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Global Deforestation: Contribution to Atmospheric Carbon Dioxide

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Summary. A study of effects of terrestrial biota on the amount of carbon dioxide in the atmosphere suggests that the global net release of carbon due to forest clearing between 1860 and 1980 was between 135×10^{15} and 228×10^{15} grams. Between 1.8×10^{15} and 4.7×10^{15} grams of carbon were released in 1980, of which nearly 80 percent was due to deforestation, principally in the tropics. The annual release of carbon from the biota and soils exceeded the release from fossil fuels until about 1960. Because the biotic release has been and remains much larger than is commonly assumed, the airborne fraction, usually considered to be about 50 percent of the release from fossil fuels, was probably between 22 and 43 percent of the total carbon released in 1980. The increase in carbon dioxide in the atmosphere is thought by some to be increasing the storage of carbon in the earth's remaining forests sufficiently to offset the release from deforestation. The interpretation of the evidence presented here suggests no such effect; deforestation appears to be the dominant biotic effect on atmospheric carbon dioxide. If deforestation increases in proportion to population, the biotic release of carbon will reach 9×10^{15} grams per year before forests are exhausted early in the next century. The possibilities for limiting the accumulation of carbon dioxide in the atmosphere through reduction in use of fossil fuels and through management of forests may be greater than is commonly assumed.

The accumulation of CO_2 in the atmosphere (*1, 2*) over the past century is expected to cause a warming of the earth (*3*). The increase in CO_2 is due to the fact that more carbon is released into the atmosphere than is removed by the biota and the oceans. Two sources of CO_2 are especially important, the combustion of fossil fuels (*4, 5*) and deforestation (*6–10*). The analysis presented here indicates that the terrestrial biota, especially forests and their soils, have been a net source of CO_2 for the atmosphere over the past century and are currently releasing between 1.8×10^{15} and 4.7×10^{15} g of carbon annually.

Recent rates of accumulation of CO_2 have been high enough to produce, if continued, an atmospheric burden before the middle of the next century of about 600 parts per million, approximately twice the amount thought to have been present in 1900. The doubling can be expected to increase the mean global temperature by 2° to 4°C (*11*). Polar regions will undergo the greatest changes; climatic zones will shift, agriculture will be displaced, and the earth's major zones of vegetation will be disrupted. Over a century there may be sufficient melting of polar ice to raise sea level by 5 m.

In earlier analyses of the global carbon cycle (*2, 12*), it was assumed that the role of the oceans is well known and that the oceanic absorption of CO_2 is limited to about half the release from the combustion of fossil fuels. This assumption led to the conclusion that the net effect of the terrestrial biota must be the absorption of CO_2 from the atmosphere. In 1954 Hutchinson suggested (*13*) that the net effect of the terrestrial biota was probably a release of CO_2 into the atmosphere. This conclusion was supported in discussion at the Brookhaven Symposium in 1972 (*14*) and in several subsequent studies (*6–10, 15, 16*). Such analyses have produced a wide range of estimates of the amount of CO_2 released from terrestrial systems. Our purpose is to present the results of recent analyses of the net exchanges of carbon between the atmosphere and terrestrial ecosystems since 1860, the approximate beginning of the rapid increase in use of fossil fuels, and to interpret these data for the global carbon cycle.

Methods

A model has been used to compute and summarize year-by-year changes in the carbon content of vegetation and soils after disturbance (*17*). The land was divided into ten geographical regions, each with 14 potential ecosystems. In actuality 69 combinations of regions and ecosystems were used. Two types of data were needed to determine changes in the carbon content of each ecosystem: changes in the carbon content per unit area after disturbance and the total area disturbed. Several types of disturbances were included in the model: clearing for agriculture, the harvest and regrowth of forests, the abandonment of agricultural land, afforestation, and clearing for pasture. Carbon lost from vegetation was either burned, transferred to the soil as slash, or removed as wood products. Products decayed in the model with turnover times of 1, 10, 100, or 1000 years. The pattern of changes in the carbon content per unit area of a forest cleared for agriculture is shown in Fig. 1.

We have assumed that the conversion

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of forestland to permanent agricultural use reduces the carbon stock in the upper 1 m of soil by 50 percent and that the conversion of forestland to grazing land reduces the carbon content of soil by 25 percent. This latter conversion has been applied only in Latin American tropical forests. We have also assumed that primary forests, once cut, return to 75 percent of their original biomass. We approximated the total areas of different ecosystems in 1700 by distributing the world vegetation types of Whittaker and Likens (*18*) among regions on the basis of Kuchler's map (*19*). These areas of natural ecosystems were then reduced by the areas devoted to agriculture in 1700, estimated from population (*20*). The carbon content of vegetation per unit area in 1700 was from Whittaker and Likens (*21*). The carbon content of soil was from Schlesinger (*22*).

The rates of disturbance used in the model were based on several sources (*23*). For the pre–World War II period, these data were combined to provide a single estimate. For the post–World War II period, three different sets of data were used: (i) the Food and Agriculture Organization of the United Nations (FAO) agricultural statistics (*24*), (ii) a recent review of deforestation in the tropics by Myers (*25*), and (iii) an estimate of changes in land use based on population (*20, 26*).

Results

The data on the rates of expansion of agriculture and on the harvest of tropical forests between 1949 and 1980 (1941 to 1980 in South Asia) do not agree (*25, 27*).

Production Yearbooks of the FAO. The most comprehensive and apparently detailed data are those compiled by the FAO since 1949 (*24*). We have used the annual data on the area devoted to agriculture to obtain the rates of clearing for each region of the earth. The data show a sharp drop in the rate of clearing of land for agriculture after 1950, a drop that appears to have continued through 1980. We find this set of data anomalous in that, despite improvements in yields, there appears to be little possibility that the rate of expansion of agricultural lands worldwide has declined by a factor of 5 over the period in which both global economic activity and human populations have grown more rapidly than ever before (*28*).

The net annual release of carbon according to these data over the 120-year period from 1860 to 1980 reached a peak in 1955 of 3.22×10^{15} g/year. In 1980 the release was 1.8×10^{15} g (Fig. 2). The total release over the 120 years was 184×10^{15} g.

The Myers data. An independent estimate of recent rates of clearing of tropical moist forests has been offered by Myers (*25, 29*). Myers's rates of deforestation for these forests alone are greater than the rates for agricultural expansion given by the FAO for the earth as a whole. Myers's rates of conversion apply to many kinds of disturbances. We assumed that only two-thirds of the total rate resulted in permanent deforestation (*30*).

Over the period between 1860 and 1980, the total release of carbon based on the use of the Myers data, modified as indicated above, was 185×10^{15} g, about the same as the estimate based on the FAO data. The total net flux of carbon in 1980 was 4.7×10^{15} g (Fig. 3), considerably higher than the FAO data.

A population-based estimate. A third set of data was developed on the assumption that in tropical regions the rate of agricultural expansion since 1950 has been proportional to the rate of growth of the human population. Reports of the Department of Agriculture (*31*) show that the increase in world agricultural production has been caused in part by increased crop yields per unit area and in part by the conversion of land to agricultural use. The expansion of agricultural area provided about 60 percent of the increased production for the tropical regions (Latin America, tropical Africa, North Africa and the Middle East, southern Asia, and Southeast Asia) (*31*). This fraction was used to adjust the rates of

Table 1. The flux of carbon between the atmosphere and forests due to harvest and other forest transformations from 1860 through 1980, according to the three sources of data used in this study, and the results of tests based upon the use of various assumptions about these data.

Source of data or test	Total release ($\times 10^{15}$ g)		Release in 1980 ($\times 10^{15}$ g)						
	1860 to 1980	1958 to 1980	Clearing for agriculture	Harvest of forests	Decay of wood removed	Abandonment of agriculture	Afforestation	Clearing for pasture	Total
			Source of data						
FAO Production Yearbooks (*24*)	184	52	0.59	0.63	0.47	−0.066	−0.039	0.23	1.82
N. Myers (*25*)	185	70	2.70	1.06	0.74	−0.066	−0.039	0.31	4.71
Population data (*31*)	180	57	1.30	0.63	0.56	−0.066	−0.039	0.23	2.62
			Tests of the population data (*16*)						
Heavy clearing in 1860 to 1914	210	62	1.45	0.63	0.58	−0.062	−0.039	0.23	2.79
Forests cleared	228	76	1.97	0.63	0.76	−0.066	−0.039	0.23	3.49
Nonforests cleared	135	38	0.62	0.63	0.33	−0.066	−0.039	0.23	1.71
Increased clearing and abandonment	186	60	1.49	0.60	0.60	−0.20	−0.039	0.23	2.68
Storage as charcoal	175	56	1.16	0.63	0.59	−0.066	−0.039	0.23	2.51
Reduced loss from soil	150	51	1.01	0.63	0.56	−0.041	−0.039	0.23	2.35
			Tests of forest recovery						
Doubled harvest of wood	175	55	1.30	0.29	0.78	−0.066	−0.039	0.23	2.50
Increased rates of recovery	152	47	1.30	0.06	0.55	−0.093	−0.050	0.23	1.99
Reduced carbon per area	152	45	1.03	0.43	0.49	−0.066	−0.039	0.14	1.99

agricultural clearing calculated on the basis of per capita use of cropland. For the other regions the permanent cropland statistics of the FAO were used.

The annual net release of carbon from terrestrial ecosystems has increased almost continuously since 1860. The population-based estimate is plotted along with the estimates of the FAO and Myers in Fig. 4; also shown is Rotty's estimate (*4*) of the release from the combustion of fossil fuels. Between 1860 and 1980 the total net release of carbon from the biota according to the population-based estimate was 180×10^{15} g. In recent years the rate of release has dropped slightly; in 1980 it was 2.6×10^{15} g. Until 1960 the biotic release exceeded the release from fossil fuels (Fig. 4).

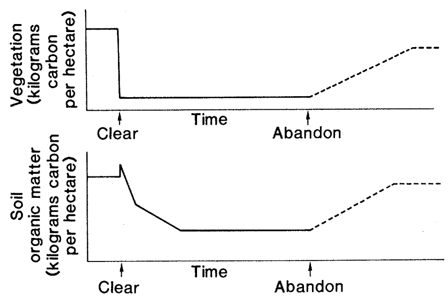
A comparison of estimates. The three sets of data produce similar total releases of carbon over the 120-year period, about 180×10^{15} g (Table 1). The 1980 releases varied between 1.8×10^{15} and 4.7×10^{15} g. The result based on the *FAO Production Yearbooks* seems less reasonable because of the decline in the rate of expansion of agriculture in the period in which population growth has set new records. The results based on the Myers data are almost twice the estimate based on population, despite the adjustment for regrowth of forests (*32*). We have used the population-based estimate, which falls between the other two estimates, for later tests.

All three estimates show that the clearing of land for agriculture, especially in the tropics, is now the largest source of carbon released into the atmosphere from the biota and soils globally. These estimates for 1980 differ by a factor of 2 to 3, due almost entirely to differences in the rates of clearing of tropical forests. Agricultural lands are occasionally abandoned and return to forest, but the effect on the global cycle of carbon has been small, estimated as a net absorption of 0.06×10^{15} g in 1980.

Although the harvest of forests releases nearly the same amount of carbon as clearing for agriculture, harvested forests store carbon again in trees and soil as the forests recover. The net fluxes of carbon for various regions of the earth are indicated in Fig. 5. There has been a net accumulation of carbon in the forests of North America and Europe, but that accumulation is small when compared with the losses from other segments of the temperate zone and from the tropics. The absorption of carbon by the biota and soils as a result of afforestation, the planting of forests where none has existed within the memory of those living, was also small (0.04×10^{15} g in 1980).

Tests of the data and assumptions. The use of a model offers the opportunity to test the effect of changes in assumptions and data. The results of the tests for the population-based estimates have been summarized from Houghton *et al.* (*16*) in Table 1.

The tests included each of the assumptions listed below, considered individually: (i) that rates of clearing for agricultural expansion were higher in the late 19th and early 20th centuries than assumed in the three major tests; (ii) that most of the agricultural expansion came from forests or from nonforested areas such as grasslands that have lower initial stocks of



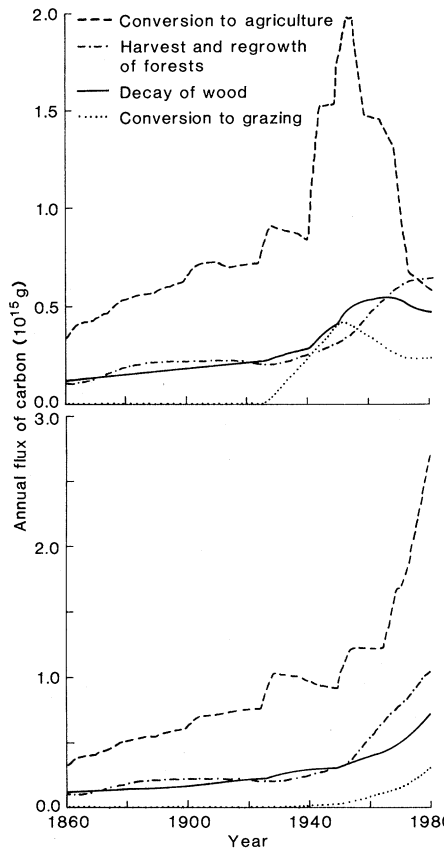


Fig. 1 (above). Idealized curves of the carbon content of vegetation and forest soils before and after clearing, during cultivation, and after the abandonment of agriculture. Such curves were used to describe changes in the vegetation and soils of each of the ecosystems recognized for the ten geographic regions. Fig. 2 (top right). Release of carbon from the vegetation and soils globally according to data based on several sources (*23*) prior to 1949 and FAO data subsequently (*24*). Decay refers to wood removed from the site; harvest includes release of carbon after disturbance and subsequent storage of carbon during regrowth. Fig. 3 (bottom right). Release of carbon from the biota and soils globally according to the population-based estimate (below) through 1965; data after 1965 based on an analysis of deforestation in the tropics by Myers (*25*). Decay refers to wood harvested from the forest; harvest includes release of carbon after clearing and subsequent storage of carbon during regrowth.

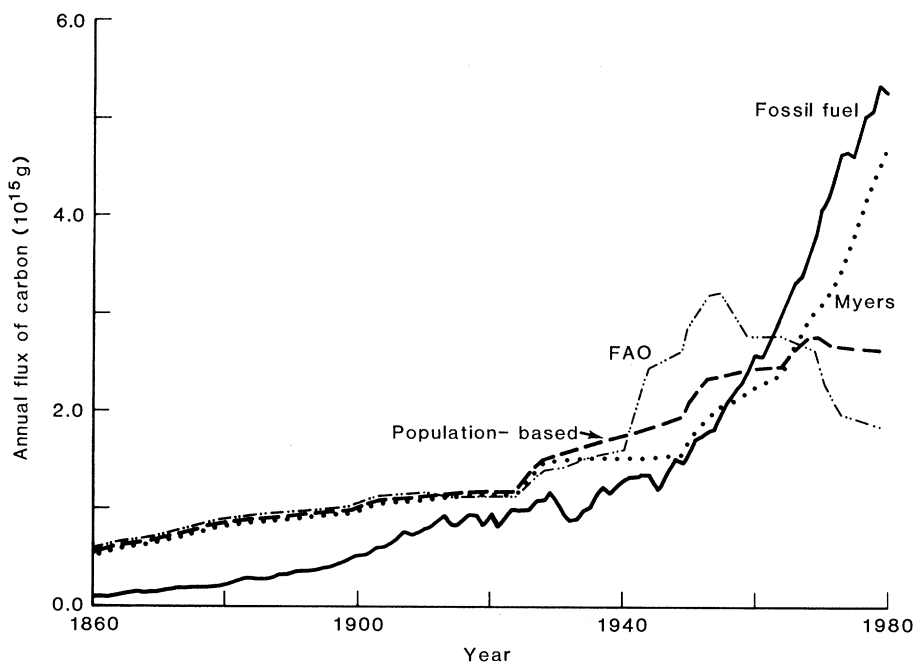
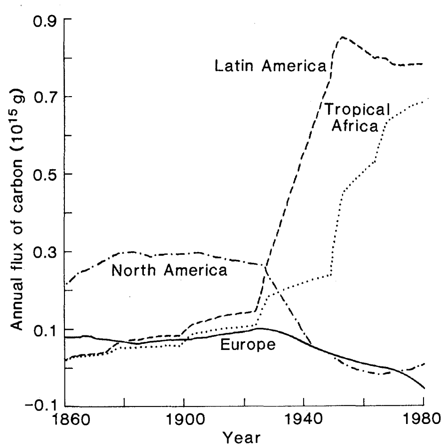


Fig. 4. Release of carbon from the biota and soils globally according to various estimates (*24, 25, 31*). The fossil fuel flux is from data of Rotty (*4*).



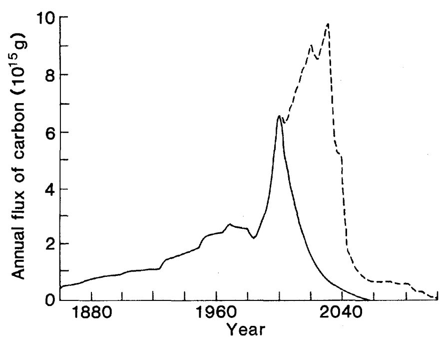


Fig. 5 (left). Net annual release of carbon from various regions of the earth between 1860 and 1980. Fig. 6 (right). Two predictions of the biotic release of carbon based on (i) the assumption that the growth in population continues at current rates until the year 2000 and declines exponentially to zero in 2100 (solid line) and (ii) that the growth in population continues indefinitely (dashed line). In the latter instance the decline in the carbon release is due to the exhaustion of forests.

carbon; (iii) that increased rates of clearing for shifting agriculture (*25, 30*) accompanied by increased rates of abandonment of land have increased the amount of land in successional forests in recent decades; (iv) that substantial quantities of carbon may be stored as charcoal in soils and sediments (*33*); and (v) that the transformation of forestland to agricultural use results in the release as CO_2 of as little as 20 percent of the carbon in the forest soil. In addition the most conspicuous assumptions about the harvest and recovery of forests have been tested, including the following: (vi) that the FAO data on the harvest of wood from forests are low (*34*); (vii) that forests recover from harvest substantially more rapidly than we had originally estimated (*35*); and (viii) that, as suggested by Olson for the world and Brown and Lugo for the tropics (*36*), there may be less carbon stored per unit area in the vegetation and soils than others have assumed.

The range of the net release of carbon in 1980 from these tests of the population-based estimate was from 1.7×10^{15} to 3.5×10^{15} g. The single most important factor affecting the estimate was the area of forest as opposed to nonforest cleared for agriculture (Table 1). Other factors that reduce the flux to the atmosphere were the rate of regrowth of forests and the initial stock of carbon per unit area (Table 1). These results apply both to the 1980 release and to the total release over the 120-year period. The estimate over the longer period ranged in the extreme tests, considered unrealistic, from 135×10^{15} to 228×10^{15} g.

Had the FAO data or the Myers data been selected as the basis of comparison instead of the population-based estimate, the range would have been similar but would have been distributed around the higher or lower estimate. The range of results introduced by these tests of the assumptions and data was less than the range resulting from the three primary sets of data.

Discussion

Three methods are now available to appraise how the terrestrial biota and soils affect the CO_2 content of the atmosphere: direct estimates, such as those summarized here, based on changes in the areas of ecosystems; indirect estimates based on the distribution of carbon isotopes (*37*); and other indirect estimates based on the mass balances of carbon between the atmosphere, oceans, and the terrestrial biota. Our direct estimate does not include any storage of carbon due to increased CO_2. The indirect analyses include such storage to the extent that it occurs and therefore could give different results from those obtained in direct analyses.

Direct estimates. The approach summarized here includes not only the transformation of forests and other natural communities to agricultural use but also the harvest and recovery of forests, the effects of the abandonment of agriculture (*38*), and afforestation. It includes the release of carbon from organic matter in soil and from the decay of wood products. Analyses that do not consider all of these components estimate the release of carbon from forests incorrectly. For example, if soils and wood products had been excluded from the analyses the net flux of carbon to the atmosphere in 1980 would have been about half that of the reference estimate (*39*).

Because we have assumed that undisturbed ecosystems neither gain nor lose carbon from year to year, disturbance is the most important consideration in these analyses. Carbon exchanges are based on the changes in the carbon content per unit area that follow disturbance. The changes due to harvest or clearing and regrowth are large and easily measured. Because our analysis deals only with those areas that have changed with respect to land use, the approach does not require accurate measurement of the total areas of major types of vegetation.

The assumption that undisturbed natural ecosystems are in a steady state may be questionable. One of the highest rates of accumulation of carbon must have been in the soils, muskeg, and forests of the boreal and tundra zones. Since the retreat of glacial ice 5,000 to 15,000 years ago, these regions have accumulated about 500×10^{15} g of carbon. The rate of accumulation of carbon, however, 0.1×10^{15} to 0.03×10^{15} g/year, has been slow by comparison with current rates of release due to deforestation. The assumption of a steady state seems appropriate (*40*).

Distribution of carbon isotopes. The results of analyses based on interpretation of ratios of carbon isotopes (*37*) have suggested that the total net release of carbon from vegetation and soils during the past 100 to 135 years has been between 70×10^{15} and 200×10^{15} g. The total net release from our direct analysis is consistent with these indirect estimates, but the time course of the estimated releases differs. A detailed comparison is not appropriate because of uncertainties in both types of analyses.

Mass balances of carbon. In the type of analysis used in oceanographic and atmospheric models, the role of the biota has been calculated by difference on the basis of the assumption that the rate of absorption of CO_2 by the oceans is known accurately. The equation in Table 2 states that the accumulation in the atmosphere is the sum of the release from fossil fuels, transfer to the oceans, and net transfer between atmosphere and the biota. The equation can be evaluated but not balanced. In the first (the median) evaluation in Table 2, we give the means of ranges commonly cited for all values. For the second (the best) case, we have selected the extremes of ranges to provide the closest approximation of balance within acceptable limits of errors. In the third (the worst) case, we have assumed the greatest imbalance (*41*). The differences range from an imbalance of 1.1×10^{15} to 6.8×10^{15} g of carbon per year.

The range of the biotic carbon flux in 1980 was 1.8×10^{15} to 4.7×10^{15} g (Table 1). If the actual flux was at the upper end of the range, there are important errors in the current estimates of the major terms in the equation; if the actual biotic flux was at the lower end of this range, the equation is still not balanced.

A significant release of carbon from vegetation and soils globally means that the common assumption that about 50 percent of the carbon released from fossil fuels remains in the atmosphere is wrong. If the biotic releases are as indicated in Table 2, the range of the airborne fraction, based on estimates for 1980, is between 22 and 43 percent. If the airborne fraction is calculated for the period between 1958 and 1980, the fraction, based on the first three estimates available for the biota (Table 1), is between 30 and 41 percent.

Table 2. Three evaluations of the carbon balance equation obtained by using ranges of values ($\times 10^{15}$ g/year) reported within assumed limits of uncertainty for 1980. We calculated the airborne fraction by dividing the annual increment in the atmosphere by the sum of the total releases into the atmosphere.

Case	Increment of atmospheric carbon	=	Fossil fuel release	−	Oceanic uptake of carbon	±	Terrestrial carbon release	Imbalance in 1980	Airborne fraction (%)
Median	2.5	=	5.2	−	2.0	+	3.3	4.0	30
Best	2.7	=	4.5	−	2.5	+	1.8	1.1	43
Worst	2.3	=	5.9	−	1.5	+	4.7	6.8	22

Possible CO_2-Induced Stimulation of Stored Carbon in Terrestrial Ecosystems

The increase in the CO_2 content of the atmosphere over the 120 years since 1860 exceeds 15 percent; it may be as much as 30 percent. Such an increase is thought by some to be sufficient to stimulate the storage of carbon in soils and in the biota on land by stimulation of photosynthesis (*9, 42*). Storage is affected, however, by several factors in addition to the concentration of CO_2. Among these, temperature and the availability of mineral nutrients and water are most important. A rise in temperature without a change in other factors can be expected to increase the total respiration more than the gross photosynthesis of a terrestrial ecosystem (*43*) and to reduce the stock of stored carbon, at least within the short term of years, to some new, lower equilibrium. A drop in temperature will cause the reverse. An increase in the availability of water and nutrients, especially nitrogen and phosphorus, will usually increase photosynthesis disproportionately over total respiration until a new equilibrium of stored carbon is established. Many factors would be affected by changes in climate, but it is probable that changes in temperature dominate in determining whether undisturbed terrestrial ecosystems store or release carbon at any moment. The general warming of the past century would probably cause a loss of carbon stored on land in addition to the loss reported in this work. A further warming would, of course, accentuate the loss if other factors remained constant.

A stimulation of carbon storage (net ecosystem production) in undisturbed forests in the range of the imbalances indicated in Table 2, 1.1×10^{15} to 6.8×10^{15} g, would be equivalent to the storage of 2 to 14 percent of the annual net primary production. Because it is unusual for more than half the net primary production to accumulate as net ecosystem production, the actual increase in net primary production would probably be 4 to 28 percent.

As far as we know, there is no evidence at present that the biomass of forests or the storage of carbon in soils has increased globally over the past century. The topic is worthy of more careful analysis than it is currently receiving.

Conclusions

The biotic release of CO_2 to the atmosphere is large, according to direct estimates (*24, 25, 31*). The range of uncertainty in the carbon flux in 1980 is indicated by the three evaluations of the equation in Table 2. If the lower value (1.8×10^{15} g) is correct, the imbalance is probably in the range of uncertainty of terms in the equations. If the upper value (4.7×10^{15} g) is correct, either there must have been a large increase in carbon stocks in undisturbed ecosystems or current estimates of the capacity of the oceans for absorbing atmospheric CO_2 are low.

In any case the biota is important enough that its management will affect the CO_2 content of the atmosphere appreciably. On the one hand, there may be a significant increase in the rate of release of CO_2 into the atmosphere through continued deforestation. Projections made on the basis of the assumption that deforestation will be proportional to the growth in the human population appear in Fig. 6. The limiting factor if the growth in population continues indefinitely is the availability of forests; they are expected to disappear during the first half of the 21st century. The rates of carbon release in the interim, however, are expected to reach 7×10^{15} to 9×10^{15} g/year early in the next century. They would rise considerably more abruptly if the estimates of the current rates of deforestation provided by Myers (*25*) or by the recent Tropical Forest Assessment Project of the FAO (*44*) prove correct and are used instead of the population-based estimate.

On the other hand, appropriate action taken now might reduce or eliminate the problem. Stabilization of the rate of combustion of fossil fuels combined with a program of reforestation would contribute toward stabilizing the CO_2 content of the atmosphere. The spectacular reduction in the U.S. consumption of oil since 1973 and the decline in the rate of growth in use of fossil fuels globally (*4*) offer evidence that such transitions are possible and that we need not accept as inexorable a global warming due to the accumulation of CO_2 in the atmosphere.

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21. The tabulation of the mass of carbon per unit area for various ecosystems provided by R. H. Whittaker and G. E. Likens (*18*) was thought to apply to the world of 1950. As primary forests are replaced by secondary forests, which are also harvested, the standing stock of carbon per area drops. This change was accommodated in the model as outlined here. The result was that the global standing stock of 1980, as interpreted by means of the model, was diminished to 595×10^{15} g of carbon, substantially below the 1950 estimates of Whittaker and Likens. The calculation tends to support the estimate of J. S. Olson [*Nature (London)*, in press] of the global inventory for 1980 at 560×10^{15} to 590×10^{15} g.
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23. Rates of clearing for agriculture were calculated from changes in the area of cropland given by D. B. Grigg [*Agricultural Systems of the World: An Evolutionary Approach* (Cambridge Univ. Press, Cambridge, England, 1974)]; C. J. Robertson [*Scott. Geogr. Mag.* **72**, 1 (1956)]; *The First World Agricultural Census, 1930* (International Institute of Agriculture, Rome, 1939), vols. 1 through 5; the *FAO Production Yearbooks* [see (*24*)]; and the Canadian and U.S. census bureaus. These sources provided data on area of cropland to about 1860 for all the regions except North Africa–Middle East, Latin America, and tropical Africa. For these three regions areas of cropland before 1950 were estimated on the basis of population. The source used for all per capita calculations was McEvedy and Jones (*20*). For a more detailed discussion, see Houghton *et al.* (*16*).
24. *FAO Production Yearbook* (FAO, Rome, 1949 through 1977).
25. N. Myers, *Conversion of Tropical Moist Forests* (National Research Council, Washington, D.C., 1980).
26. We have had extensive discussions with colleagues, including K. D. Singh of FAO and with N. Myers, in three conferences held as part of this work.
27. The longest record of systematically collected data comes from the *FAO Production Yearbooks* (*24*). These data are reports by nations, not questioned, at least in the past, by the FAO. The problems with the data have been discussed by R. Persson, *Research Notes No. 17* (Department of Forest Survey, Royal College of Forestry, Stockholm, 1974). Recent efforts by the FAO, reported to us by K. D. Singh, have been aimed at improving these records. For an emphasis on the tropics, see also the following: A. Sommer, *Unasylva* **18**, 5 (1976); *The Global 2000 Report to the President of the United States, Entering the 21st Century* (Pergamon, New York, 1980), vols. 1 and 2; A. Grainger, *Ecologist* **10**, 6 (1980).
28. L. R. Brown [*Science* **214**, 995 (1981)] reported a sharp decline between 1960 and 1970 in the rate of growth of land planted with cereal grains. The rate of growth in the succeeding 10 years has more than doubled, however, from 2.2×10^6 to 5.4×10^6 hectares per year.
29. A recent detailed review of the study by Myers (*25*), carried out jointly with us, produced no large change in the data published earlier and used here.
30. J. P. Lanly and M. Gillis, *Provisional Results of the Food and Agriculture Organization–United Nations Environment Program Tropical Forest Resources Assessment Project: Tropical America* (FAO, Rome, 1980).
31. "Changes in agriculture in 26 developing nations, 1948 to 1963" (Foreign Agricultural Economic Report 27, Economic Research Service, Department of Agriculture, Washington, D.C., 1965); "Economic progress of agriculture in developing nations, 1950 through 1968" (Foreign Agricultural Economic Report 59, Economic Research Service, Department of Agriculture, Washington, D.C., 1970).
32. Although the Myers data (*25*) provide the upper limit used in this study, use of the data provided by the *Global 2000 Report to the President* [see (*27*)] would produce an appreciably higher estimate.
33. W. Seiler and P. J. Crutzen, *Climatic Change* **2**, 207 (1980).
34. K. Openshaw, *New Sci.* **61**, 271 (1974).
35. S. Brown has reported that some tropical forests may recover in 20 years [in *Carbon Dioxide Effects Research, and Assessment Program: The Role of Tropical Forests in the World Carbon Cycle*, S. Brown, A. E. Lugo, B. Liegel, Eds. (Department of Energy, Washington, D.C., 1980), p. 118].
36. See J. S. Olson (*21*). Our estimate, derived as outlined in the text, suggests a biotic pool for a comparable period (1975 to 1980) of about 595×10^{15} g. S. Brown and A. E. Lugo [in *The Role of Tropical Forests in the World Carbon Cycle*, S. Brown, A. E. Lugo, B. Liegel, Eds. (Department of Energy, Washington, D.C., 1980), p. 65] suggested that the standing stock of carbon in tropical forests is substantially less than assumed by R. H. Whittaker and G. E. Likens (*18*).
37. M. Stuiver [*Science* **199**, 253 (1978)] presented an analysis that seemed to suggest that isotopic ratios could be used to infer the relative magnitude of the release from both fossil fuels and the biota. R. D. Freyer [*Tellus* **31**, 124 (1979)] seems to have confirmed the strength of this approach, while Stuiver has suggested recently (personal communication) that it has been weakened by new discoveries of sources of variation in the $^{13}C/^{12}C$ record.
38. Certain studies of eastern North America have shown that forests are or have been expanding during this century [(*7*); T. V. Armentano and C. W. Ralston, *Can. J. For. Res.* **10**, 53 (1980); H. R. Delcourt and W. F. Harris, *Science* **210**, 321 (1980)]. These analyses appear to be confirmed in this work (Fig. 5), which shows the forests of eastern North America and Europe to be absorbing of carbon in the net from the atmosphere. The analysis of Armentano and Ralston, however, which seems to show that the Northern Hemisphere supports forests that are expanding in the net and are therefore absorbing carbon from the atmosphere, remains questionable.
39. S. Brown and A. E. Lugo, "The role of the terrestrial biota in the global CO_2 cycle" (symposium preprint, American Chemical Society, Washington, D.C., 1981); A. E. Lugo and S. Brown, paper presented at the Bloomington Symposium, American Institute of Biological Sciences, Bloomington, Ind., 1981; *Unasylva* **32**, 8 (1980); R. P. Detwiler, C. A. S. Hall, P. Bogdonoff, C. McVoy, S. Tartowski, paper presented at the International Symposium on Energy and Ecological Modeling, Louisville, Ky., 1981; see also T. V. Armentano and C. W. Ralston (*38*).
40. G. M. Woodwell *et al.*, "Report of the Woods Hole Conference on the biotic contributions to the global carbon cycle" (Marine Biological Laboratory, Woods Hole, Mass., 1982). The total amount of carbon in the boreal tundra is about 500×10^{15} g. If the accumulation occurred over 10,000 years, the rate was 0.05×10^{15} g/year.
41. R. Bacastow and C. D. Keeling, in *Carbon and the Biosphere*, G. M. Woodwell and E. V. Pecan, Eds. [Atomic Energy Commission, Washington, D.C., 1973), p. 86; L. Machta, *ibid.*, p. 21; see also H. Oescheger *et al.* (*12*); U. Siegenthaler and H. Oeschger, *Science* **199**, 388 (1978); see also W. S. Broecker *et al.* (*12*).
42. The subject has been reviewed by E. Lemon [in *The Fate of Fossil Fuel CO_2 in the Oceans*, N. R. Anderson and A. Malahoff, Eds. (Plenum, New York, 1977), p. 97] and by B. R. Strain, Ed. ["Report of the workshop on anticipated plant responses to the global carbon dioxide enrichment (Duke University, Durham, N.C., 1978)]. Both reports show that the effects of CO_2 fertilization are limited. A more recent study by R. M. Gifford [*Search* **10**, 316 (1979); *Aust. J. Plant Physiol.* **6**, 367 (1979)] suggests that plants under moisture stress respond more powerfully to increased CO_2. P. J. Kramer [*BioScience* **31**, 29 (1980)] has provided an evaluation of the factors that might result in enhanced storage. He came to the conclusion that the enhancement is improbable. See also J. Goudriaan and D. L. Ajtay, in *The Global Carbon Cycle*, B. Bolin, E. J. Degens, S. Kempe, P. Ketner, Eds. (SCOPE 13, Wiley, New York, 1979), p. 237.
43. These observations are based on well-known principles of plant physiology, summarized in the following: A. H. Fitter and R. H. Hay, *Environmental Physiology of Plants* (Academic Press, New York, 1981), p. 173; W. Lancher, *Physiological Plant Ecology* (Springer-Verlag, New York, ed. 2, 1980), p. 111; W. D. Billings, J. O. Luken, D. A. Montemsen, K. M. Peterson, *Oecologia (Berlin)* **53**, 7 (1982).
44. *FAO Forestry Paper No. 30, Tropical Forest Resources* (FAO, Rome, 1982). The *Global 2000 Report to the President* [see (*27*)] would give a still higher estimate.
45. Supported by NSF grant DEB-79-23329 and by the Ecosystems Center, Marine Biological Laboratory, Woods Hole, Mass.