=North America, EURO=Europe, FSU=Former Soviet Union, PCDV=Pacific Developed, CHIN=China, SCAM=South and Central America, NAFM=North Africa–Middle East, TAF=Tropical Africa, and ASIA=South and Southeast Asia.

Figure 5. Diagram showing the file combinations used in calculating land cover change and carbon flux in each region (NAM=North America, EURO=Europe, FSU=Former Soviet Union, PCDV=Pacific Developed, CHIN=China, SCAM=South and Central America, NAFM=North Africa–Middle East, TAF=Tropical Africa, and ASIA=South and Southeast Asia).

Data Formats

The data within this NDP were initially received as Lotus 1-2-3TM WK1 or WK3 spreadsheets. The Lotus 1-2-3TM spreadsheets have been standardized into the WK1 file format, and data from two summary spreadsheets have been exported into flat ASCII data files to allow their use by a wider audience.

This NDP consists of 1 flat ASCII documentation file, 2 flat ASCII data files, 2 SASTM programs, 2 FORTRAN programs, and 20 Lotus 1-2-3TM data files; for a total of 27 digital files. The flat ASCII documentation file contains most of the information contained in Part 2 of this document, with postscript graphics and special control characters or symbols removed. The two flat ASCII data files contain exported versions of the AREAS.WK1 and NETFLUX.WK1 summary spreadsheets. The SASTM and FORTRAN files are in a ASCII format and contain programs to read the flat ASCII data files. The 20 Lotus 1-2-3TM files contain the land cover change rates (9 files), vegetation-soil response curves (6 files), decay pool partitioning tables (2 files), initial and ending land cover areas (1 file), annual carbon flux by region (1 file), and a simplified bookkeeping model (1 file) customized for Tropical Africa.

All land cover change values in the spreadsheets are expressed in units of 10⁶ ha. The vegetation-soil response curves are calibrated for 1 ha of land and have values in megagrams of Carbon (1 Mg of carbon = 1 metric ton of carbon). The carbon flux values for each region were obtained using the carbon flux equations shown in Part 1 of this document and are based on the land cover change and response curve data. The calculated carbon flux values are expressed in 10⁶ Mg of C.

Flat ASCII Data Files

Two flat ASCII data files (i.e., AREAS.ASC and NETFLUX.ASC) are provided with this data package along with two SASTM and two FORTRAN programs designed to read and print the contents of each data file. The information within these files allows the user to ascertain the total amount of land in each ecosystem in 1700 (for most regions), 1850, and 1980, and to determine the annual regional and global carbon flux from vegetation and soils due to land cover change.

The following pages contain a description of the contents and formats of the two flat ASCII data files distributed with this NDP.

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File: AREAS.ASC

The name of the first flat ASCII data file is AREAS.ASC. The FORTRAN and SASTM programs provided to read this data file are named AREAS.FOR and AREAS.SAS, respectively. A summary of the FORTRAN statements used to read the data file follows:

```

10    READ (5,100,END=999) REGION
20    READ (5,110) ECOSYS, A1700, A1850, A1980, CHANGE
      IF (ECOSYS .EQ. ' ') GOTO 10
      GOTO 20
100    FORMAT(1A28)
110    FORMAT(1A28,3I9,1F9.2)

```

The variables in AREAS.ASC, listed below, are shown in the same order as they appear in the data file.

Table 5. Variable formats for AREAS.ASC

Variable name	Variable type	Variable width	<u>Column</u>		Variable description
			Start	End	
REGION	Character	28	1	28	Region name
---SECOND LINE, Repeated until all ecosystems are read---					
ECOSYS	Character	28	1	28	Ecosystem name
A1700	Integer	9	29	37	Land in ECOSYS in the year 1700; values are in 10 ⁶ ha
A1850	Integer	9	38	46	Land in ECOSYS in the year 1850; values are in 10 ⁶ ha
A1980	Integer	9	47	55	Land in ECOSYS in the year 1980; values are in 10 ⁶ ha
CHANGE	Real	9	56	64	Percent change in the land area in ECOSYS from 1850 to 1980

Missing data values in this file are indicated with the value -9999.00.

File: NETFLUX.ASC

The name of the second flat ASCII data file is NETFLUX.ASC. The FORTRAN and SASTM programs provided to read this data file are named NETFLUX.FOR and NETFLUX.SAS, respectively. A summary of the FORTRAN statements used to read the data file follows:

```
10    READ (5,100,END=999) YEAR, NAM, SCAM, EURO, NAFM,  
1    TAF, FSU, CHIN, ASIA, PCDV, FLUX  
      GOTO 10  
100   FORMAT(1I4,9F10.2,1F10.3)
```

The variables in NETFLUX.ASC, listed below, are shown in the same order as they appear in the data file.

Table 6. Variable formats for NETFLUX.ASC

Variable name	Variable type	Variable width	<u>Column</u>		Variable description
			Start	End	
YEAR	Integer	4	1	4	Year for which the flux data was calculated
NAM	Real	10	5	14	Carbon flux in YEAR from land cover change in North America; values are in 10 ⁶ Mg C
SCAM	Real	10	15	24	Carbon flux in YEAR from land cover change in South and Central America; values are in 10 ⁶ Mg C
EURO	Real	10	25	34	Carbon flux in YEAR from land cover change in Europe; values are in 10 ⁶ Mg C

Table 6. (continued)

Variable name	Variable type	Variable width	Column		Variable description
			Start	End	
NAFM	Real	10	35	44	Carbon flux in YEAR from land cover change in North Africa–Middle East; values are in 10^6 Mg C
TAF	Real	10	45	54	Carbon flux in YEAR from land cover change in Tropical Africa; values are in 10^6 Mg C
FSU	Real	10	55	64	Carbon flux in YEAR from land cover change in the Former Soviet Union; values are in 10^6 Mg C
CHIN	Real	10	65	74	Carbon flux in YEAR from land cover change in China; values are in 10^6 Mg C
ASIA	Real	10	75	84	Carbon flux in YEAR from land cover change in South and Southeast Asia; values are in 10^6 Mg C
PCDV	Real	10	85	94	Carbon flux in YEAR from land cover change in the Pacific Developed Region; values are in 10^6 Mg C
FLUX	Real	10	95	104	Total carbon flux in YEAR from land cover change in the world; values are in 10^6 Mg C

Missing data values in this file are indicated with the value -9999.00.

Lotus 1-2-3™ WK1 Spreadsheet Files

Twenty Lotus 1-2-3™ WK1 spreadsheet files are provided with this NDP. The first two files (AREAS.WK1 and NETFLUX.WK1) contain the same data contained in the ASCII files AREAS.ASC and NETFLUX.ASC. Seventeen of the remaining 18 spreadsheets contain the data used in the carbon flux model to calculate the annual net flux of carbon to or from the atmosphere for each region. The 18th file (MODEL-EX.WK1) is an implementation of the simplified carbon flux equations given in Part 1 of this documentation for one ecosystem in Tropical Africa.

Rate Files:

The land cover change rate data for each region are contained in nine spreadsheets (ASIA-RAT.WK1, CHIN-RAT.WK1, EURO-RAT.WK1, FSU-RAT.WK1, NAFM-RAT.WK1, NAM-RAT.WK1, PCDV-RAT.WK1, SCAM-RAT.WK1, and TAF-RAT.WK1). Historical land cover data were collected at the global, regional, and country level and used to derive rates of land cover change for natural ecosystems in each region of the world. These regions cover most of the vegetated land on Earth, with only small, undeveloped islands and large unvegetated regions excluded from the database (e.g., Antarctica and Greenland).

Geographic location and data availability determined the name and number of ecosystems contained within a region. Data were collected on, and divided among, the natural ecosystems occurring in each region. Each rate spreadsheet contains data for one region, with individual land cover change rates provided for each ecosystem and clearing method. Each ecosystem may have up to seven types of conversion curves: (1) clearing for cropland, (2) clearing for pasture, (3) industrial logging, (4) nonindustrial logging, (5) shifting cultivation, (6) degradation, and (7) afforestation. In most cases, however, only two or three conversion curves are needed for a given ecosystem within a region. Because the number of ecosystems and number of clearing curves vary by region, the format of the spreadsheets differ slightly. However, each region file contains the same data variables for each ecosystem.

The following table depicts a portion of the Lotus 1-2-3™ land cover change rate file (from PCDV-RAT.WK1) for a portion of the Pacific Developed Region. The variable location and definitions identified in this example are consistent within all nine rate spreadsheets. The file contains data for "rates of land cover change" for the Pacific Developed Region. This portion of the file contains the rates of change for "Clearing for Cropland". The rates of change are shown for four time periods, three ecosystems, and are in 10^6 ha per year. The numeral to the left, and just below the first time period (year range) indicates the method used to extrapolate between the clearing rates.

In this case the "method" value of 1 indicates that a stepwise function was used for the conversion of the natural ecosystems to cropland, while a value of 2 would indicate that a linear equation was developed that viewed the rates as points on a line. For example, this table shows that 0.001×10^6 ha of Tropical Moist Forest were cleared from 1700 to 1869 and in 1870 this rate increased to 0.038×10^6 ha. If the method value had been equal to 2, then 0 ha would have been the initial clearing rate for 1700 and the amount of land cleared would have increased by a constant amount until 0.001×10^6 ha was reached in 1869.

PCDV-RAT.WK1

Pacific Developed Region						
Rates of land cover change						
Clearing for Croplands (1E+06 ha)						
			1700-1869	1870-1949	1950-1969	1970-1980
		1				
Tropical Moist Forest			0.001	0.038	0.220	0.030
Tropical Grassland			0.004	0.152	0.860	0.120
Tropical Woodland Shrubland			0.002	0.064	0.360	0.050

Response Files:

The response to disturbance data are contained in six Lotus 1-2-3™ files (ASIA-RE.WK1, ASIA-SH.WK1, FSU-RE.WK1, SCAM-RE.WK1, TAF-RE.WK1, and TEM-RE.WK1). File TEM-RE.WK1 contains the response curves used for five regions (China, Europe, North Africa—Middle East, North America, and Pacific Developed Region). Each ecosystem within a region has a corresponding response curve that contains information on the initial carbon content (per hectare) of vegetation and soil. These values were first computed as dry matter and then multiplied by 0.45 to obtain the carbon values shown in the response curves. In this study, estimates of the organic carbon were made for the top 1 m of soil. The data contained in these response curves includes information on the minimum carbon content reached after clearing, time (in years) to reach this minimum, carbon in live vegetation (e.g., crops) left on site, time for carbon levels to recover after abandonment, time for recovered area to reach initial carbon levels, and the fraction of cleared vegetation assigned to decay pools (i.e., the carbon in harvested vegetation decays at different rates based on the use to which the vegetation is put).

In the carbon flux model five different decay pools were used, the first contained slash, dead vegetation left on-site at the time of clearing. Biomass in this pool is released to the atmosphere based on an ecosystem and region specific on-site decay rate. The second is the 1-year decay pool. Biomass assigned to this pool is assumed to be burned and is released to the atmosphere in the year following clearing. The third, fourth, and fifth pools are the 10-year, 100-year, and 1000-year decay pools.

North America, China, Europe, Pacific Developed Region, North Africa-Middle East			
Response Curve - Clearing			
Changes in the carbon in vegetation and soils during the clearing of natural ecosystems.			
	Ecosystem -->	1	2
		Tropical	Tropical
		Moist	Seasonal
Carbon in vegetation of undisturbed ecosystem (10^6 g/ha)		200	160
Carbon in vegetation of "recovered" ecosystem (10^6 g/ha)		150	120
Carbon in Crops		5	5
Time for abandoned system to "recover" (yr)		50	50
Time for veg. to recover to primary state from "recovered"		1	1
Carbon in soils of undisturbed ecosystems		117	117
Carbon in soils of "recovered" ecosystems		103	103
Carbon content of soil after initial rapid change following clearing		94	94
Minimum carbon content of soil in cultivated system		88	88
Time initial rapid change		3	3
Time to soil minimum		15	15
Time for soil to "recovered"		15	15
Time for soil to recover to primary state from "recovered"		1	1
Fraction of original veg. assigned to decay pools at time of clearing			
1-yr		0.4	0.4
10-yr		0.27	0.27
100-yr		0	0
1000-yr		0	0
Left to decay on site		0.33	0.33
Rate constant for on-site decay		0.5	0.4

The proceeding table depicts the general format of the Lotus 1-2-3™ data files for a portion of the response curve file (TEM-RE.WK1) for the Pacific Developed Region. The variable location and definitions identified in this example are consistent within all response spreadsheets.

Data values contained in these files are expressed in Mg of carbon per hectare, years, or percentages. For example, in the Pacific Developed Region the initial carbon content of an undisturbed tropical moist forest is 200 Mg C per ha, after clearing it will take 51 years for the forest to recover to its primary state, and 33% of the carbon in the cleared forest was left to decay on-site as slash.

Partition Files:

The logging decay pool partitioning tables are contained in two Lotus 1-2-3™ files (FSULOGPT.WK1 and TEMLOGPT.WK1) and are used in conjunction with the response curve spreadsheets for six of the world's nine regions. File TEMLOGPT.WK1 contains the decay pool partitioning data used for China, Europe, North Africa–Middle East, North America, and Pacific Developed Region, while FSULOGPT.WK1 contains the data for the Former Soviet Union.

These files provide decay pool assignments for the 1-year, 10-year, 100-year, and 1000-year decay rates for industrial and nonindustrial logging. The decay pool distribution varies in these six regions because of the significant technological changes that have occurred over the last 120 years as they made the transition from agricultural to industrial economies.

The decay rate values for each pool are valid for a range of years or are point values that have had linear equations derived to calculate the annual rate for a given pool (similar to stepwise and linear methods used in the rate files). In each file a "method" variable is located under the "Decay Pool" label. A value of 1 indicates that a stepwise function was used for the decay pool rate, while a value of 2 indicates that a linear equation was developed that viewed the rates as points on a line.

Model File:

Simplified versions of the equations used by the original carbon flux bookkeeping model are contained in Part 1 of this document. These equations produce results that are within 10% of those obtained by the original model. To provide the user with an example of how these equations would be implemented, file MODEL-EX.WK1 has been included with this NDP. The file implements the carbon flux equation for the closed forest ecosystem in Tropical Africa.

The carbon flux equation, shown below, calculates the annual carbon flux (CF) with the atmosphere for one ecosystem. The carbon flux for each ecosystem would then be aggregated to obtain an annual carbon flux for a region.

$$CF = \text{Soil}_r + \text{Slash}_r + P1_r + P10_r + P100_r + P1000_r - (\text{Crop}_a + \text{Soil}_a + \text{Veg}_a)$$

where Soil_r is the carbon released from disturbed soil, Slash_r is the carbon released from dead vegetation left on-site after clearing, $P1_r$ through $P1000_r$ contain the amount of carbon released from the 1-, 10-, 100-, and 1000-year decay pools, and Crop_a , Soil_a , and Veg_a are the amount of carbon removed from the atmosphere from the growth of crops and regrowth and recover of soils and vegetation.

The model file distributed with this NDP uses the acronyms in this carbon flux equation (above) to identify each column in the spreadsheet. The model file also includes pertinent data

from the Tropical Africa land cover change rate and vegetation-soil response curve data files for the closed forest ecosystem. The equations in the column under each acronym contain a detailed equation for each function.

The model file has had the "protect" option in Lotus 1-2-3™ enabled to prevent accidental changes to the carbon flux equations. Three user-modifiable ranges are available to allow the user to input data from any of the ecosystem response spreadsheets and to alter the ecosystem change rates. It should be noted that some of the equations have been customized for Tropical Africa (e.g., the reforestation recovery time is built into the Soil_a and Veg_a equations). For regions other than Tropical Africa the protect option may be disabled and the equations modified. (*Users should review all equations in Part 1 of this document before making modifications to the model.*)

What follows is a portion of file MODEL-EX.WK1. The columns for P100_r and P1000_r are not shown here (but are in the file) because material was not assigned to these decay pools by the Tropical Africa response curve.

	Closed		Soil	+	Slash	+ P1	+	P10	- (	Crop +	Soil +	Veg)	=	CF
	Forest		r		r	r		r		a	a	a		
	Land	land	soil	Slash	Slash	forest	forest	forest	Total	Crop	Soil	Veg	Total	flux
Year	cleared	abon-	out	pool	out	1-yr	10-yr	10-yr	output	in	in	in	input	total
		doned				out	pool	out						
1800	0.02088	0.000	-	0.937	0.369	-	0.767	0.077	0.445	0.313	0.000	0.000	0.313	0.132
1801	0.02088	0.000	-	1.505	0.592	1.136	1.457	0.146	1.874	0.313	0.000	0.000	0.313	1.561
1802	0.02088	0.000	-	1.850	0.728	1.136	2.078	0.208	2.072	0.313	0.000	0.000	0.313	1.759
1803	0.02088	0.000	-	2.059	0.810	1.136	2.637	0.264	2.210	0.313	0.000	0.000	0.313	1.897
1804	0.02088	0.000	0.522	2.186	0.860	1.136	3.140	0.314	2.832	0.313	0.000	0.000	0.313	2.519
1805	0.02088	0.000	0.522	2.263	0.890	1.136	3.592	0.359	2.908	0.313	0.000	0.000	0.313	2.594
1806	0.02088	0.000	0.522	2.310	0.909	1.136	4.000	0.400	2.967	0.313	0.000	0.000	0.313	2.654
1807	0.02088	0.000	0.522	2.338	0.920	1.136	4.367	0.437	3.015	0.313	0.000	0.000	0.313	2.701
1808	0.02088	0.000	0.522	2.355	0.927	1.136	4.697	0.470	3.054	0.313	0.000	0.000	0.313	2.741
1809	0.02088	0.000	0.522	2.366	0.931	1.136	4.994	0.499	3.088	0.313	0.000	0.000	0.313	2.775
1810	0.02088	0.000	0.522	2.372	0.933	1.136	5.261	0.526	3.117	0.313	0.000	0.000	0.313	2.804
1811	0.02088	0.000	0.522	2.376	0.935	1.136	5.502	0.550	3.143	0.313	0.000	0.000	0.313	2.830

The carbon flux equation is primarily designed to model and track the transfer of forested lands to land uses with lower carbon contents (e.g., to pasture from tropical forest). During initial human habitation of a region, only undisturbed high carbon content primary forests are available for clearing. Once the minimum amount of land required for subsistence agriculture is obtained, further forests are cleared to obtain wood products. The primary forests harvested for wood products, unlike those cleared for agriculture, may be allowed to revert back to forest and, with time, will recover to their previous high carbon levels.

In modern agroforestry, trees are planted on previously cleared forestland and are allowed to grow for a few decades. These managed forest have a carbon content very close to that of primary forest when they have reached maturity (i.e., recovered) and are ready to be harvested in 20 to 30-years and will have the same carbon content as primary forest in 30 to 100-years.

In the bookkeeping carbon model, forestlands that have *just recovered* in a given year will be cleared before a similar undisturbed primary forest will be cleared. For example, the land cover rate curve for North America shows that 0.905×10^6 ha of temperate evergreen forest were logged in 1969, and the model has determined (based on the North America response curve) that 0.895×10^6 ha of forest has "just recovered" from being logged in 1919, thus the 0.895×10^6 ha of recovered forest will be recleared along with 0.01×10^6 ha of primary forest. This distinction is important because the recovered forest contains 25% less carbon than that of primary forest.

In South and Southeast Asia a differentiation has been made between undisturbed and degraded ecosystems. In this region each forest ecosystem is represented by two pools of land (e.g., degraded moist forest and undisturbed moist forest). Similarly, separate land cover change rates and vegetation-soil response curves are provided. When a given amount of undisturbed forest is degraded (per the land cover change rate file for South and Southeast Asia) it is transferred to the degraded pool. The amount of carbon released is determined by subtracting the amount of "carbon in vegetation of undisturbed ecosystem" for the undisturbed forest from that of the disturbed forest. This carbon is released based on the five decay pool definitions given in the undisturbed forest response curve. (Note that during the conversion from undisturbed to disturbed forest that the "carbon in soils of undisturbed ecosystems" remains unchanged.)

14. LISTING OF THE FORTRAN AND SAS™ DATA RETRIEVAL PROGRAMS

This section lists the two FORTRAN and two SAS™ data retrieval programs provided by CDIAC to read and write the contents of the flat ASCII data files. The two programs shown below (AREAS.FOR and AREAS.SAS) are designed to read and write the contents of AREAS.ASC.

```
C*****
C*   FORTRAN PROGRAM TO READ AND PRINT AREAS.ASC   *
C*****

      INTEGER A1700, A1850, A1980
      REAL    CHANGE
      CHARACTER*28 REGION, ECOSYS

C*****
C*   OPEN FILES FOR INPUT/OUTPUT   *
C*****

      OPEN(UNIT=5,FILE='areas.asc')
      OPEN(UNIT=6,FORM='PRINT')

C*****
C*   READ AND PRINT REGION NAME, ECOSYSTEM NAME, AND   *
C*   DATA FOR FOUR VARIABLES.   *
C*****

      ECOSYS = ' '
10    READ (5,100,END=999) REGION
      WRITE (6,105) REGION
20    READ (5,110) ECOSYS, A1700, A1850, A1980, CHANGE
      IF (ECOSYS .EQ. ' ') GOTO 10
      WRITE(6,115) ECOSYS, A1700, A1850, A1980, CHANGE
      GOTO 20

C
100   FORMAT(1A28)
105   FORMAT('0',1A28)
110   FORMAT(1A28,3I9,1F9.2)
115   FORMAT(1X,1A28,3I9,1F9.2)

C*****
C*   CLOSE FILES AND EXIT GRACEFULLY   *
C*****

999   CLOSE(UNIT=5)
      CLOSE(UNIT=6)
      STOP
      END
```

```

/*
  This program reads and prints the contents
  of file AREAS.ASC
*/
OPTIONS LINESIZE=78 PAGESIZE=60;
DATA IN;
INFILE './areas.asc';
INPUT REG $ 1-28 / ECOSYS $ 1-28 @;
DO WHILE (ECOSYS NE '');
  INPUT A1700 29-37 A1850 38-46 A1980 47-55 CHANGE 56-64;
  OUTPUT;
  INPUT ECOSYS $ 1-28 @;
END;
DELETE;
PROC PRINT NOOBS;
RUN;

```

The third and forth programs (NETFLUX.FOR and NETFLUX.SAS) read and write the contents of NETFLUX.ASC.

```

C*****
C*   FORTRAN PROGRAM TO READ AND PRINT NETFLUX.ASC   *
C*****

      INTEGER YEAR
      REAL    NAM, SCAM, EURO, NAFM, TAF, FSU
      REAL    CHIN, ASIA, PCDV, FLUX

C*****
C*   OPEN FILES FOR INPUT/OUTPUT   *
C*****

      OPEN(UNIT=5,FILE='netflux.asc')
      OPEN(UNIT=6,FORM='PRINT')

C*****
C*   READ AND PRINT YEAR, FLUX FOR EACH REGION, AND   *
C*   THE TOTAL FLUX FOR ALL NINE REGIONS.   *
C*****

      10  READ (5,100,END=999) YEAR, NAM, SCAM, EURO, NAFM,
           1  TAF, FSU, CHIN, ASIA, PCDV, FLUX
           WRITE(6,105) YEAR, NAM, SCAM, EURO, NAFM,
           1  TAF, FSU, CHIN, ASIA, PCDV, FLUX
           GOTO 10

C
      100  FORMAT(1I4,9F10.2,1F10.3)
      105  FORMAT(1X,1I4,9F10.2,1F10.3)

C*****
C*   CLOSE FILES AND EXIT GRACEFULLY   *
C*****

      999  CLOSE(UNIT=5)

```

```

CLOSE (UNIT=6)
STOP
END

```

```

/*
  This program reads and prints the contents
  of file NETFLUX.ASC
*/
OPTIONS LINESIZE=78 PAGESIZE=60;
DATA IN;
INFILE './netflux.asc';
INPUT YEAR 1-4 NAM 5-14 SCAM 15-24 EURO 25-34 NAFM 35-44
      TAF 45-54 FSU 55-64 CHIN 65-74 ASIA 75-84
      PCDV 85-94 FLUX 95-104;
PROC PRINT NOOBS;
RUN;

```

15. PARTIAL LISTING OF THE FLAT ASCII DATA FILES

This section lists the first 15 data lines from the two flat ASCII files provided with this database.

Sample listing from AREAS.ASC

North America				
Temperate Evergreen Forest	236	222	214	-0.04
Temperate Deciduous Forest	157	125	117	-0.06
Boreal Forest	394	394	391	-0.01
Temperate Woodland Shrubland	229	229	219	-0.04
Temperate Grassland	568	479	172	-0.64
South and Central America				
Tropical Evergreen Forest	-9999	226	217	-0.04
Tropical Seasonal Forest	-9999	616	506	-0.18
Tropical Open Forest	-9999	380	252	-0.34
Temperate Evergreen Forest	-9999	49	40	-0.19
Temperate Seasonal Forest	-9999	42	40	-0.04
...				

Sample listing from NETFLUX.ASC

1850	139.20	22.17	57.04	3.95	5.61	36.70	58.28	27.30
1.83	352.081							
1851	140.82	21.87	57.02	3.95	6.47	36.72	58.26	55.73
1.83	382.670							
1852	143.78	21.60	57.00	3.95	6.60	36.75	58.25	67.19
1.84	396.939							
1853	146.66	21.35	56.98	3.95	6.69	36.77	58.24	75.42
1.84	407.887							
1854	149.47	21.13	56.96	3.95	6.77	36.80	58.23	81.48
1.84	416.611							
1855	152.24	20.93	56.93	3.95	6.83	36.82	58.22	86.09
1.84	423.852							
1856	154.99	20.76	56.91	3.95	6.86	36.84	58.20	89.20

1.84	429.551							
1857	157.73	20.60	56.89	3.95	6.88	36.87	58.19	91.60
1.84	434.549							
1858	160.46	20.46	56.87	3.95	6.90	36.89	58.18	93.55
1.84	439.103							
1859	163.19	20.33	56.85	3.95	6.92	36.91	58.17	95.18
1.85	443.348							
1860	164.51	19.89	56.82	3.95	6.93	36.94	58.16	96.59
1.85	445.634							
1861	168.08	20.68	56.91	9.06	8.02	37.01	58.03	97.32
1.93	457.036							
1862	171.81	20.91	57.02	10.02	8.18	37.03	57.88	97.94
2.05	462.832							
1863	175.70	21.02	57.14	10.89	8.31	37.04	57.72	98.47
2.18	468.469							
1864	179.73	21.07	57.28	11.33	8.41	37.06	57.56	98.94
2.33	473.701							

...

16. VERIFICATION OF DATA TRANSPORT: FLAT ASCII DATA FILES

After the data files provided with this NDP are loaded onto a system, or downloaded from CDIAC's anonymous FTP area, the user should check to verified that they have not been corrupted in transport. This can be done by generating some or all of the statistics presented in Tables 7 and 8. These statistics were obtained for AREAS.ASC (file 4) and NETFLUX.ASC (file 8) using the SASTM software package (with the PROC MEANS command). These statistics may be duplicated using other statistical packages or computer languages.

These statistics are included as a tool to ensure proper reading of the two flat ASCII data files and should not be construed as either a summary or an indicator of trends in the data.

Table 7. Statistical characteristics of the numeric variables in AREAS.ASC

Variable	N	Mean	Std. Dev.	Minimum	Maximum
A1700	40	-4405.43	5126.08	-9999.00	723.00
A1850	40	179.75	200.68	14.00	750.00
A1980	40	149.27	184.27	3.00	750.00
CHANGE	40	-0.197	0.269	-0.92	0.26

Table 8. Statistical characteristics of the numeric variables in NETFLUX.ASC

Variable	N	Mean	Std. dev.	Minimum	Maximum
YEAR	141	1920.00	40.84	1850.00	1990.00
NAM	141	-598.40	2608.10	-9999.00	222.23
SCAM	141	196.11	187.10	19.16	595.39
EURO	141	-668.80	2587.12	-9999.00	71.53
NAFM	141	-687.78	2581.78	-9999.00	44.57
TAF	141	67.47	86.07	5.61	341.50
FSU	141	-285.32	1869.96	-9999.00	280.73
CHIN	141	-643.60	2594.14	-9999.00	147.96
ASIA	141	208.92	159.32	27.30	698.79
PCDV	141	-678.33	2584.51	-9999.00	93.87
FLUX	141	-7.94	2784.16	-9999.00	1423.08

17. VERIFICATION OF DATA TRANSPORT: LOTUS 1-2-3™ DATA FILES

After loading the twenty Lotus 1-2-3™ files provided with this data package onto a system, the user should check to ensure that the files have not been corrupted during transport. This can be done by obtaining the size of each file (in bytes) using operating system commands such as "ls -l" or "dir" and comparing the results with those presented in Table 9. If the file size obtained differs from those presented by more than 1 byte, then the file may have been corrupted in transport.

Table 9. File characteristics of the 20 Lotus 1-2-3™ spreadsheet files

File name	File contents	File number	File size
AREAS.WK1	Land areas for each ecosystem and region	5	7,200
NETFLUX.WK1	Carbon fluxes for each region and the world	9	29,700
ASIA-RAT.WK1	Rate files for: South and Southeast Asia	10	10,600
CHIN-RAT.WK1	China	11	5,400
EURO-RAT.WK1	Europe	12	5,500
FSU-RAT.WK1	Former Soviet Union	13	5,700
NAFM-RAT.WK1	North Africa—Middle East	14	4,800
NAM-RAT.WK1	North America	15	10,900
PCDV-RAT.WK1	Pacific Developed Region	16	5,300
SCAM-RAT.WK1	South and Central America	17	10,700
TAF-RAT.WK1	Tropical Africa	18	3,500

Table 9. (continued)

File name	File contents	File number	File size
ASIA-RE.WK1	Response curve files for: South and Southeast Asia	19	5,400
ASIA.SH.WK1	Shifting cultivation in South and Southeast Asia	20	4,500
FSU-RE.WK1	Former Soviet Union	21	6,400
SCAM-RE.WK1	South and Central America	22	13,500
TAF-RE.WK1	Tropical Africa	23	3,900
TEM-RE.WK1	China, Europe, North Africa-- Middle East, North America, and Pacific Developed Region	24	8,800
FSULOGPT.WK1	Decay pool partition files for: Former Soviet Union	25	4,600
TEMLOGPT.WK1	China, Europe, North Africa-- Middle East, North America, and Pacific Developed Region	26	4,900
MODEL-EX.WK1	Implementation of the carbon flux equations shown in this document for the Closed Forest ecosystem in Tropical Africa	27	180,500

APPENDIXES

APPENDIX A

DEFINITION OF ECOSYSTEM NAMES USED IN THIS DATABASE

DEFINITION OF ECOSYSTEM NAMES USED IN THIS DATABASE

Many vegetation classification systems exist. Variations in these systems are based on the needs of the data consumer for whom they were developed. This database was developed to allow carbon fluxes from land use change to be derived; thus, an ecological classification system that could be converted into estimates of carbon content for a given ecosystem was needed. In this study the ecosystem names used within each region (see Part 1, Table 2, which is reprinted on page A-7) were obtained by distributing the world vegetation types of Whittaker and Likens (1973) based on A.W. Küchler's map of natural vegetation (Espenshade 1986).

The definitions listed below were derived from Lanly (1982) and Strahler and Strahler (1984) and are provided to assist the data user in interpreting the ecosystem names used in this database. The ecosystem names combine three different concepts to obtain a descriptive name for each ecosystem. In general, each ecosystem name consists of a locational component, a vegetation descriptive term, and a biome name.

Ecosystems of the globe fall into two major groups, aquatic and terrestrial. In this study the focus is on terrestrial ecosystems. The terrestrial ecosystems have been divided into five biomes based on the availability of soil moisture and heat. Biomes include both the animal and plant life within the life layer; however, green vegetation dominates the biome due to its enormous biomass (Strahler and Strahler 1984). The principal biomes are listed below.

Biomes

<i>Forest</i>	Abundant water and heat. Consists of closely set trees whose crowns form a continuous canopy that provide shade for the ground and lower layers of vegetation.
<i>Woodland (Open Forest)</i>	Transitional biome between forest and grassland. Consists of widely spaced trees whose crowns do not form a continuous canopy. Ground is usually covered with a dense layer of grass, shrubs, or forbs.
<i>Grassland</i>	Moderate water shortage, adequate heat. Consists of tall or short grasses that form a continuous and dense cover. Trees, shrubs, and forbs may occur in widely spaced patches near water sources.
<i>Desert</i>	Extreme water shortage, adequate heat. Consists of sparse vegetation cover and areas of bare ground. Vegetation may consist of thorny trees and shrubs, cactus, hardy grass, and annuals that become dormant in the dry season.

Tundra

Insufficient heat.

Consists of low herbaceous plants and dwarf trees. Sedges, grasses, and lichen are also found.

Soil of this biome is frozen throughout the winter with only the top few feet thawing during the summer.

The ecosystem names used in this database often combine a biome name with a descriptive term for the world latitude zones. These zones identify world geographical belts that receive similar amounts of solar energy.

Latitude Zones

<i>Equatorial</i>	Latitude zone centered on the equator, within the range 10°S and 10°N
<i>Tropical</i>	Latitude zones centered on the tropics of Cancer and Capricorn, within the ranges 10° to 25°N and 10° to 25°S
<i>Subtropical</i>	Latitude zones within the ranges 25° to 35°N and 25° to 35°S
<i>Midlatitude</i>	Latitude zones within the ranges 35° to 55°N and 35° to 55°S
<i>Subarctic (Subantarctic)</i>	Latitude zones within the ranges 55° to 60°N and 55° to 60°S
<i>Arctic (Antarctic)</i>	Latitude zones within the ranges 60° to 75°N and 60° to 75°S
<i>Polar</i>	Latitude zones within the ranges 75° to 90°N and 75° to 90°S

For purposes of this database, two of the latitude zones (polar and arctic/antarctic) and one of the biomes (tundra) have not been used because the extreme cold temperatures experienced in these zones preclude the growth of significant amounts of vegetation. The latitude zones have been combined to form the following latitudinal regions.

Latitudinal Regions

<i>Tropical</i>	Includes the equatorial, tropical, and half of the subtropical zones
<i>Temperate</i>	Includes half of the subtropical zones and the midlatitude zones
<i>Boreal</i>	Includes the subarctic zone

Ecosystem names often contain a term that describes the dominant vegetation cover or the precipitation regime within a ecosystem (e.g., tropical moist forest, temperate deciduous forest). The terms used are as follows.

Precipitation Regimes

<i>Moist</i>	A continuously hot, frost-free climate with abundant precipitation in all months of the year.
<i>Seasonal</i>	A continuously hot, frost-free climate with marked seasonality in the distribution of rainfall. This variation in precipitation is often due to seasonal changes in the monsoon and trade winds.
<i>Warm</i>	A continuously cool, frost-free climate with abundant precipitation. This type occurs on highlands within the seasonal and moist regions.

Dominant Vegetation Covers

<i>Broadleaf</i>	Occurs in moist climates of the subtropical and lower midlatitudes where winters are mild and precipitation is abundant most months of the year. The number of tree species and their size tends to be less than would be found in tropical rainforests with similar amounts of precipitation, leaves tend to be smaller and more leathery and the leaf canopy less dense.
<i>Coniferous</i>	Occurs in all cool locations of the world (e.g., tropical highlands). However, most of these forests occur in the subarctic and midlatitudes, where winters are cold, summers are warm, and water is adequate or abundant in the spring with shortages in the summer. The dominant tree species are straight-trunked, needle-leafed trees (pine) that provide deep shade to the ground. Species are few, with only one or two tree species often dominating hundreds of square miles.
<i>Deciduous</i>	Occurs in the midlatitudes where winters are cold, summers are warm, and precipitation is adequate all months of the year. Consists of tall broadleaf trees that develop a continuous canopy in the summer but shed their leaves in the winter. Lower layers are weakly developed, with a dense layer of herbs developing in the spring.
<i>Evergreen</i>	Occurs in climates where the dominant tree species grow continuously throughout the year.
<i>Scrub</i>	Occurs in hot locations of the world that experience long dry seasons with brief, but intense, rainy periods. Vegetation cover consists of small drought-tolerant trees, shrubs, grasses, and cactus.

Based on the definitions shown in this appendix, the ecosystem names used for each of the nine regions of the world may be compared. In several cases, the reader will note that different names have been used for regions with similar ecosystems (e.g., tropical equatorial forest in South and Central America and tropical moist forest in South and Southeast Asia). This "duplication" is caused by the different terminology found in the original data sources.

Because of data limitations in Tropical Africa, the ecosystem types were combined into a open and a closed forest category; in South and Southeast Asia, distinctions were made between degraded and undisturbed ecosystems. The two Tropical African ecosystem names are super sets of the following ecosystem types.

Special Ecosystems Types in Tropical Africa and South and Southeast Asia

<i>Closed Forest</i>	Includes the tropical equatorial forest, tropical seasonal forest, and warm coniferous forest ecosystems (including bamboo forests)
<i>Open Forest</i>	Includes the tropical woodland ecosystems
<i>Degraded</i>	Land where the gradual removal of carbon over long periods of time (e.g., removal for firewood) has reduced the amount of carbon in the ecosystem
<i>Undisturbed</i>	Land where external forces have not altered the amount of carbon in the ecosystem (all ecosystems are assumed to be in this state unless stated otherwise)

Table 2 from Part 1 of this document is reprinted here to allow the data user to partition the ecosystem names used for each region based on the definitions provided in this appendix.

Natural ecosystems within each of the nine regions

North America

Temperate Evergreen Forest
Temperate Grassland
Boreal Forest

Temperate Deciduous Forest
Temperate Woodland and Shrubland

South and Central America

Tropical Equatorial Forest
Tropical Woodland
Temperate Broadleaf Forest
Desert Scrub

Tropical Seasonal Forest
Warm Coniferous Forest
Grassland

Europe

Temperate Evergreen Forest
Boreal Forest

Temperate Grassland
Temperate Deciduous Forest

North Africa—Middle East

Temperate Evergreen Forest
Tropical Moist Forest
Desert Scrub

Tropical Grassland
Tropical Woodland and Shrubland

Tropical Africa

Closed Forest
(includes Bamboo Forests)

Open Forest

Former Soviet Union

Temperate Deciduous Forest
Temperate Grassland

Boreal Forest

China

Temperate Evergreen Forest
Temperate Deciduous Forest

Temperate Grassland
Tropical Moist Forest

South and Southeast Asia

Degraded:

Tropical Moist Forest
Tropical Seasonal Forest

Tropical Open Forest
Tropical Grassland

Undisturbed:

Tropical Moist Forest
Tropical Seasonal Forest

Tropical Open Forest
Tropical Grassland

(continued)

Pacific Developed Region

Temperate Evergreen Forest
Tropical Moist Forest
Tropical Woodland and Shrubland

Temperate Deciduous Forest
Tropical Grassland
Desert Scrub

References

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- Lanly, J.-P. 1982. *Tropical Forest Resources*. Forestry Paper No. 30, Food and Agriculture Organization of the United Nations, Rome.
- Strahler, A. N. and A. H. Strahler. 1984. *Elements of Physical Geography, 3rd Edition*. John Wiley and Sons, New York.
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APPENDIX B

VEGETATION-SOIL RESPONSE CURVE PRINTOUTS FOR THE NINE REGIONS

VEGETATION-SOIL RESPONSE CURVE PRINTOUTS FOR THE NINE REGIONS

Each region has a set of ecosystem response curves that contain information on the initial carbon content (per hectare) of vegetation and soil in each region and information on how the carbon would be released to the atmosphere from a given type of disturbance (e.g., clearing for cropland). The data contained in these response curves include information on: the minimum carbon content reached after clearing; time (in years) to reach this minimum; carbon in live vegetation (e.g., crops) left on site; time for carbon levels to recover after abandonment; time for recovered area to reach initial carbon levels; and the fraction of cleared vegetation assigned to five decay pools (i.e., the carbon in harvested vegetation decays at different rates based on the use to which the vegetation was put). The first decay pool contains slash and dead vegetation left on site at the time of clearing. Biomass in this pool is released to the atmosphere based on an ecosystem and region specific on-site decay rate. The second is the 1-year decay pool. It is assumed that biomass assigned to this pool is burned and is released to the atmosphere in the year following clearing. The third, fourth, and fifth pools are the 10-, 100-, and 1000-year decay pools. The biomass assigned to these pools are released to the atmosphere using a 0.1, 0.01, or 0.001 decay constant.

Six response curve spreadsheets are included with this database. Data for the nine regions of the world are contained in the following six files: ASIA-RE.WK1 and ASIA-SH.WK1 (South and Southeast Asia), FSU-RE.WK1 (Former Soviet Union), SCAM-RE.WK1 (South and Central America), TAF-RE.WK1 (Tropical Africa), and TEM-RE.WK1 (China, Europe, North Africa-Middle East, North America, and Pacific Developed Region). Because the partitioning of carbon between decay pools changes over time in the industrial and nonindustrial logging response curves for five of the world's nine regions (i.e., China, Europe, North Africa-Middle East, North America, the Former Soviet Union, and Pacific Developed Region), two special files containing decay pool partitioning data were developed. Partitioning data for logging in the Former Soviet Union is contained in file FSULOGPT.WK1, while partitioning data for China, Europe, North Africa-Middle East, North America, and the Pacific Developed Region are in TEMLOGPT.WK1.

The printouts in this appendix are from the six response spreadsheets (ASIA-RE.WK1, ASIA-SH.WK1, FSU-RE.WK1, SCAM-RE.WK1, TAF-RE.WK1, and TEM-RE.WK1) and the two special partitioning spreadsheets (FSULOGPT.WK1 and TEMLOGPT.WK1). The first line of each file contains a list of the regions for which the data are applicable.

TEM-RE.WK1

North America, China, Europe, Pacific Developed Region, North Africa-Middle East											
Response Curve - Clearing											
Changes in the carbon in vegetation and soils during the clearing of natural ecosystems.											
	Ecosystem -->	1	2	3	4	5	6	7	8	9	10
		Tropical	Tropical	Temperate	Temperate	Boreal	Tropical	Temperate	Tropical	Temperate	Desert
		Moist	Seasonal	Evergreen	Deciduous	Forest	Woodland	Woodland	Grassland	Grassland	Scrub
Carbon in vegetation of undisturbed ecosystem (10 ⁶ g/ha)		200	160	160	135	90	27	27	18	7	3
Carbon in vegetation of "recovered" ecosystem (10 ⁶ g/ha)		150	120	120	100	68	27	27	18	7	3
Carbon in Crops		5	5	5	5	5	5	5	5	3	1
Time for abandoned system to "recover" (yr)		50	50	50	50	50	25	50	5	10	10
Time for veg. to recover to primary state from "recovered"		1	1	1	1	1	1	1	1	1	1
Carbon in soils of undisturbed ecosystems		117	117	134	134	206	69	69	42	189	58
Carbon in soils of "recovered" ecosystems		103	103	127	127	185	69	69	42	189	58
Carbon content of soil after initial rapid change following clearing		94	94	107	107	164	55	55	34	151	80
Minimum carbon content of soil in cultivated system		88	88	101	101	155	52	34	32	142	87
Time initial rapid change		3	3	15	15	50	3	3	3	15	5
Time to soil minimum		15	15	30	30	50	15	15	15	30	10
Time for soil to "recovered"		15	15	40	40	35	15	15	15	45	10
Time for soil to recover to primary state from "recovered"		1	1	1	1	1	1	1	1	1	1
Fraction of original veg. assigned to decay pools at time of clearing											

1-yr		0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5
10-yr		0.27	0.27	0.2	0.2	0.2	0.1	0.1	0	0	0
100-yr		0	0	0.07	0.07	0.07	0	0	0	0	0
1000-yr		0	0	0	0	0	0	0	0		
Left to decay on site		0.33	0.33	0.33	0.33	0.33	0.5	0.5	0.5	0.5	0.5
Rate constant for on-site decay		0.5	0.4	0.05	0.05	0.03	0.3	0.4	0.4	0.3	0.3
North America, China, Europe, Pacific Developed Region, North Africa-Middle East											
Response Curve - Logging											
Changes in the carbon in vegetation and soils during the clearing of natural ecosystems for logging.											
	Ecosystem -->	1	2	3	4	5					
		Tropical	Tropical	Temperate	Temperate	Boreal					
		Moist	Seasonal	Evergreen	Deciduous	Forest					
Carbon in vegetation of undisturbed ecosystem (10^6 g/ha)		200	160	160	135	90					
Carbon in vegetation of "recovered" ecosystem (10^6 g/ha)		150	120	120	100	68					
Carbon left in live forest on site		5	5	5	5	5					
Time for abandoned system to "recover" (yr)		50	50	50	50	50					
Time for veg. to recover to primary state from "recovered"		1	1	1	1	1					
Carbon in soils of undisturbed ecosystems		117	117	134	134	206					
Carbon in soils of "recovered" ecosystems		103	103	127	127	185					
Carbon content of soil after initial rapid change following clearing		76	76	108	108	165					

[illegible]

TEMLOGPT.WK1

China, Europe, North Arica and Middle East, North America, Pacific Developed Region								
Partitioning of Logging Products - see TEM-RE.WK1 for response curve data								
All Forest Types for the regions below								
Region		Decay Pool	1700	1875	1900	1925	1950	1980
		2						
China		1-yr	0.9	0.9	0.9	0.86	0.8	0.75
		10-yr	0.04	0.04	0.04	0.06	0.08	0.1
		100-yr	0.06	0.06	0.06	0.08	0.12	0.15
		1000-yr	0	0	0	0	0	0
		2						
Europe		1-yr	0.5	0.5	0.5	0.48	0.42	0.18
		10-yr	0.2	0.2	0.2	0.21	0.23	0.33
		100-yr	0.3	0.3	0.3	0.31	0.35	0.49
		1000-yr	0	0	0	0	0	0
		2						
North Africa and		1-yr	0.9	0.9	0.9	0.87	0.75	0.63
Middle East		10-yr	0.04	0.04	0.04	0.05	0.1	0.15
		100-yr	0.06	0.06	0.06	0.08	0.15	0.22
		1000-yr	0	0	0	0	0	0
		2						
North America		1-yr	0.5	0.44	0.4	0.3	0.2	0.04
		10-yr	0.2	0.22	0.24	0.28	0.32	0.38
		100-yr	0.3	0.34	0.36	0.42	0.48	0.58
		1000-yr	0	0	0	0	0	0
		2						
Pacific Developed		1-yr	0.81	0.81	0.81	0.81	0.42	0.27
Region		10-yr	0.08	0.08	0.08	0.08	0.23	0.29
		100-yr	0.11	0.11	0.11	0.11	0.35	0.44
		1000-yr	0	0	0	0	0	0

SCAM-RE.WK1

South and Central America								
Response Curve - Clearing								
The fate of carbon in vegetation and soils following the clearing of natural ecosystems for cropland.								
	Ecosystem -->	1	2	3	4	5	6	7
		Tropical	Tropical	Tropical	Warm	Temperate	Grassland	Desert
		Equatorial	Seasonal	Woodland	Coniferous	Broadleaved		Scrub
Carbon in vegetation of undisturbed ecosystem (10^6 g/ha)		200	140	55	168	100	10	6
Carbon in vegetation of "recovered" ecosystem (10^6 g/ha)		200	140	55	168	100	10	6
Carbon in Crops		5	5	5	5	5	5	5
Time for abandoned system to "recover" (yr)		40	35	18	42	25	2	1
Time for veg. to recover to primary state from "recovered"		1	1	1	1	1	1	1
Carbon in soils of undisturbed ecosystems		98	98	69	134	134	42	58
Carbon in soils of "recovered" ecosystems		98	98	69	134	134	42	58
Carbon content of soil after initial rapid change following clearing		78	78	55	107	107	34	46
Minimum carbon content of soil in cultivated system		74	74	52	100	100	32	44
Time initial rapid change		5	5	5	5	5	5	5
Time to soil minimum		20	20	20	20	20	20	20
Time for soil to "recovered"		40	35	18	42	40	2	1
Time for soil to recover to primary state from "recovered"		1	1	1	1	1	1	1
Fraction of original veg. assigned to decay pools at time of clearing								
1-yr		0.3	0.3	0.3	0.3	0.3	0.48	0.48

10-yr		0.35	0.35	0.3	0.35	0.35	0	0
100-yr		0	0	0	0	0	0	0
1000-yr		0.02	0.02	0.02	0.02	0.02	0.02	0.02
Left to decay on site		0.33	0.33	0.38	0.33	0.33	0.5	0.5
Rate constant for on-site decay		0.5	0.4	0.3	0.3	0.5	0.4	0.3
South and Central America								
Response Curve - Pasture Clearing								
The fate of carbon in vegetation and soils following the clearing of natural ecosystems for pasture.								
	Ecosystem -->	1	2	3	4	5	6	7
		Tropical	Tropical	Tropical	Warm	Temperate	Grassland	Desert
		Equatorial	Seasonal	Woodland	Coniferous	Broadleaved		Scrub
Carbon in vegetation of undisturbed ecosystem (10^6 g/ha)		200	140	55	168	100	10	6
Carbon in vegetation of "recovered" ecosystem (10^6 g/ha)		200	140	55	168	100	10	6
Carbon in Crops		10	10	28	10	10	10	6
Time for abandoned system to "recover" (yr)		40	35	18	42	25	2	1
Time for veg. to recover to primary state from "recovered"		1	1	1	1	1	1	1
Carbon in soils of undisturbed ecosystems		98	98	69	134	134	42	58
Carbon in soils of "recovered" ecosystems		98	98	69	134	134	42	58
Carbon content of soil after initial rapid change following clearing		87	87	69	118	118	42	58
Minimum carbon content of soil in cultivated system		87	87	69	118	118	42	58
Time initial rapid change		20	20	20	20	20	20	20

Time to soil minimum		20	20	20	20	20	20	20
Time for soil to "recovered"		40	35	18	42	40	2	1
Time for soil to recover to primary state from "recovered"		1	1	1	1	1	1	1
Fraction of original veg. assigned to decay pools at time of clearing								
1-yr		0.3	0.3	0.3	0.3	0.3	0.48	0.48
10-yr		0.35	0.35	0.3	0.35	0.35	0	0
100-yr		0	0	0	0	0	0	0
1000-yr		0.02	0.02	0.02	0.02	0.02	0.02	0.02
Left to decay on site		0.33	0.33	0.38	0.33	0.33	0.5	0.5
Rate constant for on-site decay		0.5	0.4	0.3	0.3	0.5	0.4	0.3
South and Central America								
Response Curve - Shifting cultivation								
The fate of carbon in vegetation and soils following the clearing of natural ecosystems for shifting cultivation.								
	Ecosystem -->	1	2					
		Closed	Open					
		Forests	Forests					
Carbon in vegetation of undisturbed ecosystem (10^6 g/ha)		140	55					
Carbon in vegetation of "recovered" ecosystem (10^6 g/ha)		65	20					
Carbon in Crops		15	5					
Time for abandoned system to "recover" (yr)		17	6					
Time for veg. to recover to primary state from "recovered"		18	12					

Carbon in soils of undisturbed ecosystems		98	69					
Carbon in soils of "recovered" ecosystems		91	64					
Carbon content of soil after initial rapid change following clearing		83	59					
Minimum carbon content of soil in cultivated system		83	59					
Time initial rapid change		2	2					
Time to soil minimum		2	2					
Time for soil to "recovered"		17	6					
Time for soil to recover to primary state from "recovered"		1	1					
Fraction of original veg. assigned to decay pools at time of clearing								
1-yr		0.3	0.3					
10-yr		0.35	0.35					
100-yr		0	0					
1000-yr		0.02	0.02					
Left to decay on site		0.33	0.33					
Rate constant for on-site decay		0.4	0.3					
South and Central America								
Response Curve - Logging								
The fate of carbon in vegetation following the harvest of forests. The amount of carbon in soils was assumed to be constant								
	Ecosystem -->	1	2					
		Tropical	Warm					
		Seasonal	Coniferous					

TAF-RE.WK1

Tropical Africa			
Response Curve - Clearing			
Changes in the carbon in vegetation and soils during the clearing of natural ecosystems.			
	Ecosystem -->	1	2
		Closed	Open
		Forest	Forest
Carbon in vegetation of undisturbed ecosystem (10^6 g/ha)		136	30
Carbon in vegetation of "recovered" ecosystem (10^6 g/ha)		136	30
Carbon in Crops		15	15
Time for abandoned system to "recover" (yr)		29	29
Time for veg. to recover to primary state from "recovered"		1	1
Carbon in soils of undisturbed ecosystems		100	50
Carbon in soils of "recovered" ecosystems		100	50
Carbon content of soil after initial rapid change following clearing		80	40
Minimum carbon content of soil in cultivated system		75	37
Time initial rapid change		1	1
Time to soil minimum		5	5
Time for soil to "recovered"		29	29
Time for soil to recover to primary state from "recovered"		1	1
Fraction of original veg. assigned to decay pools at time of clearing			
1-yr		0.4	0.4
10-yr		0.27	0.27
100-yr		0	0
1000-yr		0	0
Left to decay on site		0.33	0.33
Rate constant for on-site decay		0.5	0.3
Rates: TAF-RAT.WK1			

Former Soviet Union					
Response Curve - Clearing					
Changes in the carbon in vegetation and soils during the clearing of natural ecosystems.					
	Ecosystem	1	2	3	
		Temperate	Temperate	Boreal	
		Grassland	Deciduous	Forest	
Carbon in vegetation of undisturbed ecosystem (10^6 g/ha)		10	135	90	
Carbon in vegetation of "recovered" ecosystem (10^6 g/ha)		10	108	72	
Carbon in Crops		5	5	5	
Time for abandoned system to "recover" (yr)		10	40	80	
Time for veg. to recover to primary state from "recovered"		1	1	1	
Carbon in soils of undisturbed ecosystems		189	134	206	
Carbon in soils of "recovered" ecosystems		189	134	206	
Carbon content of soil after initial rapid change following clearing		161	114	175	
Minimum carbon content of soil in cultivated system		151	107	165	
Time initial rapid change		15	10	15	
Time to soil minimum		30	30	65	
Time for soil to "recovered"		45	40	80	
Time for soil to recover to primary state from "recovered"		1	1	1	
Fraction of original veg. assigned to decay pools at time of clearing					
1-yr		0.4	0.48	0.48	
10-yr		0.1	0.24	0.24	
100-yr		0	0.08	0.08	
1000-yr		0	0	0	
Left to decay on site		0.5	0.2	0.2	
Rate constant for on-site decay		0.5	0.04	0.05	
Former Soviet Union					
Response Curve - Logging					
The amount of carbon in soils was assumed to be unaffected by harvest. Units are t/ha or years.					

	Ecosystem	1	2	3	4
		Nonindustrial Harvest		Industrial Logging	
		Temperate	Boreal	Temperate	Boreal
		Deciduous	Forest	Deciduous	Forest
Carbon in vegetation of undisturbed ecosystem (10 ⁶ g/ha)		135	90	135	90
Carbon in vegetation of "recovered" ecosystem (10 ⁶ g/ha)		108	72	108	72
Carbon left in uncleared forest on site		97	46	0	0
Time for abandoned system to "recover" (yr)		14	29	40	80
Time for veg. to recover to primary state from "recovered"		1	1	1	1
Carbon in soils of undisturbed ecosystems		134	206	134	206
Carbon in soils of "recovered" ecosystems		134	206	134	206
Carbon content of soil after initial rapid change following clearing		124	72	108	72
Minimum carbon content of soil in cultivated system		124	72	108	72
Time initial rapid change		4	5	10	15
Time to soil minimum		4	5	10	15
Time for soil to "recovered"		10	24	30	65
Time for soil to recover to primary state from "recovered"		1	1	1	1
Fraction of original veg. assigned to decay pools at time of clearing					
1-yr					
10-yr					
100-yr					
1000-yr					
Left to decay on site		0.059	0.1	0.704	0.444
Rate constant for on-site decay		0.04	0.05	0.04	0.05
Decay rates vary by year, see FSULOGPT.WK1					
Rate: FSU-RAT.WK1					

FSULOGPT.WK1

Former Soviet Union							
Partitioning of Logging Products - see FSU-RE.WK1 for response curve data							
Temperate Deciduous Forest							
		Decay Pool	1700	1945	1960	1975	1980
		2					
Industrial Logging		1-yr	0.21407	0.40296	0.18259	0.11333	0.09444
		10-yr	0.00000	0.00000	0.00000	0.00000	0.00000
		100-yr	0.41556	0.22667	0.44704	0.51630	0.53519
		1000-yr	0	0	0	0	0
			1700-1944	1945-1959	1960-1974	1975-1979	1980-1985
		1					
Non-industrial Logging		1-yr	0.71132	0.73342	0.59211	0.65211	0.64737
		10-yr	0.00000	0.00000	0.00000	0.00000	0.00000
		100-yr	0.07816	0.05605	0.19737	0.13737	0.14211
		1000-yr	0	0	0	0	0
Boreal Forest							
		Decay Pool	1700	1945	1960	1975	1980
		2					
Industrial Logging		1-yr	0.23611	0.44444	0.20139	0.12500	0.10417
		10-yr	0.00000	0.00000	0.00000	0.00000	0.00000
		100-yr	0.45833	0.25000	0.49306	0.56944	0.59028
		1000-yr	0	0	0	0	0
			1700-1944	1945-1959	1960-1974	1975-1979	1980-1985
		1					
Non-industrial Logging		1-yr	0.71670	0.73898	0.59659	0.65705	0.65227
		10-yr	0.00000	0.00000	0.00000	0.00000	0.00000
		100-yr	0.07875	0.05648	0.19886	0.13841	0.14318
		1000-yr	0	0	0	0	0

ASIA-RE.WK1

South and Southeast Asia								
Response Curve - Clearing								
Changes in the carbon in vegetation and soils during the clearing of natural ecosystems.								
	Ecosystem -->	1	2	3	4	5	6	7
		Moist	Seasonal	Woodland	Moist	Seasonal	Woodland	Grassland
		Degraded	Degraded	Degraded	Undisturbed	Undisturbed	Undisturbed	(in pasture)
Carbon in vegetation of undisturbed ecosystem (10^6 g/ha)		135	150	40	250	150	60	60
Carbon in vegetation of "recovered" ecosystem (10^6 g/ha)		135	150	40	250	150	60	60
Carbon in Crops		5	5	5	5	5	5	60
Time for abandoned system to "recover" (yr)		37	29	12	37	29	12	12
Time for veg. to recover to primary state from "recovered"		1	1	1	1	1	1	1
Carbon in soils of undisturbed ecosystems		120	80	50	120	80	50	50
Carbon in soils of "recovered" ecosystems		120	80	50	120	80	50	50
Carbon content of soil after initial rapid change following clearing		96	64	40	96	64	40	50
Minimum carbon content of soil in cultivated system		84	56	37	84	56	37	50
Time initial rapid change		1	5	5	1	5	5	5
Time to soil minimum		6	7	5	5	5	5	5
Time for soil to "recovered"		35	29	12	35	29	12	12
Time for soil to recover to primary state from "recovered"		1	1	1	1	1	1	1
Fraction of original veg. assigned to decay pools at time of clearing								
1-yr		0.4	0.4	0.4	0	0	0	0.4

10-yr			0.27	0.27	0.27	0.0375	0.0375	0.0375	0.27
100-yr		0	0	0	0	0.3375	0.3375	0.3375	0
1000-yr		0	0	0	0	0	0	0	0
Left to decay on site		0.33	0.33	0.33	0.33	0.625	0.625	0.625	0.33
Rate constant for on-site decay		0.5	0.4	0.3	0.5	0.4	0.3	0.3	0.3
Rate: ASIA-RAT.WKI									

ASIA-SH.WK1

South and Southeast Asia					
Response Curve - Shifting Cultivation					
Changes in the carbon in vegetation and soils during the clearing of natural ecosystems.					
	Ecosystem →	1	2	3	4
		Moist	Woodland	Moist	Woodland
		Degraded	Degraded	Undisturbed	Undisturbed
Carbon in vegetation of undisturbed ecosystem (10^6 g/ha)		135	40	250	60
Carbon in vegetation of "recovered" ecosystem (10^6 g/ha)		90	35	90	35
Carbon in Crops		15	5	15	5
Time for abandoned system to "recover" (yr)		15	10	15	10
Time for veg. to recover to primary state from "recovered"		22	2	22	2
Carbon in soils of undisturbed ecosystems		120	50	120	50
Carbon in soils of "recovered" ecosystems		108	45	108	45
Carbon content of soil after initial rapid change following clearing		90	38	90	38
Minimum carbon content of soil in cultivated system		90	38	90	38
Time initial rapid change		2	2	2	2
Time to soil minimum		2	2	2	2
Time for soil to "recovered"		15	10	15	10
Time for soil to recover to primary state from "recovered"		22	2	22	2
Fraction of original veg. assigned to decay pools at time of clearing					
1-yr		0.380	0.41	0.380	0.41
10-yr		0.070	0.100	0.070	0.100
100-yr		0.000	0.000	0.000	0.000
1000-yr		0.020	0.020	0.020	0.020
Left to decay on site		0.530	0.470	0.530	0.470
Rate constant for on-site decay		0.5	0.3	0.5	0.3
Clearing Responses: AISA-RE.WK1					
Rates: ASIA-RAT.WK1					

APPENDIX C

**PRINTOUT OF THE CALCULATED CARBON FLUX FOR
ALL NINE REGIONS AND THE WORLD**

PRINTOUT OF THE CALCULATED CARBON FLUX FOR ALL NINE REGIONS AND THE WORLD

The following printout is from the NETFLUX.WK1 spreadsheet included in this data package. All regional values are in 10⁶ Mg of Carbon and were obtained by summing the individual ecosystem flux values in each region. Values of -9999.00 indicate years without data.

Net flux of carbon from regional changes in land-use.										
V1.0										
Year	North America	South and Central America	Europe	North Africa and Middle East	Tropical Africa	Former Soviet Union	China	South and Southeast Asia	Pacific Developed Region	TOTAL FLUX 10 ⁶ Mg C
1850	139.20	22.17	57.04	3.95	5.61	36.70	58.28	27.30	1.83	352.081
1851	140.82	21.87	57.02	3.95	6.47	36.72	58.26	55.73	1.83	382.670
1852	143.78	21.60	56.99	3.95	6.60	36.75	58.25	67.19	1.84	396.939
1853	146.66	21.35	56.98	3.95	6.69	36.77	58.24	75.42	1.84	407.887
1854	149.47	21.13	56.95	3.95	6.76	36.80	58.23	81.48	1.84	416.611
1855	152.24	20.93	56.93	3.95	6.83	36.82	58.22	86.09	1.84	423.852
1856	154.99	20.75	56.91	3.95	6.86	36.84	58.20	89.20	1.84	429.551
1857	157.73	20.60	56.89	3.95	6.88	36.87	58.19	91.60	1.84	434.549
1858	160.46	20.46	56.87	3.95	6.90	36.89	58.18	93.55	1.84	439.103
1859	163.19	20.33	56.85	3.95	6.92	36.91	58.17	95.18	1.85	443.348
1860	164.51	19.89	56.82	3.95	6.93	36.94	58.16	96.59	1.85	445.634
1861	168.08	20.68	56.91	9.06	8.02	37.01	58.03	97.32	1.93	457.036
1862	171.81	20.91	57.02	10.02	8.18	37.02	57.88	97.94	2.05	462.832
1863	175.70	21.02	57.14	10.89	8.31	37.04	57.72	98.47	2.18	468.469
1864	179.73	21.07	57.28	11.33	8.41	37.05	57.56	98.94	2.33	473.701
1865	184.25	21.11	57.43	11.72	8.48	37.06	57.38	99.36	2.49	479.288
1866	185.90	20.70	57.60	12.08	8.53	37.07	57.19	99.74	2.65	481.464
1867	187.69	20.30	57.79	12.41	8.56	37.07	57.00	100.10	2.81	483.731
1868	189.62	19.92	57.98	12.71	8.59	37.08	56.81	100.42	2.95	486.083
1869	191.67	19.55	58.19	13.00	8.62	37.09	56.61	100.72	3.10	488.542
1870	194.47	19.53	58.64	13.42	8.64	37.14	56.29	101.01	3.22	492.364
1871	197.33	19.47	52.64	13.66	8.66	37.15	55.98	106.05	10.34	501.271
1872	200.24	19.32	51.86	13.89	8.68	37.15	55.68	107.61	12.52	506.941
1873	203.21	19.25	51.12	14.11	8.69	37.15	55.39	108.73	14.34	511.979

Net flux of carbon from regional changes in land-use.										
V1.0										
Year	North	South and	Europe	North	Tropical	Former	China	South and	Pacific	TOTAL
	America	Central		Africa and	Africa	Soviet		Southeast	Developed	FLUX
		America		Middle East		Union		Asia	Region	10 ⁶ Mg C
1874	206.23	19.20	50.41	14.32	8.70	37.15	52.20	109.57	15.07	512.851
1875	210.43	19.16	49.67	14.52	8.71	37.16	51.50	110.25	15.67	517.076
1876	213.02	19.27	49.09	14.69	9.79	37.16	50.96	110.80	16.16	520.944
1877	215.27	19.70	48.56	14.85	9.96	37.16	50.49	111.20	16.57	523.776
1878	217.19	20.12	48.08	15.02	10.08	37.17	50.06	111.55	16.94	526.203
1879	218.80	20.51	47.63	15.16	10.18	37.17	49.67	111.86	17.27	528.245
1880	220.08	20.89	46.08	15.30	10.26	37.18	49.30	112.14	17.57	528.796
1881	221.06	51.16	45.81	15.45	10.30	37.18	48.96	112.40	17.88	560.193
1882	221.74	59.58	45.57	15.59	10.33	37.18	48.63	112.64	18.19	569.455
1883	222.13	66.36	45.36	15.73	10.36	37.19	47.84	112.87	18.50	576.341
1884	222.23	71.98	45.18	15.88	10.39	37.19	47.61	113.09	18.81	582.341
1885	220.94	76.74	44.81	16.09	10.41	37.19	47.50	113.30	19.33	586.297
1886	219.48	79.52	45.34	16.29	11.71	37.20	47.39	113.50	19.84	590.257
1887	217.86	81.50	45.87	16.49	11.91	37.20	47.29	113.70	20.34	592.149
1888	216.08	83.14	46.41	16.68	12.06	37.20	47.20	113.88	20.82	593.471
1889	214.15	84.51	46.94	16.87	12.18	37.20	47.17	114.07	21.25	594.329
1890	210.02	85.67	47.58	17.05	12.28	37.21	47.14	114.24	21.66	592.845
1891	215.77	69.39	48.20	17.23	12.34	37.21	47.12	127.23	22.06	596.552
1892	214.40	66.11	48.82	17.40	12.38	37.21	47.11	131.30	22.45	597.187
1893	213.00	63.60	49.42	17.57	12.42	37.22	47.09	134.26	22.83	597.402
1894	211.56	61.66	50.01	17.73	12.45	37.22	47.09	136.50	23.20	597.414
1895	209.89	60.15	50.58	17.89	12.47	37.22	47.08	138.26	23.56	597.112
1896	208.13	59.13	51.13	18.05	12.50	37.22	47.08	139.53	23.92	596.682
1897	206.38	58.35	51.67	18.20	12.52	37.22	47.08	140.46	24.26	596.133
1898	204.65	57.75	52.20	18.35	12.53	37.23	47.09	141.23	24.59	595.616
1899	202.95	57.29	52.71	18.50	12.55	37.23	47.09	141.91	24.91	595.131
1900	202.70	56.93	53.20	18.64	12.56	37.23	47.10	142.51	25.23	596.114
1901	201.24	115.25	53.78	21.18	15.57	37.18	47.23	142.92	25.64	659.978
1902	199.88	131.95	54.37	21.71	16.02	37.18	47.38	143.28	26.06	677.836

Net flux of carbon from regional changes in land-use.										
V1.0										
Year	North	South and	Europe	North	Tropical	Former	China	South and	Pacific	TOTAL
	America	Central		Africa and	Africa	Soviet		Southeast	Developed	FLUX
		America		Middle East		Union		Asia	Region	10 ⁶ Mg C
1903	198.61	145.53	54.97	22.20	16.35	37.18	47.55	143.61	26.50	692.503
1904	197.44	156.87	55.59	22.47	16.61	37.19	47.73	143.92	26.93	704.765
1905	196.59	166.63	56.22	22.99	16.82	37.20	47.93	144.21	27.37	715.969
1906	194.06	171.07	56.86	23.19	16.93	37.21	48.13	150.88	27.81	726.155
1907	191.64	174.68	57.51	23.37	17.02	37.22	48.34	152.95	28.23	730.962
1908	189.31	177.66	58.16	23.53	17.10	37.23	48.55	154.46	28.65	734.645
1909	187.08	180.17	58.82	23.67	17.16	37.25	48.75	155.61	29.06	737.566
1910	185.17	181.91	59.71	23.73	17.21	37.20	49.00	156.53	29.50	739.970
1911	183.23	122.99	60.57	23.80	21.53	37.22	49.27	157.25	29.90	685.751
1912	181.36	106.06	61.40	23.85	22.20	37.23	49.53	157.76	30.29	669.683
1913	179.58	92.17	62.23	23.90	22.69	42.35	49.79	142.67	30.66	646.033
1914	177.87	80.40	63.03	23.95	23.08	45.81	56.62	137.70	31.01	639.476
1915	176.68	70.11	63.62	23.99	23.40	49.23	57.80	134.07	31.36	630.251
1916	175.52	66.27	64.57	23.99	23.57	52.62	58.87	137.15	31.69	634.244
1917	174.39	63.18	65.48	23.98	23.71	56.18	59.78	136.44	32.02	635.169
1918	173.32	60.65	66.37	23.97	23.82	59.91	60.51	136.00	32.33	636.891
1919	172.28	58.53	67.22	23.95	23.92	63.50	61.32	135.54	32.64	638.916
1920	171.14	56.67	67.99	23.93	24.00	66.96	62.12	135.09	32.94	640.854
1921	170.05	99.08	68.75	23.91	28.35	70.29	62.89	134.72	33.23	691.270
1922	169.03	110.98	69.47	23.88	29.04	73.50	63.63	134.23	33.51	707.266
1923	168.06	120.58	70.18	23.85	29.56	76.63	65.42	134.15	33.78	722.216
1924	167.16	128.62	70.86	23.82	29.97	79.62	66.00	134.10	34.04	734.177
1925	166.05	135.59	71.53	23.79	30.30	82.48	66.54	134.06	34.29	744.619
1926	164.32	137.53	71.32	32.38	30.49	85.20	66.89	129.87	34.56	752.548
1927	162.53	138.97	70.96	34.29	30.64	87.77	67.19	128.30	34.84	755.481
1928	160.68	140.04	70.45	36.00	30.77	89.75	67.47	127.21	35.11	757.474
1929	137.20	140.81	69.79	36.42	30.88	91.65	67.59	126.43	35.39	736.163
1930	129.26	141.78	68.99	36.74	30.97	93.48	67.67	125.87	35.66	730.433
1931	121.49	152.91	68.06	37.36	35.33	95.23	67.75	125.51	35.93	739.575

Net flux of carbon from regional changes in land-use.										
V1.0										
Year	North America	South and Central America	Europe	North Africa and Middle East	Tropical Africa	Former Soviet Union	China	South and Southeast Asia	Pacific Developed Region	TOTAL FLUX 10 ⁶ Mg C
1932	113.88	155.91	67.00	37.91	36.02	96.88	67.81	125.27	36.20	736.884
1933	106.41	158.25	65.82	38.42	36.55	97.49	67.86	125.08	36.46	732.342
1934	99.04	160.09	64.52	38.90	36.96	98.04	70.90	124.95	36.71	730.111
1935	91.87	161.54	61.97	39.41	37.30	98.51	71.57	124.84	36.98	723.987
1936	84.11	163.15	59.41	39.89	37.49	98.76	72.14	137.29	37.24	729.494
1937	76.45	164.94	56.87	40.35	37.65	98.75	72.57	141.54	37.50	726.601
1938	65.72	166.51	54.33	40.79	37.78	98.83	72.94	144.70	37.75	719.331
1939	58.52	167.94	51.79	41.21	37.89	98.98	73.29	147.12	37.99	714.727
1940	50.63	169.25	48.92	41.62	37.98	97.99	73.61	149.04	38.23	707.274
1941	42.85	167.89	46.09	41.99	53.04	83.97	73.92	153.55	38.46	701.755
1942	35.19	167.36	43.31	42.35	55.30	80.05	74.21	158.74	38.68	695.183
1943	27.20	166.98	40.57	42.70	56.99	76.45	73.82	164.01	38.89	687.620
1944	23.30	166.75	37.87	42.98	58.30	73.16	74.16	169.27	39.11	684.887
1945	19.49	166.53	35.22	43.38	59.36	69.94	74.48	174.46	39.31	682.182
1946	15.83	169.39	32.62	43.63	59.92	67.58	74.80	232.58	39.51	735.857
1947	12.40	172.32	30.06	43.88	60.38	63.76	75.11	253.15	39.70	750.752
1948	9.03	175.43	27.55	44.11	60.75	59.84	75.41	268.85	39.88	760.869
1949	5.77	178.69	25.09	44.34	61.06	55.71	75.43	280.65	40.06	766.805
1950	2.60	183.83	22.67	44.56	61.33	52.64	75.45	290.65	40.23	773.956
1951	-5.85	240.91	20.52	35.39	82.95	161.93	76.48	299.98	73.53	985.842
1952	-10.11	259.34	18.57	33.62	86.28	180.74	77.56	308.54	82.66	1037.192
1953	-14.01	274.26	16.81	31.82	88.76	198.21	78.66	280.82	90.05	1045.376
1954	-17.61	286.51	15.24	29.60	90.71	214.67	79.78	276.87	91.89	1067.658
1955	-20.90	296.82	13.85	27.39	92.29	230.79	100.19	275.15	92.97	1108.555
1956	-23.91	302.82	12.63	26.71	93.16	247.98	105.27	270.03	93.57	1128.269
1957	-26.64	307.73	11.58	26.06	93.86	264.63	109.81	264.88	93.84	1145.748
1958	-29.12	311.79	10.69	25.43	94.44	280.73	113.84	253.96	93.87	1155.625
1959	-31.34	316.97	9.96	24.84	94.92	207.28	117.28	249.89	93.73	1083.519
1960	-32.55	321.13	10.49	23.64	95.34	204.21	121.64	246.76	93.12	1083.794

Net flux of carbon from regional changes in land-use.										
V1.0										
Year	North	South and	Europe	North	Tropical	Former	China	South and	Pacific	TOTAL
	America	Central		Africa and	Africa	Soviet		Southeast	Developed	FLUX
		America		Middle East		Union		Asia	Region	10 ⁶ Mg C
1961	-33.60	430.49	7.93	23.33	129.92	193.47	125.74	247.13	92.44	1216.852
1962	-34.50	463.32	7.93	23.04	135.24	190.52	129.59	248.60	91.74	1255.481
1963	-35.26	489.04	7.99	22.74	139.22	187.22	133.24	258.05	91.00	1293.252
1964	-35.89	512.19	8.10	22.46	142.32	183.89	136.68	262.16	90.26	1322.175
1965	-34.85	531.35	8.46	22.18	144.85	180.61	139.92	265.61	89.50	1347.631
1966	-32.83	540.90	8.86	23.50	146.24	168.23	141.06	269.79	88.75	1354.512
1967	-30.78	548.79	9.27	23.90	147.36	155.91	143.15	274.14	87.99	1359.719
1968	-28.73	555.61	9.70	24.24	148.28	143.45	145.17	283.51	87.26	1368.497
1969	-26.66	566.03	10.14	24.20	149.06	132.73	147.20	288.42	86.28	1377.413
1970	-25.08	574.31	8.21	24.45	149.73	99.03	147.96	292.79	85.32	1356.713
1971	-22.97	521.78	6.25	24.66	184.53	84.46	117.74	284.51	48.69	1249.639
1972	-20.55	510.77	4.10	24.86	190.04	70.32	114.30	283.49	37.18	1214.501
1973	-18.83	502.08	1.76	25.06	194.18	56.70	110.93	333.02	27.44	1232.349
1974	-15.29	495.02	-0.75	25.26	197.43	51.82	107.81	348.63	23.46	1233.406
1975	-11.48	489.16	-3.60	25.46	200.09	49.16	104.65	360.00	20.21	1233.635
1976	-8.01	488.75	-6.10	25.62	201.60	48.92	101.46	453.97	17.50	1323.714
1977	-4.71	488.91	-8.77	25.76	202.82	45.65	98.20	487.02	15.13	1350.012
1978	-1.56	489.16	-11.58	25.88	203.84	42.16	94.97	510.98	12.99	1366.848
1979	1.43	497.14	-14.54	25.99	233.70	38.00	91.48	528.90	11.02	1413.130
1980	5.67	501.83	-19.54	26.01	238.69	34.24	84.11	543.26	8.80	1423.075
1981	-9999.00	509.63	-9999.00	-9999.00	256.24	33.40	-9999.00	620.81	-9999.00	-9999.00
1982	-9999.00	512.33	-9999.00	-9999.00	261.24	31.38	-9999.00	645.29	-9999.00	-9999.00
1983	-9999.00	512.81	-9999.00	-9999.00	265.19	29.96	-9999.00	661.89	-9999.00	-9999.00
1984	-9999.00	548.55	-9999.00	-9999.00	267.79	28.34	-9999.00	673.93	-9999.00	-9999.00
1985	-9999.00	559.95	-9999.00	-9999.00	269.92	26.07	-9999.00	683.09	-9999.00	-9999.00
1986	-9999.00	564.18	-9999.00	-9999.00	318.45	-9999	-9999.00	691.36	-9999.00	-9999.00
1987	-9999.00	590.23	-9999.00	-9999.00	326.57	-9999	-9999.00	687.85	-9999.00	-9999.00
1988	-9999.00	595.39	-9999.00	-9999.00	332.71	-9999	-9999.00	691.13	-9999.00	-9999.00
1989	-9999.00	578.81	-9999.00	-9999.00	337.54	-9999	-9999.00	694.87	-9999.00	-9999.00

Net flux of carbon from regional changes in land-use.										
V1.0										
Year	North	South and	Europe	North	Tropical	Former	China	South and	Pacific	TOTAL
	America	Central		Africa and	Africa	Soviet		Southeast	Developed	FLUX
		America		Middle East		Union		Asia	Region	10 ⁶ Mg C
1990	-9999.00	573.41	-9999.00	-9999.00	341.50	-9999	-9999.00	698.79	-9999.00	-9999.00

APPENDIX D

REPRINT OF PERTINENT LITERATURE

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Note: The carbon fluxes and land cover change values shown in this article have been revised. The revised data are contained within the digital data distributed with this document.

CHANGES IN THE CARBON CONTENT OF TERRESTRIAL BIOTA AND SOILS BETWEEN 1860 AND 1980: A NET RELEASE OF CO₂ TO THE ATMOSPHERE¹

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Abstract. Changes in land use over the past two centuries have caused a significant release of CO₂ to the atmosphere from the terrestrial biota and soils. An analysis of this release is based on amounts of organic carbon within an ecosystem following changes such as harvest of forests; it is also based on rates of changes, such as conversion of forest to agriculture, deduced from agricultural and forestry statistics. A model is used to calculate the net amount of carbon stored or released each year by the biota and soils of 69 regional ecosystems. Some of the changes, such as afforestation, the growth of harvested forests, and buildup of soil organic matter, result in a storage of carbon; others, such as harvest of forests and increase in pasture and agricultural areas, result in a loss of carbon to the atmosphere.

According to this analysis, there has been a net release of carbon from terrestrial ecosystems worldwide since at least 1860. Until ~1960, the annual release was greater than release of carbon from fossil fuels. The total net release of carbon from terrestrial ecosystems since 1860 is estimated to have been 180×10^{15} g (a range of estimates is $135\text{--}228 \times 10^{15}$ g). The estimated net release of carbon in 1980 was $1.8\text{--}4.7 \times 10^{15}$ g; for the 22 yr since 1958 the release of C was $38\text{--}76 \times 10^{15}$ g. The ranges reflect the differences among various estimates of forest biomass, soil carbon, and agricultural clearing. Improvements in the data on the clearing of tropical forests alone would reduce the range of estimates for 1980 by almost 60%.

Estimates of the other major terms in the global carbon budget, the atmospheric increase in CO₂, the fossil fuel release of CO₂, and the oceanic uptake of CO₂, are all subject to uncertainties. The combined errors in these estimates are large enough that the global carbon budget appears balanced if the low estimate for the biotic release of carbon given above is used (1.8×10^{15} g released in 1980) with the higher estimates of oceanic uptake. If higher estimates for biotic release are used, then the carbon budget does not balance, and the estimates of oceanic uptake or of other factors require revision.

Key words: agricultural expansion; atmospheric CO₂; carbon; carbon cycle; CO₂; deforestation; global carbon budget; land use; soil carbon loss; terrestrial biota.

INTRODUCTION

The concentration of atmospheric CO₂ has increased by 15–25% over the past 100 yr. The evidence for this rise comes primarily from the continuous record started in 1958 at Mauna Loa, Hawaii (Pales and Keeling 1965, Keeling et al. 1976b), and from a parallel record at the South Pole (Keeling et al. 1976a). Evidence for changes before 1958 comes from direct measurements of oceanic water masses of known age (Brewer 1978, Chen and Millero 1979) and from models (Keeling 1973a, Oeschger et al. 1975). The trend of the atmospheric record suggests that the rate of increase of the CO₂ content of air is accelerating, and concen-

trations will reach ~500 μL/L by 2030 (Keeling and Bacastow 1977). This concentration is approximately double the level of 1900 A.D. A doubling in atmospheric CO₂ is expected to cause a global warming of 2°–4°C, with climatic warming greater at the poles than at the equator (Manabe and Stouffer 1979, Manabe and Wetherald 1980). The resultant problems of such climate modification for humans will include a shift in the area and the distribution of arable lands and a rise in sea level of as much as 5 m over 100–200 yr (MacDonald 1978, Woodwell et al. 1979, Council on Environmental Quality 1981).

There is no doubt about the size of the changes in atmospheric CO₂ since 1958, but there is some argument about the causes of the changes. Not only is additional CO₂ released to the atmosphere from the

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burning of fossil fuels, but CO_2 is also released by the clearing of forests. Much of the CO_2 is taken up by the oceans, and some is also stored in plants. The annual changes in these components of the carbon cycle are given by:

$$A = F - S \pm L, \quad (1)$$

where A = the annual increase in atmospheric CO_2 , now $1.0\text{--}1.5 \mu\text{L/L}$ or $2\text{--}3 \times 10^{15} \text{ g of C}$; F = the annual release of carbon as CO_2 from combustion of fossil fuels, currently $5\text{--}6 \times 10^{15} \text{ g of C}$; S = the average annual net movement of carbon as CO_2 into the oceans, estimated as $1.8\text{--}2.4 \times 10^{15} \text{ g of C}$ (37–40% of F); and L = the net exchange of C between the atmosphere and the land surface, estimated as between -2 and $+20 \times 10^{15} \text{ g/yr}$, due to changes in the amount of carbon held in the biota and soils.

The terms are not known with equal precision. The increase in the atmosphere (A) and the release from fossil fuels (F) are thought to be known within $<15\%$; the net transfer to the oceans (S) is less certain, as is the role of the biota (L). Our objective is to refine the estimates of the biotic change.

Certain analyses of the causes of the increase in atmospheric CO_2 (Bacastow and Keeling 1973, Keeling 1973a, Machta 1973, Oeschger et al. 1975) assumed that the only net source of CO_2 was from the combustion of fossil fuels. The amount of CO_2 not absorbed by the oceans or observed in the atmosphere was assumed to accumulate on land. The rate of storage of carbon by the terrestrial biota was assumed to increase as the concentration of CO_2 increased. These assumptions may not have been warranted, as calculations indicate the biota is currently releasing additional carbon to the atmosphere rather than storing carbon (Bolin 1977, Woodwell and Houghton 1977, Woodwell et al. 1978). Furthermore, the amount of carbon released through conversion of forested land to agriculture and through the increased harvest of forests is believed to be larger than any increase in storage of carbon stimulated by higher levels of CO_2 (Bolin 1977, Woodwell and Houghton 1977, Woodwell et al. 1978).

Recent analyses of the global carbon cycle based on oceanic models have not included a net flux of carbon from the biota (Siegenthaler and Oeschger 1978, Broecker et al. 1979). As in the earlier oceanic models, the role of the biota has been determined by difference: $L = F - S - A$. There is no model that calculates directly the net carbon flux between the atmosphere and terrestrial ecosystems, although several attempts have been made to calculate the exchange over various time intervals (Bolin 1977, Revelle and Munk 1977, Woodwell and Houghton 1977, Woodwell et al. 1978, Hampicke 1979, Seiler and Crutzen 1980). In this paper we describe a model that does calculate directly that part of the net terrestrial flux (L) due to changes in the use of land worldwide. The types of

land-use change considered are harvest of forests, clearing of natural ecosystems for agriculture, and afforestation. We believe that these are responsible for the most important changes in the amount of carbon held on land.

In the next sections, we describe the model and identify the sources of information and the data used. We then present the results of several tests of alternative assumptions and data and discuss the implications of these and other results of the modelling for the global carbon cycle and for future research.

A MODEL OF EXCHANGES OF TERRESTRIAL CARBON WITH THE ATMOSPHERE

The reduction in the mass of vegetation that accompanies most disturbances of terrestrial ecosystems is obvious. Harvest of wood from a forest and replacement of trees with crops are examples of reduction in standing stocks. Less obvious but well documented is the reduction in soil carbon that also follows many kinds of disturbances. These generally rapid losses of carbon are followed by slower accumulations of carbon, as trees regrow and soils build up again after harvest or after abandonment of agriculture.

The most important part of this model is a curve that describes changes in carbon stocks that follow disturbance. In one form of the curve, harvest of a forest (Fig. 1) reduces forest biomass; some of the carbon is transferred to domestic or commercial use where it decays at various rates, some is transferred to soil as slash and dead roots, and some remains as

FIG. 1. Idealized curves describing the changes per unit land area in the carbon content of vegetation and soil, following harvest of a forest. The second arrows indicate where the forest has regrown sufficiently to be harvested again. The dashed line shows one of several responses.

living material. Soil organic matter declines for several years after harvest until regrowth of vegetation results in a net accumulation of soil carbon. Response curves for afforestation are similar in form to the curves describing regrowth of forests following harvest. In another form of the curve, clearing of land for agriculture (Fig. 2) reduces carbon in both vegetation and soils, with no subsequent change unless the fields are abandoned.

An analysis of the net flux of carbon between terrestrial systems and the atmosphere must account for the changes over time that follow disturbance: changes in vegetation, soil, and products removed from the forest. Each of these components regrows or decays at various rates. The rates of buildup and decay, as well as the rates of disturbance, vary with geographic regions and with vegetation types. Time lags associated with growth and decay make an annual flux calculated in the model very different and more realistic than a flux calculated on the basis of one year's clearing and harvest. The large number of different quantities that must be accounted for each year requires a computer model.

The model we have developed is a bookkeeping, not a process, model (Moore et al. 1981). It keeps track of the yearly changes of carbon in terrestrial ecosystems (including both biota and soils). Theoretically, the model can contain 10 geographic regions (Appendix 1) with up to 14 types of ecosystems (Table 1), including agroecosystems, within each region. In the analyses reported here, the model contained 69 ecosystems based upon a regional breakdown of Whittaker and Likens' (1973) world classification scheme.

For each ecosystem included, the model describes the response of vegetation and soils to different kinds of disturbances. The direction and magnitude of the responses are different for each ecosystem, although

FIG. 2. Idealized curves describing the changes per unit land area in the carbon content of vegetation and soil following clearing of forest for agriculture. The dashed line shows the changes that occur if agricultural land is abandoned.

the form of each response curve is the same. Specific response curves were developed for both vegetation and soil for each ecosystem and for the following six kinds of disturbance: harvest of a forest followed by regrowth, clearing of natural ecosystems for cultivation, clearing of natural systems for pasture, abandonment of cultivated land, abandonment of pasture, and afforestation. By use of these curves the model keeps track of the area, age, and carbon content of each disturbed ecosystem. It also computes the oxidation of fuelwood and wood products removed from forest

TABLE 1. Areas (in 10^6 ha) of ecosystems in each region of the world in 1700.

	North America	Europe	USSR	Pacific devel- oped	China	Latin America	North Africa and Middle East	Tropical Africa	South Asia	South- east Asia
Tropical moist forest	0	0	0	166	14	500	19	426	12	215
Tropical seasonal forest	0	0	0	0	0	175	0	481	134	38
Temperate evergreen forest	236	85	108	32	40	26	19	0	0	0
Temperate deciduous forest	157	65	148	49	81	112	0	0	0	0
Boreal forest	394	35	750	0	0	0	0	0	0	0
Tropical woodland and shrubland	0	0	0	20	0	285	0	451	189	0
Temperate woodland and shrubland	229	45	132	0	0	347	0	0	0	0
Tropical grassland	0	0	0	497	0	74	90	459	182	123
Temperate grassland	568	88	175	0	723	497	0	0	0	0
Tundra and alpine meadow	343	27	336	0	0	0	0	0	0	0
Desert scrub	0	0	504	118	145	0	979	406	0	0
Swamp and marsh	0	0	0	0	0	0	0	0	0	0
Cultivated land	3	67	33	5	29	7	20	44	53	4
Pasture land	4	75	53	24	83	37	54	187	7	2
Total	1934	487	2239	911	1115	2060	1181	2454	577	382

ecosystems. The computed net flux of carbon between the atmosphere and the land for any year depends on the balance of the factors affecting the loss and accumulation of carbon on land. Our approach is thus to account for changes in net carbon storage through time rather than to model processes such as photosynthesis and respiration.

The annual flux of carbon between terrestrial ecosystems and the atmosphere was calculated by the model from 1700 AD to the present. Because of the time lags inherent in the response of terrestrial ecosystems to disturbance and hence in the calculations of the model, we allowed the computations to proceed for 160 yr before considering the results. The results reported here are the annual net flux in 1980, the total net flux for the period of the atmospheric CO₂ record from Mauna Loa (1958–1980), and the total net flux for the 120-yr period for which estimates of fossil fuel use exist, 1860–1980.

THE DATA FOR THE MODEL: A SUMMARY INCLUDING DOCUMENTATION AND ASSUMPTIONS

In the following pages we describe the assumptions and data used in the model. These, along with alternative sets of data and assumptions, are used in the next two sections (Use of the Model and Testing Data and Assumptions) to construct 16 tests of the sensitivity of the model.

Parameters that define the response curves

In the response curves (Figs. 1 and 2), we use the data of Whittaker and Likens (1973) for the mass of carbon in undisturbed ecosystems (Tables 2 and 3).

Secondary forests, those that develop following harvest or abandonment of agriculture, reach 75% of their undisturbed biomass in the model. In those locations where nonforest vegetation is transformed to agriculture, the biomass recovers to the original nonforest mass after abandonment. In the model, all forests can be harvested after 50 yr of regrowth. Where abandonment of agricultural land leads to a vegetation other than forest, we have used periods of 50 yr or less (Table 3).

When forests are harvested and allowed to regrow, some vegetation is left on the site at harvest. This dead vegetation, including stumps, roots, branches, leaves, and other debris, is assigned to the pool of carbon in soil. The mass of carbon in the dead plant material left on site is calculated from harvest data summarized by Weck and Wiebecke (1961) for different forest types (Table 2).

When natural systems are transformed to agriculture, a similar assignment of vegetation is needed. When forests are transformed to agriculture, 33% of the carbon is transferred to the soil, while in the transformation of nonforest systems, 50% is transferred.

We use Schlesinger's data (1977, 1983) for the carbon in the upper 1 m of soil in undisturbed systems (Tables 2 and 3).

Between 25 and 50% of the litter and humus may be lost from a forest after harvest or other severe disturbance. The net loss of humus, termed the "assart effect" in the boreal forest (Tamm and Pettersson 1969), has also been observed in the temperate forests of the northeastern United States (Morey 1942, Sartz and Huttinger 1950, Trimble and Lull 1956, Covington 1977) and in tropical forests (Popenoe 1957, Cunningham 1963, Nye and Greenland 1964, Zinke et al. 1978, Aweto 1981). Decomposition of the soil organic matter is enhanced by increased temperature and moisture content of the soil surface (Lutz and Chandler 1946, Moller 1947, Hart 1961, Ovington 1968, Witkamp 1971, Marks and Bormann 1972). Furthermore, the addition of carbon to soil, in the form of litter and small roots, is reduced during the first years following harvest. In the model, the carbon in soil to a depth of 1 m decomposes following harvest to 65% of the original soil carbon content in tropical forests, to 50% in temperate, and to 85% in boreal forests. The loss is smaller after harvest of secondary forests (Table 2). The time to reach the minimum soil carbon value was estimated from the references given above.

The cultivation of formerly forested land also enhances decomposition because more of the soil is exposed to oxidation. In the model, clearing and cultivation result in an initial rapid loss of the organic carbon followed by a slower loss as a result of continued tillage over time (Fig. 2, Table 3) (Salter et al. 1941, Pühr and Worzella 1952, Giddens 1957, Haas et al. 1957, Nye and Greenland 1960). In regions of desert scrub that are irrigated, there is actually an increase, rather than a decrease, in the organic carbon content of soils (Schlesinger 1982). This increase is included in the model (Table 3).

We assume that the recovery of soil carbon of abandoned permanent agriculture and of harvested forests in the tropics is similar to the pattern of recovery of soil carbon during the fallow cycle of shifting cultivation (Zinke et al. 1978, Aweto 1981). In the model, the carbon content of soils took 50 yr to return to 75% of the original level in the tropics (Reed 1951) and to 90% of the original level in the temperate and boreal regions (Covington 1977). For nonforest systems the soil carbon returned to 100% of its original level during the period of recovery.

We have been unable to document any changes in carbon storage that occur when natural lands are transformed to pasture. We assume that new pastureland comes from grasslands and that the carbon does not change. In Latin America, where forests have been cleared recently for cattle grazing, we assume that tropical forest soils lose ≈25% of their carbon when converted to pasture (Krebs 1975, Buringh 1983, J. M. Street, *personal communication*).

TABLE 2. Data used in the Terrestrial Carbon Model to define the changes in the carbon in vegetation and soils during harvest and regrowth of a forest.

	Tropical moist forest	Tropical seasonal forest	Temperate evergreen forest	Temperate deciduous forest	Boreal forest
Carbon in vegetation of undisturbed forests (10^6 g/ha)*	200	160	160	135	90
Carbon in vegetation of secondary forests (10^6 g/ha)	150	120	120	100	68
Carbon in live vegetation left on site at time of harvest (10^6 g/ha)	0	0	0	0	0
Time required for forest to regrow before harvested again (yr)	50	50	50	50	50
Carbon in soils of undisturbed forests (10^6 g/ha)†	117	117	134	134	206
Carbon in soils of secondary forests (10^6 g/ha)	88	88	120	120	185
Carbon in wood harvested (10^6 g/ha)	43	23	30	30	12
Carbon in dead plant material left in soil at time of harvest (10^6 g/ha)	157‡	137	130	105	78
	107§	97	90	70	56
Minimum carbon content in soil following harvest (10^6 g/ha)	76	76	67	67	175
Time required for soil carbon to reach minimum following harvest (yr)	5	5	10	10	15
Time required for soil carbon to go from minimum to level of secondary forest (yr)	15	15	40	40	35

* Whittaker and Likens (1973).

† Schlesinger (1977).

‡ Undisturbed forests.

§ Secondary forests.

Statistics on land use and rates of harvest

We obtained data on rates of change in land use and rates of harvest from economic, agricultural, statistical, and historical sources; we concentrated on the global scale when possible and at the regional or national scale when global summaries did not exist.

The values we used for the analysis are given in Appendix 2, and the sources of information we consulted are presented below.

Harvest of wood.—Rates of wood removal prior to 1946 for Europe, European Russia, and North America were based primarily on reviews by Hough (1878, 1880, 1882), the International Institute of Agriculture (IIA) (1922), Zon and Sparhawk (1923), Ilvessalo and Jalava (1930), Reynolds and Pierson (1942), the Food and Agricultural Organization of the United Nations (FAO 1946), Tsepiyaev (1965), Mitchell (1975), and Clawson (1979). For the developing countries prior to 1946, we calculated wood harvest on the basis of per capita rates of fuelwood use given by Openshaw (1974), Arnold and Jongma (1978), and Fleuret and Fleuret (1978). Fuelwood accounts for nearly 80% of total roundwood production in these countries and for >50% of the world's total wood harvest (Openshaw 1978).

Since 1946 the FAO has conducted four *World Forest Inventories* (FAO 1948, 1955, 1960, 1966) and published annual statistics (FAO 1946–1979) on production reported as volumes of coniferous and nonconiferous wood. The harvested coniferous wood is assigned to temperate evergreen or boreal forests, and nonconiferous wood to temperate deciduous, tropical moist, or tropical seasonal forests. When several for-

est types are present, the assignment is made on the basis of area. In the model there is no harvest of fuelwood from woodlands and shrublands; thus, all wood is harvested from one of the five major forest types.

Volume of wood is converted to mass of carbon using densities of coniferous and nonconiferous woods (*Yearbook of Forest Products* [FAO 1946–1979]): carbon content is 45% of dry mass. The final conversion factors are: 1 m³ coniferous wood = 280 kg C; 1 m³ nonconiferous wood = 340 kg C.

Decay of wood removed from a forest.—Harvested wood products are oxidized over time and must be included in our estimates of carbon flux to the atmosphere. All fuelwood is oxidized within 1 yr of harvest, while industrial wood decays over 10 or 100 yr. The fraction of wood assigned to each category was obtained from the World Bank (1978): paper and paper products (10 yr) represented ≈40% of the industrial wood, while lumber and longer-lasting products (100 yr) were ≈60% of the total (Appendix 2).

Based on studies of decomposition, we have assigned to various rates of decay fractions of the biomass cleared from ecosystems after conversion to agriculture (Table 3). Forest biomass decays within 10 yr in tropical forests (John 1973) and within 100 yr in temperate zone forests (Swift et al. 1979). Biomass of nonforest systems decays within 10 yr.

Areas cleared for crops.—We calculated rates of clearing for agriculture from changes in the area of cropland given by Grigg (1974), Robertson (1956), the International Institute of Agriculture (1922, 1939), *Production Yearbooks* (FAO 1949–1978), and the

TABLE 3. Data used in the Terrestrial Carbon Model to define the changes in the carbon in vegetation and soils during the transformation of a natural ecosystem to agriculture, during cultivation, and following abandonment. Blank spaces indicate that in the model the ecosystems were not cleared for agriculture.

	Tropical moist forest	Tropical seasonal forest	Temperate evergreen forest	Temperate deciduous forest	Boreal forest	Tropical woodland shrubland	Tem- perate woodland shrubland	Tropical grass- land	Temperate grass- land	Tundra alpine meadow	Desert scrub	Swamp marsh
Carbon in vegetation of undisturbed ecosystems (10^9 g/ha)*	200	160	160	135	90	27	27	18	7	3	1	
Carbon in vegetation of "recovered" ecosystems (10^9 g/ha)	150	120	120	100	68	27	27	18	7		1	
Carbon in crops (10^9 g/ha)	5	5	5	5	5	5	5	5	3		1	
Time required for an abandoned system to "recover" (yr)	50	50	50	50	50	25	50	5	10		10	
Carbon in soils of undisturbed ecosystems (10^9 g/ha)*	117	117	134	134	206	69	69	42	189	204	58	
Carbon in soils of "recovered" systems (10^9 g/ha)	88	88	120	120	185	69	69	42	189		58	
Fraction of carbon in vegetation left dead in soil at time of clearing	0.33	0.33	0.33	0.33	0.33	0.50	0.50	0.50	0.50		0.50	
Fraction of carbon in vegetation assigned to decay pools after clearing												
1 yr	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.50	0.50		0.50	
10 yr	0.27	0.27	0.20	0.20	0.20	0.10	0.10	0.0	0.0		0.0	
100 yr	0.0	0.0	0.07	0.07	0.07	0.0	0.0	0.0	0.0		0.0	
Carbon content of soil after initial, rapid change following clearing (10^9 g/ha)	70	70	80	80	160	41	41	25	113		80	
Minimum carbon content of soil in cultivated system (10^9 g/ha)	58	58	67	67	103	34	34	21	94		87	
Time required for initial, rapid change in soil carbon following clearing (yr)	3	3	15	15	50	3	15	3	15		5	
Time required for carbon in soil to reach minimum value during cultivation (yr)	15	15	30	30	50	15	30	15	30		10	
Time required for soil carbon to reach "recovered" level in an abandoned system (yr)	15	15	40	40	35	15	45	15	45		10	

* Whittaker and Likens (1973).

† Schlesinger (1977).

Canadian and United States Census Bureaus. These sources cover the period from ≈ 1800 for all geographical regions except North Africa–Middle East, Latin America, and Tropical Africa. For these three regions we have estimated areas of cropland before 1950 on the basis of population (McEvedy and Jones 1978). Rates of clearing within each region were assigned to ecosystems, using as references Grigg (1974), Robertson (1956), Whittlesey (1964), and Küchler (1964).

Despite the importance of agriculture, we found that the agricultural data were surprisingly sparse. The First World Agriculture Census was not conducted until 1930 (by the International Institute of Agriculture [1939]); it covered 37 of 200 countries. The remaining 163 countries, representing $>50\%$ of the world's land area and almost 75% of its population, had never taken an agricultural census. After 1946, the FAO collected and issued statistics on the area of land in various

uses. Data reported in the *Production Yearbooks* of the FAO (1949–1978) still suffer from inappropriate application of definitions, as the agricultural data on returned questionnaires often refer only to crops that reach national or international markets (Ajtay et al. 1979).

Assignment based on comparisons of areas of natural vegetation with mapped world agricultural regions introduces uncertainty, particularly in assignment of dates to the conversions.

Afforestation.—Changes in total afforested area over time were obtained from Zon and Sparhawk (1923), and the FAO's *European Timber Trends and Prospects 1950 to 2000* (1976). Because species of pines are most commonly planted, all afforested land has been classified as temperate evergreen forest. In those regions where afforestation has been important (Europe, USSR, and China), the ecosystem selected for afforestation was temperate zone grasslands.

Areas cleared for grazing.—We have used the FAO *Production Yearbooks* to estimate rates of land clearing for pasture since 1960. There is no reliable source for rates before 1960, so for our first estimate we used the per capita use of grazing land. Such estimates are questionable because populations of nomadic herds-men have declined during the last century (Grigg 1974). Therefore, in the model, pastures are usually derived from grasslands, and the transformation leads to no change in carbon storage. The only exception occurs in Latin America, where there is good evidence that forests at the edge of the Amazon forest have been cleared in recent years for grazing.

Starting the model: areas of different ecosystems in 1700

The total areas of different ecosystems in 1700 (Table 1) were approximated by distributing the world vegetation types of Whittaker and Likens (1973) among regions on the basis of Kuchler's map (1964) of natural vegetation. These areas of natural ecosystems were then reduced by the areas of agriculture in 1700, estimated on the basis of population (McEvedy and Jones 1978).

It is important to note that calculations of carbon flux with the model do not include forests or other ecosystems that are undisturbed. We assume that these systems are in a steady state and that there is no net change in their carbon content. Therefore, the total area of natural ecosystems is not important for this analysis. Errors in area of various ecosystems only affect the analysis when rates of clearing require more land than is available or when land is cleared from ecosystems on the basis of their relative areas.

This assumption of steady state means that our analysis is incomplete to the extent that undisturbed systems are not in steady state. For example, the soils of previously glaciated areas may still be accumulating carbon (Billings et al. 1982). Also the primary production of terrestrial systems may have increased more than respiration, as a result of the higher concentrations of CO_2 in the atmosphere. We believe these changes in carbon stocks to be small relative to the changes analyzed here.

USE OF THE MODEL

Estimating the values for early years

The model is a useful tool in revealing certain inconsistencies in the values chosen. In early model runs, it was found necessary to adjust rates of clearing, the types of vegetation cleared, or the original distribution of vegetation types in 1700 in order to make the data internally consistent. Similarly, the harvest of forests required the internal consistency of areas of forests assigned in 1700, wood harvest through time, rates of wood harvest per hectare, and rates of forest regrowth. The interaction of different types of data in

FIG. 3. Worldwide area in agriculture (---) and rate of clearing (—). The data for the period after 1945 were derived from the *Production Yearbooks* (FAO 1949–1978).

these ways imposed constraints on input data. Thus, some of the data that were clearly wrong have been taken out of our calculations, but inherent uncertainties still remain in the original data.

Assessing the values for recent years

Data on areas of vegetation and rates of clearing and harvest in the 18th and early 19th centuries were difficult to obtain. The difficulty with data since 1950 is not their availability but the multiplicity of sources and the variability. We present below three independent estimates of recent agricultural expansion in the tropics and include each of them in a separate analysis. In general, the data used in each analysis were the same until 1950 (Appendices 2, 3, and 4).

1. *The low estimate (FAO Production Yearbooks).*—We used the *Production Yearbooks* of the Agricultural Division of the FAO to obtain rates of agricultural expansion for each region of the world (Appendix 3). The data on expansion, summarized for the world in Fig. 3 (solid line), show an irregular rise in the rate of expansion until about 1950, followed by a sharp drop that appears to be continuing through the present. The results (Fig. 4) show a net release of carbon that parallels the rate of change in agricultural area. Over the 120-yr period since 1860, the net release of carbon from the terrestrial biota and soils was 184×10^{15} g (Table 4). The peak release of carbon was in 1955 (3.22×10^{15} g); in 1980 the net release was 1.82×10^{15} g.

2. *The high estimate (Myers).*—An independent estimate of rates of clearing of tropical forests has been offered by Myers (1980a, b). However, it is difficult to determine whether the clearing Myers described has

FIG. 4. Analysis based on the *Production Yearbooks* of the FAO (1949–1978). The curves show the net flux to the atmosphere as a result of the clearing and cultivation of agricultural land, harvest and regrowth of forests, oxidation of wood removed from forests, and the clearing of land for pasture.

FIG. 5. Analysis based on the data of Myers (1980a, b). The curves show the net flux of carbon to the atmosphere as a result of the clearing and cultivation of agricultural land, harvest and regrowth of forests, oxidation of wood harvested or cleared from forests, and the clearing of land for pasture.

been permanent and whether it includes the clearing of secondary forests as well as primary forests. Myers (1980b) states that much of the clearing of tropical forests, even by traditional shifting cultivators, is now permanent due to increased population density. As a result of discussions with Myers, we estimate that one-third of the cleared forests grows back to secondary forests in 50 yr. That was also the fraction recently estimated by Lanly and Gillis (1980) to regrow for Latin America.

Most of the data used for this estimate (Appendix 4) were the same as those used in the previous analysis (Appendix 3) except for the period 1965–1980 in the tropics (Latin America, North Africa–Middle East, Tropical Africa, South Asia, and Southeast Asia).

Over the 120-yr period between 1860 and 1980, the total release of carbon based on the use of the Myers data was similar to the results using the FAO data. The total was 185×10^{15} g. Between 1970 and 1980, however, the results were appreciably different (Fig. 5, Table 4). More carbon was released in the Myers estimate than in the FAO estimate from each of the major processes, and the total net flux of carbon in 1980 was 4.70×10^{15} g.

We are not able to judge the accuracy of either Myers' estimates of deforestation or the FAO tables of arable land and permanent cropland. Several authors have to some degree confirmed the FAO results, by noting the reduced rate at which new lands are being transformed to agriculture (Brown 1981, Barr

1982). On the other hand, the FAO statistics may not include clearing of tropical forests by the landless because such changes are not officially recognized by many governments. These changes are included in Myers' estimates. We believe that these two sets of data offer contrasting high and low estimates of land clearing.

3. *An estimate based on population.*—A third set of data was developed by assuming that the rate of agricultural expansion since 1950 has been proportional to the rate of growth of populations in the tropical regions. Reports of the United States Department of Agriculture (1965, 1970) have shown that increased food production in developing nations has been achieved, in part, by increased crop yields and, in part, by claiming new land for agriculture. The fraction of the increased food production due to expansion of agricultural area averaged $\approx 60\%$ for these regions. This fraction was used to adjust the rates of agricultural clearing calculated on the basis of per capita use of cropland (Appendix 2). The population-based rates were computed only after 1946 (1860 for South Asia) and only for the five tropical regions; for other regions and times, the data were the same as used in the first analysis.

According to the population-based analysis, there has been a continuous net release of carbon from the terrestrial biota and soils in response to disturbance since 1860 and, probably, much longer (Fig. 6). Between 1860 and 1980 the net release of carbon to the

atmosphere was 180×10^{15} g; in 1980 it was 2.6×10^{15} g (Table 4).

The carbon flux estimated in this analysis falls between those from the FAO and Myers-based analyses, and it is not clear which estimate is most accurate. We describe the results of the population-based analysis here to illustrate details of model results and to provide a framework for further tests of assumptions and data (see Testing Data and Assumption).

The harvest of forests releases nearly the same amount of carbon per unit area as the clearing of land for agriculture, and during the 120-yr period before 1980, about twice as much land was harvested as was transformed to agriculture. However, harvested forests regain carbon as they regrow; the vegetation and soil of regrowing forests accumulated 182×10^{15} g from the atmosphere since 1860 and 2.4×10^{15} g in 1980. Agricultural lands generally are not abandoned and, as previously discussed, usually continue to lose rather than accumulate carbon. Thus, the net flux of carbon to the atmosphere as a result of transforming natural systems to agricultural land was greater than the net flux from harvest and regrowth of forests (101×10^{15} vs. 34×10^{15} g since 1860; Fig. 6). In 1980 the net flux of carbon from agricultural expansion was nearly twice that from harvest and regrowth (1.58×10^{15} vs. 0.90×10^{15} g; Table 5).

Soils accounted for about one-third of the net flux of carbon in 1980 (Table 5), and since 1860 their contribution has been $\sim 72 \times 10^{15}$ g. Oxidation of wood and wood products other than fuelwood released 32×10^{15} g of C since 1860 and accounted for about one-fifth of the flux in 1980 (Tables 4 and 5).

According to these analyses other changes in land use, such as clearing of forest for pasture and the abandonment of agricultural lands, were less important than the expansion of agriculture or the harvest of forests (Tables 4 and 5). The results can also be presented regionally, and it is immediately seen that not all regions show the same pattern of carbon flux as the global summary (Fig. 7). In both North America and Europe, for example, there has been a net accumulation of carbon in forests in recent years, but that accumulation is small relative to the net releases from tropical regions and small in the global accounting.

FIG. 6. Analysis based on population data. The curves show the net flux of carbon to the atmosphere as a result of the clearing and cultivation of agricultural land, harvest and regrowth of forests, oxidation of wood removed from forests, and the clearing of land for pasture.

TESTING DATA AND ASSUMPTIONS

The three analyses presented above give a range of $1.8\text{--}4.7 \times 10^{15}$ g for the net flux of carbon to the atmosphere in 1980. They vary due to large uncertainties in rates of land clearing for agriculture. Are there uncertainties in other parameters large enough to extend this range? We have addressed this question by substituting contrasting sets of data and contrasting assumptions in separate analyses. The number of potential combinations of variables is large, and a complete analysis of all possibilities is not feasible. Furthermore, we have only one or two values for many parameters from the literature, so that a strict sensitivity analysis with probability distributions or standard errors for each parameter would be arbitrary. Finally, for those parameters for which there are several estimates, for example, estimates of tropical forest biomass, we thought it more important to test the extremes separately. To collapse all the estimates into a single number with a standard error would hide the effect of individual sources of data on the calculated flux of carbon.

In the following sections we report various tests of data and assumptions; each test is an alternative to the

TABLE 4. Summary of results of the low, high, and intermediate (population-based) analyses.

Basis of estimate	Annual net release in 1980								
	Total net release		All processes	Agricultural clearing	Harvest and regrowth of forests	Oxidation of wood removed from site	Abandonment of agriculture	Afforestation	Clearing for pasture
	1860–1980	1958–1980							
	Net carbon release (10 ¹⁵ g)								
1. FAO (1949–1978)	184	51.9	1.82	0.59	0.63	0.47	–0.066	–0.039	0.23
2. Myers (1980a, b)	185	69.6	4.70	2.70	1.06	0.74	–0.066	–0.039	0.31
3. Population	180	57.3	2.61	1.30	0.63	0.56	–0.066	–0.039	0.23

FIG. 7. Net flux of carbon to the atmosphere as a result of land-use changes and harvests in Latin America, Tropical Africa, North America, and Europe.

population-based estimate presented above. These tests have been summarized in Tables 6 and 7. The results can be used to set limits on the range of results considered possible.

Tests of agricultural data

In the analyses below we test the consequences of such uncertainties as the time at which major clearing of forests for agriculture occurred, the types of vegetation transformed to agriculture, and the amount of carbon released from soils during cultivation.

Test 4: the time course of clearing of natural ecosystems for agriculture.—The assumption that growth of agricultural land in the past was proportional to growth of populations has been questioned recently by Tucker and Richards (1983). Their thesis is that major expansion of agricultural area occurred in the mid-19th and early 20th centuries at the same time as

the expansion in world trade. The timing of this major expansion is supported by isotopic evidence of increased biotic release (Freyer 1978, 1979, Stuiver 1978, Wilson 1978, Tans and Mook 1980). Recently Richards (1982) has collected statistics on the change in agricultural area for 1860–1920 and 1920–1978), for countries accounting for ~60% of world land area. We based a test on these data (Appendix 5) but had to assume that his rates also applied to the remaining 40% of the world land area. We also added 1700–1859 rates and divided his 1920–1980 rates into shorter intervals: the rates after 1950 were always the same as our population-based analysis (Appendix 2).

The results showed a release of carbon between 1860 and 1980 of 210×10^{15} g, ~16% more than the population-based analysis (Table 6). While the annual net release was greater than in the population-based analysis near the turn of the century, the annual release

TABLE 5. Components of the net flux of carbon to the atmosphere in 1980 (10^{15} g).

	Vegetation			Soil	Products (Decay off site)	Total
	Burned	Decay on site	Regrowth			
Clearing for agriculture	0.38	0.38	0.0	0.54	0.28	1.58
Harvest and regrowth	0.41	1.79	-1.86	0.29	0.27	0.90
Clearing for pasture	0.10	0.09	0.0	0.04	0.01	0.24
Total	0.89	2.26	-1.86	0.87	0.56	
					Subtotal	2.72
					Afforestation and abandonment	-0.11
					Global net flux 1980	2.61

TABLE 6. Summary of results of tests of uncertainties in the estimates for agriculture with the Terrestrial Carbon Model. See text for details of each set of assumptions.

Assumptions	Annual net release in 1980								
	Total net release		All processes	Agricultural clearing	Harvest and regrowth of forests	Oxidation of wood removed from site	Abandonment of agriculture	Afforestation	Clearing for pasture
	1860-1980	1958-1980							
Net carbon release (10 ¹⁵ g)									
3. The population-based analysis	180	57.3	2.61	1.30	0.63	0.56	-0.066	-0.039	0.23
4. Time of clearing	210	62.2	2.79	1.45	0.63	0.58	-0.062	-0.039	0.23
5. a. Forests cleared	228	76.1	3.49	1.97	0.63	0.76	-0.066	-0.039	0.23
b. Nonforests cleared	135	38.4	1.72	0.62	0.63	0.33	-0.066	-0.039	0.23
6. Increased clearing and abandonment	186	59.6	2.70	1.49	0.60	0.60	-0.20	-0.039	0.23
7. Low rates of decay (charcoal)	175	55.6	2.51	1.16	0.63	0.59	-0.066	-0.039	0.23
8. Reduced soil response	150	51.0	2.35	1.01	0.63	0.56	-0.041	-0.039	0.23

since then continued to increase; this contradicts the trend of the release rates obtained from most isotopic studies.

Test 5: changing the ecosystems transformed to agriculture.—We constructed two extreme sets of input data to test the potential significance of misidentifying the type of vegetation cleared for agriculture. In the first we assumed that all the agricultural land in every region except North America, Europe, and the USSR came from forested land. In the second case we assumed that all clearing for agriculture was from non-forest ecosystems. In each case we used the same rates as reported in the population-based analysis; we changed only the relative proportions of the types of vegetation affected.

The analyses showed that between 1860 and 1980, 228×10^{15} g of carbon would have been released in the first test, and 135×10^{15} g in the second (Table 6). Although these values are extreme and set an unrealistically wide range for the 120-yr release, they demonstrate how crucial it is to be able to document, even coarsely, the type of ecosystem cleared for agriculture.

Test 6: increasing the rates of clearing and abandonment.—Estimates of rates of clearing for agriculture based on changes in crop areas are net rates, the sum of clearing and abandonment. If both clearing and abandonment had occurred over the reporting period, the larger of the two would have been underestimated; the lesser would not have appeared. This use of net instead of gross rates affects the calculations because the release of carbon from forest clearing is more rapid than the storage of carbon during regrowth of a forest on abandoned land. It is also true that estimates of net change in carbon storage may be in error because of assumptions about the ecosystem type being changed for agriculture. For example, in the United States in the 1800s, midwestern grasslands were coming under

cultivation, while abandoned croplands in New England were growing back to forests. The net change in carbon storage that resulted can only be estimated by calculating the change in both ecosystems.

We tested the effects of assuming higher rates of both clearing and abandonment. The only countries for which national statistics on farmland abandonment exist are the United States and certain Western European countries (International Institute of Agriculture 1939, Hart 1968, FAO 1976). We used an annual rate of clearing one-third greater than that used in the population-based analysis, based on evidence that about one-third of the tropical forests cleared for agriculture in Latin America return to forests (Lanly and Gillis 1980). We simultaneously increased the rate of abandonment so that the net change in agricultural land was the same as in the population-based analysis. The results of this test were close to those of the population-based estimate (Table 6).

Test 7: changing the proportions of plant material in various decay pools.—It is difficult to know what happens to plant material that is cleared from land converted to permanent agriculture. If population density is high, most of that material may be used for fuelwood and oxidized within a year. If fuelwood is not in demand locally, the wood is burned during clearing or left to decay. When forests are cleared by burning, a significant fraction of the plant material may become charcoal and last for many years (Seiler and Crutzen 1980). This would cause a greater fraction of the biomass to be transferred to the longer-term decay pools than in our population-based test.

We tested the significance of slower rates of decay with data derived from Seiler and Crutzen (1980) (Appendix 6). In the case of permanent agriculture, the charcoal produced during land clearing is of little significance in the global carbon budget (Table 6). One of the largest contributors to charcoal formation, shift-

ing cultivation, was not included in the analysis, but the amount of carbon stored in charcoal is small in comparison to the reductions in biomass and soil carbon that follow from an intensification of shifting cultivation (Went and Stark 1968, Clarke 1976, Scott 1977, UNESCO 1978).

Test 8: changing the response of soil carbon to agricultural clearing.—In the population-based analysis, one-half of the carbon in the top metre of soil was oxidized after land was cleared for agriculture. Although there are some agricultural practices that increase the amount of carbon stored in soils, such as irrigation of deserts, these make up a very small part of total agricultural land.

To test the significance of carbon lost from soils we assumed a 20% loss of carbon from all soils transferred to agriculture, as opposed to a 50% loss in the population-based analysis. The carbon originally in the vegetation of these lands was oxidized as it was for the population-based analysis.

This assumption resulted in a net exchange of carbon over the last 120 yr that was one of the low estimates, 150×10^{15} g instead of 180 in the population-based estimate (Table 6). It is important to determine the changes in soil carbon that accompany various methods of cultivation.

Tests of data on harvest

The results of the population-based estimate showed that the harvest of forests for timber and fuelwood has been less important in releasing CO_2 into the atmosphere than the clearing of land for agriculture (Fig. 6). There is a possibility, of course, that the data used have been inaccurate or that assumptions made in constructing the model are wrong. In the following section we examine several questions about our handling of the information on the harvest and recovery of forests.

Test 9: doubling the world harvest of wood.—Several studies have concluded that the FAO data suffer from inconsistent definitions, irregular records, and biased data (Persson 1974, Openshaw 1978, Myers 1980b). The volume of wood removed from forests can be two to three times greater than that reported to the FAO. Openshaw (1974) found this to be true in Tanzania, Thailand, and Gambia. We assumed in this test that the volume of wood removed from forests worldwide was double that of the population-based estimate. The increased volume could have been obtained by doubling the area of forests cut each year. Since there were several regions where the area of forest was just barely able to supply the harvest called for in the population-based analysis, we chose instead to double the efficiency of wood removed per hectare. In tropical moist forests and temperate deciduous forests, we increased the efficiency of wood removal by 50% rather than 100% and enlarged the area harvested because the removal rate was already more than half of the live biomass in those forests. In the three other

forest types we doubled the removal of wood per hectare. In brief, this test increased world harvest of wood by 100%; most of the increase came from more efficient use of the forest rather than from harvesting of a larger area.

The results differed little from those of the population-based estimate (Table 7). There was a greater release from decay in 1980 because more harvest products were being oxidized. The net release from the forests was less, however, because the greater efficiency of wood removal left less dead plant material to decay in the forest.

Test 10: assuming the residual organic matter following harvest is live.—In the population-based estimate and in other tests we assumed that all the biomass remaining after harvest was dead and left to decay. This assumption is unrealistic, but the variability of harvesting methods in various countries makes it difficult to assign this remaining biomass to live, dead, or damaged categories. We have tested the importance of this assumption in a test where all the material not harvested remained as living vegetation. The efficiencies of wood removal per hectare and the harvest rates were identical to those used in the population-based estimate. We did not change the time required for forest regrowth, although forests thinned to one-half of their standing stock probably recover to their former biomass more rapidly than forests starting with no live biomass.

The results (Table 7) suggest that whether the biomass left on site after harvest is living or dead makes little difference to the long-term carbon balance. A greater release of CO_2 from dead and decaying vegetation is balanced in the calculations of the model by a higher uptake of regrowing vegetation.

Test 11: allowing complete recovery of harvested forests.—In most of the tests when primary forests were harvested, regrowth was to secondary forests whose biomass and soil carbon were 75–90% of those in the original forest (Table 2). In the model, primary forests were cut only when there was no secondary forest available. As rates of forest harvest increased over time and as forest land became agricultural land, there was always some additional cutting of primary forests, but most harvests were of secondary forests. In a few regions, however, the rate of harvest decreased, yet forests that had "regrown" were maintained by the model at 75% of their original carbon content. The long-term net flux of carbon as a result of harvest and regrowth, therefore, was not zero but an amount potentially equal to 25% of the biomass and soil carbon in all regrown forests.

To test the significance of this artificial restriction, we ran a test in which the carbon content of regrown forests was allowed to reach that of primary forests. This 100% recovery of vegetation and soils lowered the net release of carbon from harvest and regrowth of forests by a factor of two in 1980 (0.63×10^{15} g of

TABLE 7. Summary of results of tests of uncertainties in the estimates for harvest and regrowth of forests with the Terrestrial Carbon Model. See text for details of each set of assumptions.

Assumptions	Annual net release in 1980								
	Total net release		All processes	Agricultural clearing	Harvest and regrowth of forests	Oxidation of wood removed from site	Abandonment of agriculture	Afforestation	Clearing for pasture
	1860-1980	1958-1980							
	Net carbon release (10^{15} g)								
3. The population-based analysis	180	57.3	2.61	1.30	0.63	0.56	-0.066	-0.039	0.23
9. Doubled harvest	175	55.3	2.49	1.30	0.29	0.78	-0.066	-0.039	0.23
10. Increased live residual	162	50.1	2.25	1.30	0.27	0.56	-0.066	-0.039	0.23
11. Complete recovery	164	51.6	2.27	1.30	0.36	0.56	-0.084	-0.083	0.23
12. a. Increased rates of regrowth	152	47.1	1.98	1.30	0.055	0.55	-0.093	-0.050	0.23
b. Reduced rates of regrowth	214	66.6	3.15	1.30	1.12	0.55	-0.046	-0.0007	0.23
13. No loss of carbon from soil	163	51.4	2.30	1.30	0.34	0.56	-0.073	-0.050	0.23
14. Reduced amount of carbon per unit area	152	44.7	1.98	1.03	0.43	0.49	-0.066	-0.039	0.14
15. Combination of several tests	100	32.1	1.38	0.81	0.086	0.49	-0.059	-0.083	0.14

carbon in the population-based analysis and 0.36×10^{15} g in this test; Table 7). The net flux of carbon from all land-use changes was reduced from 2.61×10^{15} g to 2.27×10^{15} g in 1980. Over the 120-yr period since 1860 the total net flux from harvest and regrowth alone was 18×10^{15} g; it was 34×10^{15} g in the population-based analysis.

Test 12: changing the rate of regrowth of forests.—In the population-based analysis the regrowth time (to 75% of the carbon level of primary forests) was 50 yr for all types of forests. We ran two extreme tests that modified this rate (Table 7). In one we permitted forests to regrow in a shorter time (30 yr for temperate and boreal forests and 15 yr for tropical forests). In another test we assumed that all forests regrew in 100 yr following harvest. With a high rate of regrowth the annual net flux of carbon in 1980 was $\approx 0.6 \times 10^{15}$ g less than in the population-based analysis because more of the harvested forests had already grown back. A slow rate of forest regrowth increased the release of carbon in 1980 by $\approx 0.5 \times 10^{15}$ g.

In the long term when forests were permitted to regrow, the effect of harvests on the carbon of the atmosphere was small. In the short term, however, the rate of forest regrowth was important. If forests regrow after harvest faster than their products decay, the harvest of forests leads to a short-term storage of carbon. If the products are oxidized more rapidly than the forests regenerate, the short-term effect will be a release of carbon.

These results are of potential use in management of

the atmospheric level of carbon dioxide. If a major increase in atmospheric carbon dioxide can be anticipated, one appropriate use of forests and forest products might be to ameliorate that increase. On the other hand, the growth of forests will store a limited quantity of carbon in the short term at best. In the longer term of decades to centuries, it is the total mass of carbon stored in both biomass and soils that is important.

Test 13: changing the response of soil carbon following harvest of a forest.—Studies of the effect of clear-cutting in northern temperate forests indicate that $\approx 50\%$ of the carbon in the forest floor is lost in the 10–15 yr following harvest. The forest floor is a layer of unincorporated organic matter 5–20 cm deep. It is not clear that the soil carbon to a depth of 1 m undergoes a similar reduction. There is recent evidence suggesting that the reduction in forest floor carbon in forests of the southern United States is considerably $< 50\%$ following harvest (Gholz and Fisher 1982), and the same may be true for soils in tropical forests. In the model, the loss of carbon from soils following harvest in the population-based estimate was 50% for temperate, 15% for boreal, and 35% for tropical forests.

The importance of the uncertainties in the loss of soil carbon was examined in this test with the assumption that the organic matter in soils is unchanged following harvest. Plant debris left in the forest at the time of harvest decayed over time, as in the population-based estimate.

The results show that while this alternative assumption made a difference of only 11% in the total net flux

TABLE 8. Estimates of annual net carbon flux between terrestrial ecosystems and the atmosphere in or about 1980. Positive values indicate net release to the atmosphere.

Reference	Carbon flux (10^{15} g/yr)
Woodwell and Houghton 1977	2.5–20
Adams et al. 1977	0.4–4
Bolin 1977	0.4–1.6
Wong 1978	1.9
Woodwell et al. 1978	4–8
Hampicke 1979	1.5–4.5
Seiler and Crutzen 1980	–2.0–2.0
Moore et al. 1981	2.2–4.7
This study	1.8–4.7

for 1980, it reduced the net flux from harvested and regrowing forests by almost 50% (Table 7).

Test 14: changing the amount of carbon per unit area in the vegetation and soils of different ecosystems.—For the population-based estimate, we used the Whittaker and Likens' (1973) review of carbon in the biota to assign carbon values to ecosystem types. Other students of world vegetation have argued that these values refer to exceptionally productive or undisturbed sites and that the mean biomass for a particular forest type is less (Olson et al. 1978, Ajtay et al. 1979, Brown and Lugo 1980). In this test (Appendix 7) we replaced the mean biomass (Whittaker and Likens 1973) and soil carbon (Schlesinger 1977) values for tropical forests with those suggested by Brown and Lugo (1980). We combined the six forest types given by Brown and Lugo into two types and calculated means weighted by area. These new values ranged from 34 to 78% of the tropical forest biomass or soil carbon values used in the population-based estimate. We assumed that these values referred to the primary or undisturbed tropical forests and that secondary forests reach 75% of the carbon in primary forests.

The results showed a total release of carbon over the 120 yr since 1860 of 152×10^{15} g and a release of 1.98×10^{15} g in 1980 (Table 7). Clearly, if the carbon content of a forest is low, less carbon will be released during its harvest or its conversion to agriculture. On the other hand, less carbon will be taken up during forest regrowth, so the total net release does not proportionately reflect the very drastic changes in forest biomass.

Test 15: combining several tests in an effort to lower the estimated net release of carbon from the biota and soils.—In the tests discussed above, we have examined one factor at a time in an effort to determine how uncertainty in data and assumptions affects the results of an analysis of the biotic release of carbon. In this test we included simultaneously several factors that individually reduced the net flux of carbon to the atmosphere. The purpose was to see if we could make the biota and soils a net accumulator of carbon in

TABLE 9. Estimates of the net release of carbon from terrestrial biota and soils to the atmosphere during the last century based on models using carbon isotope ratios in tree rings.

Reference	Time interval	Release of carbon from terrestrial biota and soils to atmosphere during interval (10^{15} g)
Stuiver 1978	1850–1950	120
Wagener 1978	1800–1935	170
Freyer 1978	1860–1974	70
Siegenthaler et al. 1978	1860–1974	157–195
Tans 1978	1850–1950	150
This study	1860–1980	135–228

1980; however, the assumptions were not considered realistic.

The factors we changed included: (1) 100% rather than 75% recovery of vegetation and soil following disturbance (Test 11), (2) a 34–78% lower amount of carbon per unit area in vegetation and soil (Test 14), (3) no loss of soil carbon following harvest of forests (Test 13), and (4) a 20% rather than 50% loss of soil carbon with conversion to agriculture (Test 8).

The results of this combination of assumptions and data showed a net flux of carbon of 1.38×10^{15} g to the atmosphere in 1980 and a total net release over the past 120 yr of 100×10^{15} g. As expected, these fluxes are smaller than those resulting from any other test (Tables 4, 6, and 7). The three factors affecting the flux of carbon from harvest of forests combined to make the net flux from harvests approach zero in 1980 (0.086×10^{15} g). The clearing of land for agriculture and the decay of wood accounted for almost the entire net release (Table 7).

The results of this test show that when the assumptions and data of individual tests are combined, they may interact such that the results of the combination are not easily predictable from the results of the individual tests. An analysis of Tests 8, 11, 13, and 14 suggests that without interaction the net release of carbon in 1980 would have been 1.07×10^{15} g instead of the 1.38×10^{15} g actually calculated. Thus, in spite of the fact that many tests produced releases in 1980 that were less than those in the population-based estimate, a test including all of those tests simultaneously would not necessarily lower the estimated net release of carbon in 1980 below 1×10^{15} g.

DISCUSSION

Three approaches have been used to determine how the terrestrial biota and soils affect the CO_2 content of the atmosphere. These include direct estimates (used in this paper) based on data showing changes in the area of ecosystems with different amounts of carbon per unit area, indirect estimates based on changes in the ratios of carbon isotopes in tree rings and corals.

and other indirect estimates based on the difference between the amount of carbon released from fossil fuels and the amount accounted for in the atmosphere (measured) and transferred to the oceans (calculated) (Eq. 1). The three approaches do not measure the same quantity and may not yield similar fluxes of carbon. The direct approach based on changes in area ignores changes in the amount of carbon per unit area that may occur within undisturbed areas. Such changes could be either positive or negative. The two indirect approaches ideally yield a flux that includes both aspects of the terrestrial carbon flux (changes in area of ecosystems and changes in the carbon content of undisturbed ecosystems), but the two aspects cannot be distinguished.

On the basis of the direct analyses presented here the estimate of the net release of carbon from vegetation and soils in 1980 ranges between 1.8 and 4.7×10^{15} g (Table 4). Other direct estimates of the global biotic flux of carbon based on statistics of worldwide forestry and agriculture have also generally indicated that terrestrial ecosystems as a whole release carbon (Table 8), although specific regions may show a net accumulation of carbon (Armentano and Ralston 1980, Deicourt and Harris 1980, and Fig. 7). Over the 120-yr period 1860–1980, the range of the net flux of carbon calculated here was 135 – 228×10^{15} g. Isotopic evidence from tree rings suggests a release of carbon of between 70 and 195×10^{15} g over the past century or more (Table 9). Global models based on oceanographic and atmospheric data, in contrast, suggest that the biota must be either in an equilibrium or accumulating on the order of 1×10^{15} g of carbon currently (see below).

The approach presented here is more complete than other direct analyses in that it includes the response of soil organic matter and the decay of wood products in the calculated flux of carbon. If only the vegetation had been included in our analyses, the net flux of carbon in 1980 would have been half as large as in the population-based estimate (Table 5). The flux would have included only the rapid oxidation of wood burned (0.89×10^{15} g of C), the slower decay of plant material left to decay on harvested or cleared sites (2.26×10^{15} g of C), and the regrowth of forests on harvested, abandoned, or afforested areas (-1.97×10^{15} g of C), for a net flux of only 1.18×10^{15} g of carbon for the world in 1980. Including soils in the analysis added another 0.87×10^{15} g of C to the net flux (similar to the Schlesinger [1983] estimate), and including the decay of wood removed from forests contributed another 0.56×10^{15} g. Thus, soils and wood products together contribute as much to the flux of carbon as does vegetation.

Oceanographic and atmospheric modellers (Bacastow and Keeling 1973, Machta 1973, Oeschger et al. 1975, Siegenthaler and Oeschger 1978, Broecker et al. 1979) have approached the role of the biota (L) by

FIG. 8. Net flux of carbon to the atmosphere as a result of land-use changes and harvests (the population-based estimate: —) and as a result of the combustion of fossil fuel (---; Rotty 1981a, b).

calculating the difference between the amount of carbon released annually from the combustion of fossil fuels (F) and the amount that accumulates in the atmosphere (A) and in the modelled oceans (S):

$$L = F - A - S \quad (2)$$

$$0.7 (\pm 1.4) = 5.2 (\pm 0.7) - 2.5 (\pm 0.2) - 2.0 (\pm 0.5)$$

The values in Eq. 2 correspond to the annual fluxes of carbon (in 10^{15} g) in 1980. The annual increase in atmospheric CO_2 was estimated from measurements made at Mauna Loa (Bacastow and Keeling 1981, R. Bacastow and C. D. Keeling, personal communication). The release of carbon from combustion of fossil fuels in 1980 is Rotty's (1981b) estimate. The uptake by the oceans was assumed to be 39% of the amount released from fossil fuels (Broecker et al. 1979). The numbers in parentheses represent rough estimates of the errors of each of the terms in the equation: 12–15% for the fossil fuel term (Keeling 1973b), 20–25% for oceanic uptake (Broecker et al. 1979), and $\approx 10\%$ or less for the atmospheric measurements (Bacastow and Keeling 1981).

To reduce the effect of short-term variations in the rate of increase in atmospheric CO_2 , the equation can be evaluated for the 22-yr period of the Mauna Loa record (1958–1980) (Fig. 9):

$$L = F - A - S \quad (3)$$

$$2.2 (\pm 19.2) = 85.5 (\pm 11.5) - 49.9 (\pm 0.2) - 33.4 (\pm 7.5)$$

The conclusions are essentially the same. When the role of terrestrial ecosystems is calculated by difference using the equation, the biota and soils are ap-

FIG. 9. Net flux of carbon (in 10^{15} grams) between terrestrial ecosystems and the atmosphere from 1958 to 1980 as a result of changes in the use of land, and the net flux of carbon between the other major components of the global carbon cycle during the same interval of time. According to the most recent analyses, the carbon cycle is not balanced; the releases are greater than the storages.

parently accumulating carbon, albeit at a rate not significantly different from zero. In contrast, the biota and soils appear to be releasing carbon when the net changes in the carbon of biota and soils are calculated directly on the basis of land-use practices during the past century. According to the analysis presented here, the net release of carbon from terrestrial systems since 1860 has equalled or exceeded the release from fossil fuels (180 vs. 160×10^{15} g). Only in the last two decades has the release of CO_2 from use of fossil fuels (Rotty 1981a, b) exceeded the rate of carbon release caused by changes in the use of land worldwide (Fig. 8). Over the period since 1958 our estimate of net release of carbon from terrestrial systems was 57.3×10^{15} g according to the population-based analysis (Fig. 9).

The range of the net release identified in this study is narrower than earlier estimates (Woodwell and Houghton 1977, Woodwell et al. 1978), but some of the values are still too high to balance the global carbon budget (Eq. 2). If the actual net flux of carbon from the biota and soils is at the low end of the range, it is within the combined error of the other terms in the equation, and the carbon budget may balance. If the actual flux is near the high end of the range, however, the budget is seriously out of balance, and our current understanding of the global carbon cycle is incomplete.

One possibility we have not considered here is that the carbon content of undisturbed ecosystems has

changed. Such changes, often referred to as the biotic growth factor, might occur as a result of increased concentration of atmospheric CO_2 (Lemon 1977, B. R. Strain, *personal communication*), increased levels of available nutrients, or changes in temperature and moisture. We have little ecological or physiological basis for expecting (Kramer 1981), and no evidence to support, an increase in biomass or soil carbon globally. On the contrary, an increase in the average temperature of the earth, as occurred during this century (Mitchell 1961, Salinger 1979), might be expected to increase ecosystem respiration relative to photosynthesis and hence release carbon to the atmosphere.

We believe several other mechanisms of carbon storage frequently invoked to balance the global carbon budget to be irrelevant in the context of the global carbon question. For example, the increased productivity of agricultural crops in recent times is irrelevant because the production is consumed (oxidized) within a year; it does not appear as an increased storage of carbon. Similarly, if fluxes of carbon are in a steady state in areas away from human influence, then the flux of carbon in net primary productivity can be ignored, even if it has been underestimated (Smith 1981). The assumption of steady state permitted us to consider only those areas that have been disturbed; the area and carbon content of undisturbed ecosystems need not be known at all and need not be considered in the analysis. In the same way, the burial of carbon as elemental carbon or charcoal as a result of fires

(Seiler and Crutzen 1980) is not important, except as the rate of burning and formation of charcoal is changing currently. Similarly the export of terrestrial carbon to the sea by rivers (Lugo and Brown 1980, Richey et al. 1980) is not important in this context, no matter how large, unless it has changed drastically in recent times. Each of these fluxes has been invoked recently to account for a net storage of carbon and to balance the equation of the global carbon cycle. We have no evidence, however, that such fluxes have changed sufficiently since preindustrial times to be important in the CO_2 question, and we have not included steady-state fluxes in this analysis.

The discrepancy between the terrestrial analyses and those of the ocean modellers is unresolved. The important questions are: what is the net flux of carbon from the terrestrial biota and soils to the atmosphere, and is it near the high or low end of the range presented here? It is therefore essential that we improve the precision of the estimate of flux. The most efficient way to improve the precision is to use the model to indicate where further information is required to help narrow the range of estimates. The model indicates that the largest source of carbon released into the atmosphere is from forested lands transformed into agriculture. This transfer at present is most important in the tropics (Fig. 7, Appendices 2, 3, and 4), yet one of the largest areas of uncertainty is the rate of transformation of tropical forests. Current estimates of this rate vary considerably. Tests of factors other than the rates of clearing or the types of ecosystems cleared gave a range of only $1.98\text{--}3.15 \times 10^{13}$ g of carbon, almost 60% less than the overall range. No other single factor we tested produced a range greater than that produced by the uncertainty in rates of clearing. Monitoring tropical regions with LANDSAT may be an effective method for measuring these rates of change since 1972, the time interval most important for contemporary analyses. The largest changes in the storage of carbon, those associated with the transformation of forest to nonforest, are the changes most easily detectable with LANDSAT, and coverage is worldwide.

The analyses given here did not include several land-use changes that have the potential for changing the amount of carbon released from terrestrial systems. Some of these changes that would reduce the estimated release of carbon include the suppression of forest fires (Pyne 1982), the expansion of paddy rice agriculture (Institute of Soil Science, Academia Sinica 1978), and the expansion of no-tillage agriculture (Phillips et al. 1980). Other changes that would increase the net release of carbon include the drainage of wetlands for agriculture (Armentano 1980), the increasing intensity of shifting cultivation (Scott 1977, UNESCO 1978), the reduction in carbon per unit area from grazing and overgrazing (Parsons 1976, Sanchez and Tergas 1979), and the increasing area of arid lands (Eckholm and Brown 1977, Council on Environmental Quality 1980).

However, Schlesinger (1982) suggests that carbonates may increase in arid lands. Including all of these changes in the analyses would probably increase the net release of carbon from the biota and soils, but, although such factors may be large locally, their importance worldwide is likely to be similar to the rather minor effects of afforestation or agricultural abandonment analyzed here.

Improvement of the estimate of the net flux of carbon from terrestrial systems requires more than the incorporation of additional land-use changes in the analysis, however. The regions and ecosystems in the model are large and heterogeneous units, while the data used to describe the response curves, for example, were obtained from studies in specific areas. Each of the parameters given in the tables and appendices was chosen on the basis of available data and judgment; each is subject to argument and change. Yet, it is important to note that despite large changes in these parameters introduced in our tests, the calculated flux of carbon for 1980 did not change $>0.6 \times 10^{13}$ g. A reasonable next step is to conduct detailed studies of important regions. If the necessary data are available, such studies will improve the precision of the estimated flux. Our best estimate of the net carbon flux at the moment, however, is: a total release of carbon since 1860 of $135\text{--}228 \times 10^{13}$ g and an annual release in 1980 of $1.8\text{--}4.7 \times 10^{13}$ g.

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APPENDIX 1

Countries comprising the 10 regions of the world in the terrestrial Carbon Model.

North America		North Africa-Middle East	
Canada	United States	Algeria	Morocco
		Bahrain	Oman
		Cyprus	Qatar
		Egypt	Saudi Arabia
		Iran	Syria
		Iraq	Tunisia
		Israel	Turkey
		Jordan	United Arab Emirates
		Kuwait	Yemen
		Lebanon	Yemen, Democratic
		Libya	
Europe		Tropical Africa	
Albania	Ireland	Angola	Mauritania
Andorra	Italy	Benin	Mauritius
Austria	Liechtenstein	Botswana	Mozambique
Belgium	Luxembourg	Burundi	Namibia
Bulgaria	Malta	Cabinda	Niger
Czechoslovakia	Monaco	Cameroon	Nigeria
Denmark	Netherlands	Central African Republic	Republic of Congo
Federal Republic of Germany	Norway	Chad	Reunion
Finland	Poland	Djibouti	Rio Muni
France	Portugal	Equatorial Guinea	Rwanda
German Democratic Republic	Rumania	Ethiopia	Senegal
Great Britain	San Marino	Gabon	Sierra Leone
Greece	Spain	Gambia	Somalia
Hungary	Sweden	Ghana	South Africa
Iceland	Switzerland	Guinea	Sudan
	Yugoslavia	Guinea-Bissau	Swaziland
		Ivory Coast	Tanzania
		Kenya	Togo
		Lesotho	Uganda
		Liberia	Upper Volta
		Madagascar	Western Sahara
		Mali	Zaire
		Malawi	Zambia
			Zimbabwe
USSR		South Asia	
Union of Soviet Socialist Republics		Afghanistan	India
		Bangladesh	Nepal
		Bhutan	Pakistan
		Burma	Sri Lanka
Pacific developed region		Southeast Asia	
Australia	Oceania	Brunei	Laos
Japan	Papua New Guinea	Kampuchea (Cambodia)	Malaysia
New Zealand	South Korea	East Timor	Philippines
North Korea (Korea DPR)	(Korea Republic)	Indonesia	Thailand
	Taiwan		Vietnam
China			
People's Republic of China	Mongolia		
Latin America			
Argentina	Guyana		
Bahamas	Haiti		
Belize	Honduras		
Bolivia	Jamaica		
Brazil	Martinique		
Chile	Mexico		
Colombia	Nicaragua		
Costa Rica	Panama (includes Canal Zone)		
Cuba	Paraguay		
Dominican Republic	Peru		
Ecuador	Puerto Rico		
El Salvador	Surinam		
Falkland Islands	Trinidad and Tobago		
French Guiana	Uruguay		
Guatemala	Venezuela		
Guadeloupe			

APPENDIX 2

Data used for the population-based estimate. The data given here and in Tables 2 and 3 are the data used in every test, except as otherwise indicated. The model interpolates annual rates linearly between the dates given.

	Roundwood production (C. 10^{12} g/yr)							
	1700	1860	1875	1900	1925	1950	1970	1980
North America								
Temperate evergreen	1.4	30	37	36	38	33	38	41
Temperate deciduous	1.2	26	31	31	32	28	32	35
Boreal	2.3	51	62	61	64	55	63	69
Total	4.9	107	130	128	134	116	133	145
Europe								
Temperate evergreen	12	26	29	35	44	41	49	44
Temperate deciduous	10	22	24	30	37	35	41	38
Boreal	2	5	5	6	8	7	8	8
Total	24	53	58	71	89	83	98	90
USSR								
Temperate evergreen	1.7	6	7	9	10	19	23	23
Temperate deciduous	2.5	8	10	14	15	28	33	33
Boreal	8.5	27	31	46	51	95	111	112
Total	14	41	48	69	76	142	167	168
Pacific developed								
Tropical moist	3.8	5	5	7	9	12	12	10
Temperate evergreen	4.5	6	6	8	11	14	13	12
Temperate deciduous	1.2	1	2	2	3	4	3	3
Total	9.5	12	13	17	23	39	28	25
China								
Tropical moist	0.8	2	2	2	3	3	5	5
Temperate evergreen	3.7	10	10	11	12	13	22	25
Temperate deciduous	4.6	12	12	13	15	16	27	31
Total	9.1	24	24	26	30	32	54	61
Latin America								
Tropical moist	2.3	7	8	12	19	32	54	62
Temperate evergreen	0.4	1	2	2	4	6	11	12
Temperate deciduous	0.5	1	1	2	3	6	10	11
Total	3.2	9	11	16	26	44	75	85
North Africa-Middle East								
Tropical moist	0.9	1	1	2	2	3	6	7
Temperate evergreen	0.5	1	1	1	1	2	3	4
Total	1.4	2	2	3	3	5	9	11
Tropical Africa								
Tropical moist	9.4	13	14	16	20	30	46	54
Tropical seasonal	11	14	16	18	23	33	52	60
Total	20	27	30	34	43	63	98	114
South Asia								
Tropical moist	1.2	2	2	2	2	3	5	5
Tropical seasonal	14	21	22	25	28	38	51	62
Total	15	23	24	27	30	41	56	67
Southeast Asia								
Tropical moist	4.1	8	10	15	22	34	61	76
Tropical seasonal	0.7	1	2	3	4	6	10	13
Total	4.8	9	12	18	26	40	71	89

APPENDIX 2

Continued.

	Fraction of roundwood assigned to decay pools					
	1700	1875	1900	1925	1950	1980
North America						
1 yr	0.50	0.44	0.40	0.30	0.20	0.04
10 yr	0.20	0.22	0.24	0.28	0.32	0.38
100 yr	0.30	0.34	0.36	0.42	0.48	0.58
Europe						
1 yr	0.50	0.50	0.50	0.48	0.42	0.18
10 yr	0.20	0.20	0.20	0.21	0.23	0.33
100 yr	0.30	0.30	0.30	0.31	0.35	0.49
USSR						
1 yr	0.65	0.65	0.65	0.46	0.41	0.22
10 yr	0.14	0.14	0.14	0.22	0.24	0.31
100 yr	0.21	0.21	0.21	0.32	0.35	0.47
Pacific developed						
1 yr	0.81	0.81	0.81	0.81	0.42	0.27
10 yr	0.08	0.08	0.08	0.08	0.23	0.29
100 yr	0.11	0.11	0.11	0.11	0.35	0.44
China						
1 yr	0.90	0.90	0.90	0.86	0.80	0.75
10 yr	0.04	0.04	0.04	0.06	0.08	0.10
100 yr	0.06	0.06	0.06	0.08	0.12	0.15
Latin America						
1 yr	0.90	0.90	0.90	0.90	0.84	0.82
10 yr	0.04	0.04	0.04	0.04	0.06	0.07
100 yr	0.06	0.06	0.06	0.06	0.10	0.11
North Africa-Middle East						
1 yr	0.90	0.90	0.90	0.87	0.75	0.63
10 yr	0.04	0.04	0.04	0.05	0.10	0.15
100 yr	0.06	0.06	0.06	0.08	0.15	0.22
Tropical Africa						
1 yr	0.93	0.93	0.93	0.91	0.90	0.87
10 yr	0.03	0.03	0.03	0.04	0.04	0.05
100 yr	0.04	0.04	0.04	0.05	0.06	0.08
South Asia						
1 yr	0.92	0.92	0.92	0.92	0.92	0.90
10 yr	0.03	0.03	0.03	0.03	0.03	0.04
100 yr	0.05	0.05	0.05	0.05	0.05	0.06
Southeast Asia						
1 yr	0.90	0.90	0.90	0.85	0.82	0.75
10 yr	0.04	0.04	0.04	0.06	0.07	0.10
100 yr	0.06	0.06	0.06	0.09	0.11	0.15

APPENDIX 2

Continued.

Conversion of land to agriculture (10 ⁶ ha/yr)							
North America	1700-1849	1850-1889	1890-1927	1928-1949	1950	1970	1980
Temperate evergreen	0.09	0.09	0.14	0.03	0	-0.09	0
Temperate deciduous	0.21	0.09	0.14	0.03	0	-0.09	0
Boreal	0	0.03	0.05	0.01	0	0	0
Temperate woodland and shrub	0	0.09	0.14	0.03	0	0	0
Temperate grassland	0	1.2	1.8	0.40	0	-0.02	0
Total	0.30	1.5	2.3	0.50	0	-0.18	0
Europe	1700-1869	1870-1959	1960	1970	1980		
Temperate evergreen	0.06	0.02	0	-0.20	-0.20		
Temperate deciduous	0.06	0.02	0	-0.20	-0.20		
Boreal	0.05	0.02	0	-0.20	-0.20		
Temperate grassland	0.26	0.09	0	-0.20	-0.20		
Total	0.43	0.15	0	-0.80	-0.80		
USSR	1700-1869	1870-1909	1910-1937	1938-1969	1970-1980		
Temperate deciduous	0.18	0.36	0.40	0.22	0		
Boreal	0.02	0.07	0.08	0.04	0		
Temperate woodland and shrub	0.08	0.29	0.32	0.18	0		
Temperate grassland	0.12	0.72	0.80	0.44	0		
Total	0.40	1.5	1.60	0.88	0		
Pacific developed	1700-1869	1870-1949	1950-1969	1970-1980			
Tropical moist	0.0011	0.038	0.22	0.03			
Temperate evergreen	0	0	0	0			
Temperate deciduous	0	0	0	0			
Tropical woodland and shrub	0.0019	0.06	0.36	0.05			
Tropical grassland	0.0044	0.15	0.86	0.12			
Total	0.0074	0.25	1.4	0.20			
China	1700-1872	1873-1912	1913-1932	1933-1953	1954-1964	1965-1969	1970-1980
Tropical moist	0.030	0.025	0.037	0.049	0.11	0.097	0.065
Temperate evergreen	0.046	0.038	0.055	0	0	0	0
Temperate deciduous	0.18	0.15	0.22	0.30	0.47	0.48	0
Temperate grassland	0.046	0.038	0.055	0.15	0.54	0.39	0.59
Total	0.30	0.25	0.37	0.49	1.1	0.97	0.65
Latin America	1700-1859	1860-1874	1875-1899	1900-1924	1925-1949	1950-1964	1965-1980
Tropical moist	0.038	0.10	0.20	0.32	0.74	0.87	0.96
Temperate evergreen	0	0	0	0	0	0.35	0.39
Temperate deciduous	0	0	0	0	0	0.18	0.19
Tropical grassland	0	0	0	0	0	0.35	0.39
Temperate grassland	0.037	0.10	0.20	0.32	0.74	0	0
Total	0.075	0.20	0.40	0.64	1.5	1.8	1.9
North Africa-Middle East	1700-1859	1860-1899	1900-1924	1925-1949	1950-1964	1965-1980	
Tropical moist	0.010	0.044	0.060	0.17	0.13	0.15	
Temperate evergreen	0.014	0.066	0.091	0.15	0	0	
Tropical grassland	0.024	0.11	0.15	0.41	0.64	0.73	
Desert scrub	0	0	0	0.10	0.51	0.59	
Total	0.048	0.22	0.30	0.83	1.3	1.5	
Tropical Africa	1700-1859	1860-1874	1875-1899	1900-1924	1925-1949	1950-1964	1965-1980
Tropical moist	0.018	0.053	0.08	0.15	0.34	1.3	1.6
Tropical seasonal	0.004	0.013	0.02	0.038	0.084	0.13	0.16
Tropical woodland and shrub	0.031	0.093	0.14	0.27	0.59	0.77	0.95
Tropical grassland	0.035	0.11	0.16	0.30	0.67	0.38	0.48
Total	0.088	0.27	0.40	0.76	1.7	2.6	3.2
South Asia	1700-1859	1860-1899	1900-1924	1925-1949	1950-1964	1965-1980	
Tropical moist	0.004	0.012	0.014	0.042	0.049	0.096	
Tropical seasonal	0.038	0.13	0.15	0.45	0.53	1.0	
Tropical woodland and shrub	0.072	0.24	0.28	0.84	0.98	1.9	
Tropical grassland	0.006	0.020	0.023	0.070	0.082	0.16	
Total	0.12	0.40	0.47	1.40	1.6	3.2	

APPENDIX 2

Continued.

	1700-1859	1860-1874	1875-1899	1900-1924	1925-1949	1950-1964	1965-1980
Southeast Asia							
Tropical moist	0.006	0.031	0.067	0.090	0.14	0.16	0.25
Tropical seasonal	0.001	0.005	0.011	0.015	0.024	0.03	0.04
Tropical grassland	0.014	0.067	0.15	0.20	0.31	0.33	0.55
Total	0.021	0.10	0.23	0.30	0.47	0.52	0.84
Afforestation (10 ⁶ ha/yr)							
Europe	1700	1850	1875	1900	1925	1950	1970
Temperate grassland	0	0.02	0.02	0.03	0.05	0.08	0.08
USSR	1700	1875	1900	1925	1950	1970	1980
Temperate woodland and shrub	0	0	0	0.01	0.05	0.03	0.03
Temperate grassland	0	0	0	0.03	0.09	0.04	0.04
China	1700	1875	1900	1925	1950	1970	1980
Temperate grassland	0	0	0	0	0	1.4	2.4
Conversion of land to pasture (10 ⁶ ha/yr)							
Latin America	1700-1925	1950	1970	1980			
Tropical moist forest	0	2.6	1.4	1.4			

APPENDIX 3

Data used for the estimate based on the Production Yearbooks of the FAO. All of the data used in this analysis, except for the clearing rates given here, are the same as used in the population-based estimate (Tables 2 and 3, Appendix 2). Data are rounded off to no more than two nonzero digits.

Annual rates for the conversion of natural ecosystems to agriculture (10 ⁶ ha/yr)						
Latin America			1950-1969	1970-1980		
Tropical moist forest			1.2	0.81		
Temperate evergreen forest			0.49	0.33		
Temperate deciduous forest			0.24	0.16		
Tropical grassland			0.49	0.33		
Total			2.4	1.6		
North Africa-Middle East			1950-1964	1965-1980		
Tropical moist forest			0.22	0.07		
Temperate evergreen forest			0	0		
Tropical grassland			0.54	0.17		
Desert and scrub			0.33	0.10		
Total			1.1	0.34		
Tropical Africa		1950-1964	1965-1969	1970-1980		
Tropical moist forest		1.5	0.94	0		
Tropical seasonal forest		0.16	0.94	0		
Tropical woodland and shrubland		0.93	0.56	0		
Tropical grassland		0.46	0.28	0		
Total		3.1	2.7	0		
South Asia	1860-1910	1911-1940	1941-1950	1951-1955	1956-1965	1966-1980
Tropical moist forest	0.017	0	0.25	0.22	0.033	0.018
Tropical seasonal forest	0.18	0	2.7	2.3	0.35	0.19
Tropical woodland and shrubland	0.34	0	5.0	4.3	0.66	0.33
Tropical grassland	0.028	0	0.41	0.36	0.055	0.03
Total	0.57	0	8.3	7.2	1.1	0.57
Southeast Asia			1950-1964	1965-1980		
Tropical moist forest			0.35	0.22		
Tropical seasonal forest			0.059	0.037		
Tropical grassland			0.76	0.49		
Total			1.2	0.75		

APPENDIX 4

Data used for the Myers estimate. All of the information used in this analysis, except for the data given here, are the same as used in the population-based estimate (Tables 2 and 3, Appendix 2). The model interpolates linearly between the dates given.

Annual rates for the conversion of natural ecosystems to agriculture (10^6 ha/yr)				
	1965	1970	1980	
Latin America				
Tropical moist forest	0.96	1.3	3.4	
Temperate evergreen forest	0.39	0.40	0	
Temperate deciduous forest	0.19	0.20	0	
Tropical grassland	0.39	0.06	0	
Temperate grassland	0	0	0	
Total	1.9	2.0	3.4	
Tropical Africa				
Tropical moist forest	1.6	1.7	2.7	
Tropical seasonal forest	0.16	0.04	0	
Tropical woodland and shrubland	0.95	0.21	0	
Tropical grassland	0.48	0.10	0	
Total	3.2	2.0	2.7	
Southeast Asia				
Tropical moist forest	0.25	2.0	5.7	
Tropical seasonal forest	0.04	0	0	
Tropical grassland	0.55	0	0	
Total	0.84	2.0	5.7	
Rates of harvest (only tropical moist forests harvested) (C , 10^{12} g/yr)				
	1950	1970	1980	
Latin America	32	81	124	
Tropical Africa	30	69	108	
Southeast Asia	34	92	152	
Rates for the conversion of natural ecosystems to pasture				
	1700-1925	1950	1970	1980
Latin America				
Tropical moist forest	0	0.2	1.0	2.0

APPENDIX 5

Data used to test the sensitivity of carbon flux to the historical course of clearing for agriculture. The values given here were derived from rates given by Richards (1982). All of the data used in this test, except for the data presented here, are in Tables 2 and 3 and Appendix 2.

Area in agriculture in 1700 AD (10^6 ha)			
North America	0	Latin America	0
Europe	100	North Africa-Middle East	35
USSR	50	Tropical Africa	3
Pacific developed	3	South Asia	25
China	45	Southeast Asia	5

APPENDIX 5

Continued.

Rates for the conversion of natural ecosystems to agriculture (10 ⁶ ha/yr) Negative values indicate net rates of agricultural abandonment					
North America	1700-1859	1860-1919	1920-1949	1950-1980	
Temperate evergreen forest	0.047	0.17	0.010	-0.084	
Temperate deciduous forest	0.11	0.17	0.010	-0.084	
Boreal forest	0.0	0.058	0.003	0.0	
Temperate woodland and shrubland	0.0	0.17	0.010	0.0	
Temperate grassland	0.0	2.3	0.13	0.0	
Total	0.16	2.8	0.16	-0.17	
Europe	1700-1859	1860-1919	1920-1959	1960-1980	
Temperate evergreen forest	0.018	0.035	0.060	-0.32	
Temperate deciduous forest	0.018	0.035	0.060	-0.32	
Boreal forest	0.016	0.030	0.051	0.0	
Temperate grassland	0.079	0.15	0.25	0.0	
Total	0.13	0.25	0.42	-0.64	
USSR	1700-1859	1860-1919	1920-1969	1970-1980	
Temperate deciduous forest	0.037	0.23	0.58	0.0	
Boreal forest	0.004	0.047	0.12	0.0	
Temperate woodland and shrubland	0.016	0.19	0.46	0.0	
Temperate grassland	0.024	0.47	1.2	0.0	
Total	0.081	0.94	2.4	0.0	
Pacific developed	1700-1859	1860-1919	1920-1949	1950-1969	1970-1980
Tropical moist forest	0.0009	0.040	0.070	0.26	0.045
Tropical woodland and shrubland	0.002	0.067	0.12	0.44	0.075
Tropical grassland	0.004	0.16	0.28	1.0	0.18
Total	0.006	0.27	0.47	1.7	0.30
China	1700-1859	1860-1919	1920-1949	1950-1980	
Tropical moist forest	0.003	0.058	0.023	0.13	
Temperate evergreen forest	0.004	0.087	0.0	0.0	
Temperate deciduous forest	0.015	0.35	0.14	0.52	
Tropical grassland	0.004	0.087	0.070	0.65	
Total	0.025	0.58	0.23	1.3	
Latin America	1700-1859	1860-1919	1920-1949	1950-1964	1965-1980
Tropical moist forest	0.0	0.43	0.55	0.87	0.96
Temperate evergreen forest	0.0	0.0	0.0	0.35	0.39
Temperate deciduous forest	0.0	0.0	0.0	0.17	0.19
Tropical grassland	0.0	0.0	0.0	0.35	0.39
Temperate grassland	0.0	0.43	0.55	0.0	0.0
Total	0.0	0.86	1.1	1.7	1.9
North Africa-Middle East	1700-1859	1860-1919	1920-1949	1950-1964	1965-1980
Tropical moist forest	0.005	0.087	0.0	0.13	0.15
Temperate evergreen forest	0.008	0.13	0.0	0.0	0.0
Tropical grassland	0.013	0.22	0.0	0.64	0.74
Desert scrub	0.0	0.0	0.0	0.51	0.59
Total	0.025	0.44	0.0	1.3	1.5
Tropical Africa	1700-1859	1860-1919	1920-1949	1950-1964	1965-1980
Tropical moist forest	0.0	0.11	0.64	1.3	1.6
Tropical seasonal forest	0.0	0.028	0.16	0.13	0.16
Tropical woodland and shrubland	0.0	0.20	1.1	0.77	0.95
Tropical grassland	0.0	0.23	1.3	0.38	0.48
Total	0.0	0.57	3.2	2.6	3.2
South Asia	1700-1859	1860-1919	1920-1949	1950-1964	1965-1980
Tropical moist forest	0.0004	0.044	0.050	0.049	0.096
Tropical seasonal forest	0.0040	0.47	0.53	0.52	1.0
Tropical woodland and shrubland	0.0075	0.89	1.0	0.98	1.9
Tropical grassland	0.0006	0.074	0.083	0.082	0.16
Total	0.013	1.5	1.7	1.6	3.2
Southeast Asia	1700-1859	1860-1919	1920-1949	1950-1964	1965-1980
Tropical moist forest	0.0	0.095	0.11	0.16	0.25
Tropical seasonal forest	0.0	0.016	0.018	0.03	0.04
Tropical grassland	0.0	0.21	0.24	0.33	0.55
Total	0.0	0.32	0.37	0.52	0.84

APPENDIX 6

Data used to test the sensitivity of carbon flux to rates of decay. All of the data used in this test, other than the values given here, are in Tables 2 and 3 and Appendix 2. The values given here were derived from estimates of charcoal production given by Seiler and Crutzen (1980).

Fraction of carbon in vegetation assigned to decay pools after clearing of forests. The same fractions apply to all types of forests.	
Soil pool	0.230
1 yr	0.270
10 yr	0.285
100 yr	0.092
1000 yr	0.123
Total	1.000

APPENDIX 7

Data used to test the sensitivity of carbon flux to lower amounts of carbon per unit area in vegetation and soil. All data used in the test, other than the values given here, are in Tables 2 and 3 and Appendix 2. The values given here were derived from estimates of biomass and soil carbon in tropical forests (Brown and Lugo 1980).

	Tropical moist forest	Tropical seasonal forest
Carbon in the vegetation of undisturbed forests	156	84
Carbon in the vegetation of secondary forests	117	63
Carbon in the soil of undisturbed forests	84	40
Carbon in the soil of secondary forests	63	30
Minimum carbon content of soil following harvest	55	26
Carbon content of soil after initial rapid change following clearing	50	24
Minimum carbon content of soil in cultivated system	42	20

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