A Simple Model for Analysis of the Role of Terrestrial Ecosystems in The Global Carbon Budget[1]

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ABSTRACT

A simple biological model has been developed to calculate the annual net exchange of carbon between terrestrial ecosystems and the atmosphere. Carbon is released to the atmosphere as harvested wood and soil organic matter are oxidized following either of two major disturbances: the harvest of forests or the transformation of natural systems to agriculture. Carbon is transferred back onto the land from the atmosphere as harvested and abandoned agricultural lands return to forests or other natural systems. In the model the world's vegetation and soils are divided into 10 geographic regions of potentially 12 different ecosystems each. Annual rates of forest harvest and land clearing in each of these systems are used to initiate the changes of carbon on land that follow disturbances. The changes on land, in turn, determine the rate of change of carbon in the atmosphere.

We present the results of a simulation based on information currently available on land-use statistics for the period 1860 to 1970. We also present six alternative scenarios designed to examine a range of variability in the data. The initial results are consistent with other analyses that have estimated the quantity of carbon released from natural systems as a result of forest harvest or land transformation. The model is simple and yet offers a systematic and direct approach to estimating the exchange of carbon between terrestrial ecosystems and the atmosphere. It accounts for the carbon in wood products, vegetation, and soil, and it includes the time lags inherent in biological oxidation and succession. The model is easily modified to incorporate new data to test different assumptions, and it is predictive to the extent that harvest and clearing rates can be predicted.

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INTRODUCTION

Most models of the global carbon budget contain the assumption that terrestrial ecosystems are accumulating CO_2 from the atmosphere. (See among others Machta 1973, Bacastow and Keeling 1973, Oeschger et al. 1975.) The assumption is derived from evidence that the oceans appear to be slow in mixing and therefore slow in reaching equilibrium with the atmosphere. More recent analyses of the role of vegetation and soils in the global carbon cycle suggest that terrestrial ecosystems, considered globally, are not accumulating carbon from the atmosphere but are an additional source of CO_2 (Adams et al. 1977, Bolin 1977, Woodwell and Houghton 1977, Stuiver 1978, Woodwell et al. 1978, Wong 1978). If so, the models that treat land vegetation and soils as increasing pools of carbon may be in error, and intepretations of the world carbon cycle based on these models may be incorrect.

Two separate processes have the potential for determining the net exchange of carbon between terrestrial ecosystems and the atmosphere. First, there is the possibility that the increase in the concentration of CO_2 in air results in an increase in the rate of fixation of carbon through photosynthesis and that this increase results in a net storage of carbon on land. Second, the transformation of forest and grasslands to other types of vegetation, the harvest of forests, and their subsequent recovery through succession, all change the amount of carbon stored on land.

The first of these processes has been defined as the biotic growth factor or β-factor by Bacastow and Keeling (1973). Although a CO_2 enhancement of growth is known to occur in greenhouses, the only current evidence for a global effect is indirect. The CO_2 produced from fossil fuel combustion that accumulates according to current estimates neither in the atmosphere nor in the oceans has been assumed to be accumulating in terrestrial systems. There is no evidence from natural communities that the atmospheric CO_2 increase has resulted in an accumulation of carbon on land (for a discussion see Goudrian and Ajtay 1979). The topic is important, but we do not treat it in detail in this paper.

The second process is the disturbance of natural communities. This process includes the transformation of natural systems into agriculture or other impoverished vegetations, the harvest of forests, and the regrowth of forests through succession. Information on rates of these disturbances is available and can be used to calculate the net flow of carbon between terrestrial ecosystems and the atmosphere. The disturbances are important because of the large amounts of carbon affected (Woodwell et el. 1978, Ajtay et al. 1979, Bramryd 1979, Hampicke 1979).

The work we report here offers one means of calculating this flow for the earth's major terrestrial ecosystems and for the world as a whole. We describe the types of information required, sources we have used, and a model we have developed to estimate changes in the pools of carbon on land. We have used the atmosphere as a passive reservoir that supplies or receives carbon as the terrestrial pools change in size. Although we have not included the oceans in these analyses, we have constructed the model to be linked easily with global models such as those of Bacastow and Keeling (1973), Oeschger *et al.* (1975), and Björkström (1979). We report here results of simulations based on data on vegetation, soils, and land use for the period 1860 to 1970. This period was chosen so that the results could be compared with the results of carbon isotope studies and with the results of other carbon models based on fossil fuel consumption from the start of the industrial revolution. We also present the results of alternative scenarios selected to examine the effects of different assumptions in use of the data. The analysis includes harvest and regrowth of forests and transformations of natural ecosystems to other types of vegetation including agriculture. The analysis does not include any direct estimate of the potential stimulation of photosynthesis by increased CO_2.

METHODS

BACKGROUND

Prediction of the future CO_2 content of the atmosphere requires an understanding not only of the processes that transfer carbon directly to the atmosphere, but also of the controls on these processes and the interactions between the cycles of carbon and other major nutrients. Models play an importand part in understanding complex interactions, and modelling of the global carbon cycle will eventually require information that is both ecologically detailed and geographically specific. While processes such as photosynthesis, litterfall, translocation, and decomposition determine the transfers of carbon in ecosystems, and hence exchanges with the atmosphere, there is no possibility of obtaining immediately data of the type required for modelling specific processes in many different types of terrestrial ecosystems. A simpler approach is necessary.

Forest cutting releases CO_2 to the atmosphere either rapidly, as wood is burned, or more slowly as wood products are oxidized through decay. Carbon dioxide is also released through decay of organic matter in soils. Part of the release of carbon from soil is from the decay of plants killed but not removed at the time of harvest, and part is from the decomposition of soil organic matter stimulated by the disturbance. The same losses of carbon from decaying vegetation and soil organic matter accompany the transformation of natural systems to agriculture. As defined here agricultural land includes tilled land only and not pasture. After forest harvest and after abandonment of agriculture the normal processes of succession lead to storage of carbon in the plants and soil of the developing forest.

THE MODEL

The need for modelling lies in the complexities of the computations. The data from diverse sources around the world are often reported by individual countries; sometimes they are given in regional summaries. The model has been designed to treat the world as ten regions (Figure 1). The vegetation and associated soils of each region have been divided into twelve ecosystems: boreal forest, tundra and alpine meadow, temperate evergreen forest, temperate deciduous forest, temperate wood-

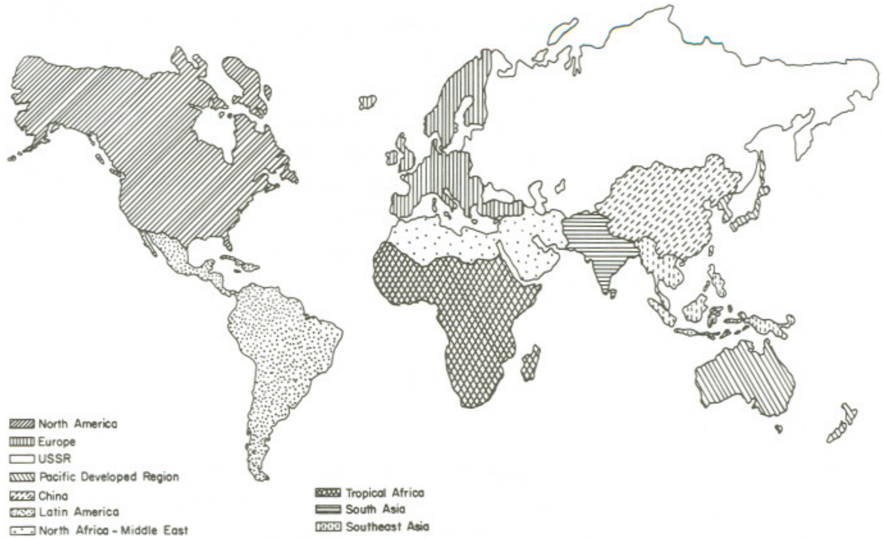

Figure 1: Divisions of the world for the terrestrial carbon model.

land, temperate grassland, tropical moist forest, tropical seasonal forest, tropical woodland, tropical grassland, swamps and marshes, and desert. Thus, there are potentially (10×12) 120 different ecological systems in the assumed natural steady state with respect to carbon, in agriculture, in the process of being cut or cleared, or in some stage of succession. In practice, since no region has all ecosystems, there are far fewer; moreover, many ecosystems do not vary greatly among regions.

To calculate the movement of carbon associated with land transformation and forest harvest, we have developed a set of curves that describe the response of the carbon in vegetation and soil to disturbance in each ecosystem. For simplicity we have used a sequence of linear functions. Examples of the curves for vegetation and soil following harvest of a forest appear in Figures 2 and 3.

The harvest removes a proportion of the aboveground biomass. The biomass of living vegetation on site immediately after harvest is represented by the low point on the curve in Figure 2; vegetation killed and left on site as slash or dead roots is transferred as carbon to the soil and appears in the soil curve as the peak immediately after cutting (Figure 3). The vegetation regrows, accumulating carbon, until it reaches a new steady state.

The pool of carbon in the soil returns to a steady state through a two-phase transformation. The first phase is a decrease in soil carbon with release to the atmosphere through oxidation. The second phase reverses this process; litterfall from the recovering vegetation remove carbon from the atmosphere and increase the soil carbon until equilibrium is attained.

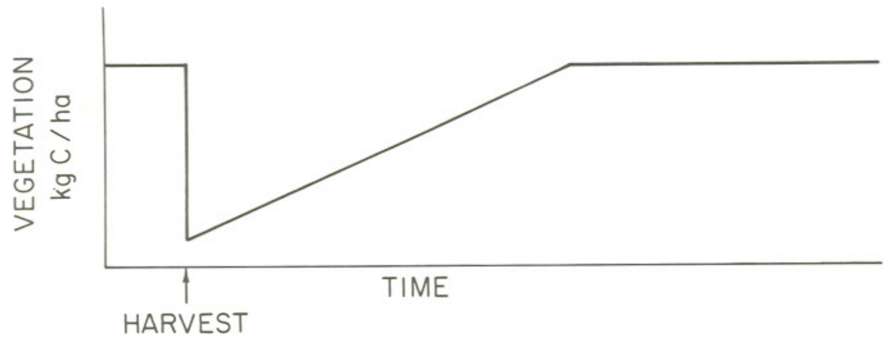

Figure 2: The carbon content of living vegetation in forests following harvest.

The curves used to describe changes in carbon pools following land-clearing for agriculture (Figures 4 and 5) are somewhat different from the curves used for harvested forests. In Figure 4 the low point represents carbon in crops. The soils of cleared lands (Figure 5) have an initial input of dead plant material, and this material decays over time. In most regions of the world continued tilling of the land oxidizes soil organic material and gradually reduces the carbon content. Unless the cleared land is abandoned and allowed to return to its original state, the clearing of land results in a net carbon release to the atmosphere both from vegetation and soils.

At the time of forest harvest or land clearing the harvested biomass is divided in this version of the model into four decay pools with residence times of 1, 10, 100, and 1000 years corresponding to different uses of wood. The division among these pools varies with time (historical changes in use of wood products), region, and ecosystem. The decay of these pools transfers carbon to the atmosphere. The rates are constant fractions of the amount of carbon in each of the pools.

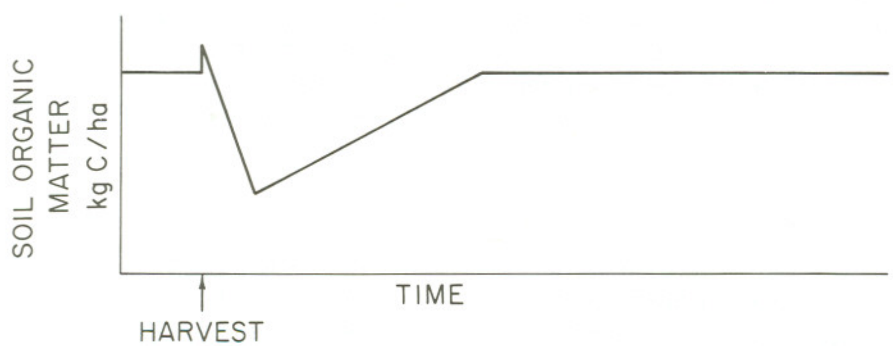

Figure 3: The carbon content of soils in forests following harvest.

Figure 4: The carbon content of living vegetation in an ecosystem following conversion to agriculture (tilled).

The vegetation and soil curves and the decay pools are used in the model to calculate the net exchange of carbon between terrestrial ecosystems and the atmosphere. Systems for which there is no net annual exchange are described by lines with zero slope. The area harvested or cleared year-by-year is assigned to the initial point on the appropriate curves. In subsequent years these areas move along the response curves. The areas either withdraw carbon from the atmospheric pool as vegetation and soil organic matter accumulate, or release carbon to the atmosphere as agricultural soils are tilled and soil organic matter is oxidized. The net exchange of carbon in any year is the sum of the derivatives of the vegetation and soil curves. Each year class of the curves is multiplied by the land area in that class. To this sum must be added the carbon released in any year from oxidation of the four decay pools.

The advantages of this kind of model are several. First, the model is simple. Complex physiological or ecological processes need not be modelled explicitly; they are included implicitly in the shapes of the response curves. Second, the data required to construct these curves for different ecosystems are available in the literature. Third, the shape of a curve for any ecosystem is directly measurable in the field. Once curves for the vegetation and soil have been established, the information required to calculate the net exchange of carbon with the atmosphere is the area of forest cut, the amount of land cleared, and the allocation of harvested biomass to the decay pools.

THE DATA

We have obtained cutting rates from records of wood removal given country by country (Zon and Sparhawk 1923, FAO 1965, 1978). For the United States, Canada, Europe, and land that is now in the Soviet Union we have been able to obtain data on wood production from 1913 to present (e.g. FAO European Timber Statistics 1913–1950). For the United States we have data and estimates for lumber and fuelwood production as far back as colonial times (U.S. Bureau of Census, Historical Statistics of the United States: Colonial Times to 1970; Reynolds and Pierson 1942; Clawson 1979). For those regions of the world where we do not have information prior to 1923 we have estimated rates of cutting back to 1860, assuming a gradually increasing rate that parallels growth in population from 1860 to 1923. The method is obviously crude; it is fortunate that those regions with the highest rates of cutting are also those with the most accessible and detailed records.

Figure 6 illustrates the procedure used to estimate from wood volumes the areas cut and the carbon assigned to live vegetation, harvest pools and soil. The figure also shows how this information is incorporated into the model. Wood production values (in cubic meters) have been converted to metric tons tons/m^3 of carbon assuming a mean wood density of 0.2 tons/m^3 wood. The harvest products themselves have been divided into pools of carbon that oxidize at rates of 1, 10, 100, 1000 years, corresponding approximately to fuelwood, paper, and a range of lumber products. From regional statistics of wood production we have calculated the area harvested on the basis of timber volume per hectare as reported by Weck and Wiebecke (1961, in Persson 1974).

The parameters used to define the curves have been obtained from a number of sources. Standing crops of carbon in the vegetation of different ecosystems have been taken from Whittaker and Likens (1973), standing stocks of carbon in soils from Schlesinger (1977). We have assumed for the present that secondary forests have the same biomass and soil carbon as undisturbed forests. The times required for regrowth have been estimated from a large number of studies in different ecosystems. The linear regrowth rates used in the curves are clearly a simplification but seem appropriate for the analyses here. Watt (1947) and Bormann and Likens (1978) have described succession for some temperate zone forests. Studies and reviews of tropical forest recovery by Kira and Shidei (1967), Kellman (1970), Snedaker (1970), and Fontaine *et al.* (1978) have characterized the biomass accumulation rates in those systems.

Figure 5: The carbon content of soils in an ecosystem following conversion to agriculture (tilled).

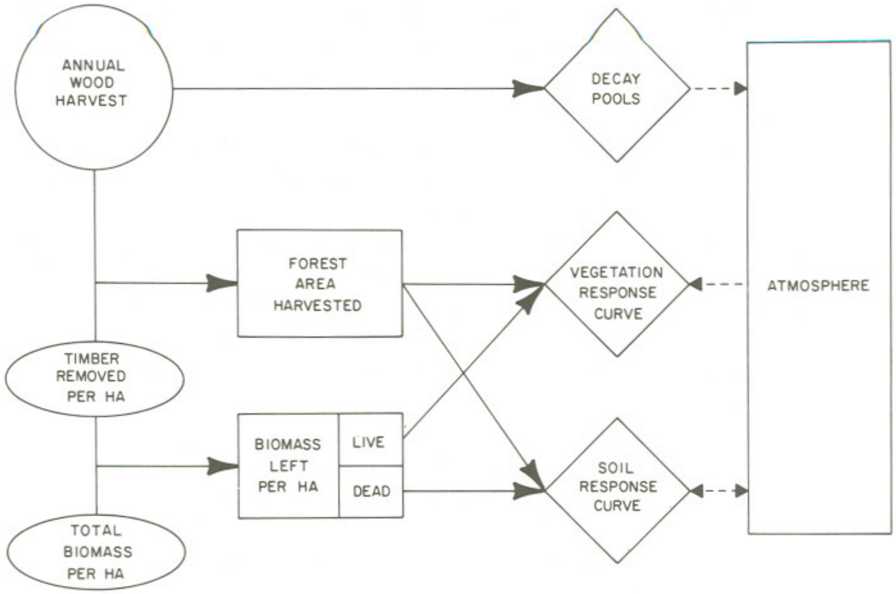

Figure 6: The procedure used to calculate the effect that forest harvest has on the transfers of global carbon.

The responses of soils to tree harvest have been described for tropical systems, for example, by Cunningham (1963) and Young (1976), and for temperate forests by Covington (1977) and Aber *et al.* (1978). Changes in the organic carbon of soils during agriculture have been studied extensively in temperate zone systems (See for example Giddens 1957, Puhr and Worzella 1952, Haas *et al.* 1957, Salte *et al.* 1941, Lee and Bray 1949.). Nye and Greenland (1960) have provided a comprehensive review of the effects of land-use change on the carbon content of tropical soils.

Two additional parameters calculated for the curves were based on the difference between total standing crops and wood harvest (Fig. 6). We have assumed that the harvest is equal to the timber volumes given by Weck and Wiebecke (1961). The difference between the amount of wood harvested and the amount of carbon prior to harvest (Whittaker and Likens 1973) is the carbon left behind in leaves, branches, bark, roots, and in the commercially unexploited species. The fact that the wood removed from a site is different from the total amount of biomass present is one reason why recent estimates of biotic carbon release have varied to such a large extent (Ralston 1979, Woodwell *et al.* 1979). In the analyses we report here all of the biomass left on a site has been assumed to be dead; it is transferred to the soil carbon pool and ultimately to the atmosphere through decay.

The procedure (Figure 7) we have used to calculate the effect that agricultural clearing has on the transfers of carbon was similar to the one described above for forest harvest, but we have used different curves (Figures 4 and 5) and have started with a different source of data. Rates of land clearing for different regions were obtained from Revelle and Munk (1977, Table 10.3). The rates were based on direct inventories of agricultural areas between 1950 and 1970. The ratios of agricultural land to population size for these years were then applied to population estimates for the period 1860 to 1950 to obtain rates of agricultural expansion for the years prior to 1950. We have supplemented the data with reports of agricultural area for land in the Soviet Union (U.S. Department of Agriculture, 1874; FAO, 1950; and FAO, 1976). The biomass originally contained in the natural systems before conversion to agriculture was assigned to decay pools of different residence times and to the associated soil carbon system (Figure 7).

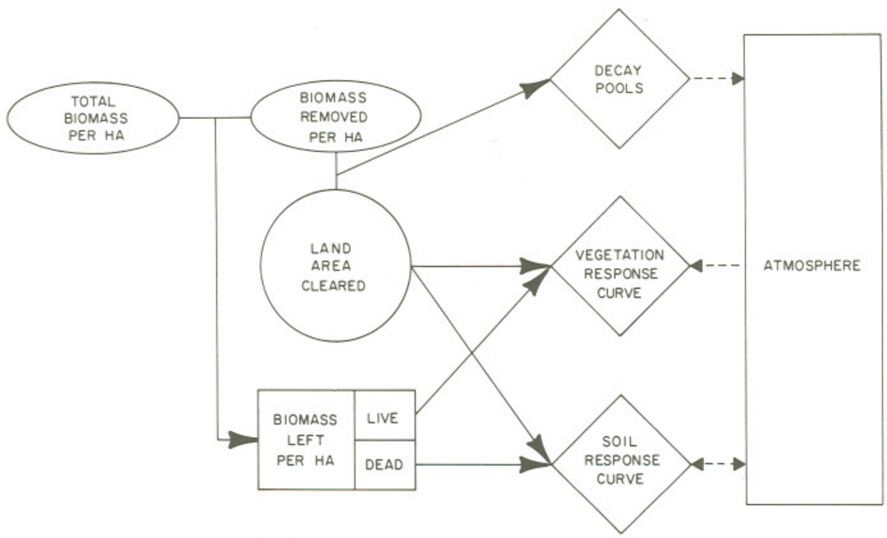

Figure 7: The procedure used to calculate the effect that land transformation to agriculture has on the transfers of global carbon.

RESULTS

We report here our initial experience with the use of this model based on the information in our current data set. The information is incomplete. We have made estimates and used judgement where the specific data were not available or where different sources gave inconsistent values. The best estimate is the reference scenario. We have used other scenarios to explore the effects of a range of variation in the data.

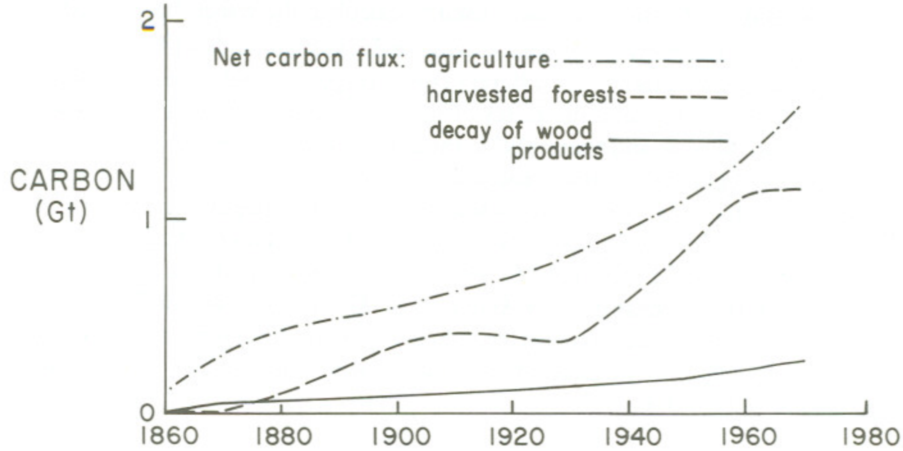

Figure 8: The components of the net terrestrial carbon flux to the atmosphere in the reference scenario.

REFERENCE SCENARIO

The annual net exchange of carbon between terrestrial systems and the atmosphere from 1860 to 1970 is shown in Figure 8. Simulations were begun in 1760 to allow 100 years for the time lags associated with the regrowth of harvested systems. The net annual exchange is the result of exchanges with forests, agricultural lands, and decay pools (Fig. 8). The net exchange between the atmosphere and forest or agricultural lands results from burning of slash and fuelwood, oxidation of soil organic matter, including the slash not immediately burned, and the regrowth of forest vegetation. Carbon released from the longer-term decay pools (10, 100, and 1000−year residence times) has not been included in either the forest or agricultural exchanges because these pools are wood products that were removed from the site.

The curves of Figure 8 show that the net effect of forest harvest and land transformation to agriculture has been to release carbon to the atmosphere every year between 1860 and 1970. At no time during this interval have terrestrial systems withdrawn carbon from the atmosphere on a global scale. The continual release of carbon is due in part to ever-increasing forest harvest rates and to oxidation of soil organic matter and slash following harvest and land transformation.

The curves in Figure 8 also show that the clearing of land for agriculture and the land's subsequent tillage results in a greater release of carbon than the harvest of forests. This relationship is true despite the fact that during most of the 111 years the area of forests harvested was about twice the land area cleared for agriculture (Figure 9). Furthermore, only some of the land transformed to agriculture was forested land; some of it was grassland or other types of vegetation with less carbon than forests. If the effect of the regrowth of vegetation is removed and the soil responses are consisered alone, harvest of forests has released more carbon from soils than has the transformation of natural systems into agriculture (Figure 10).

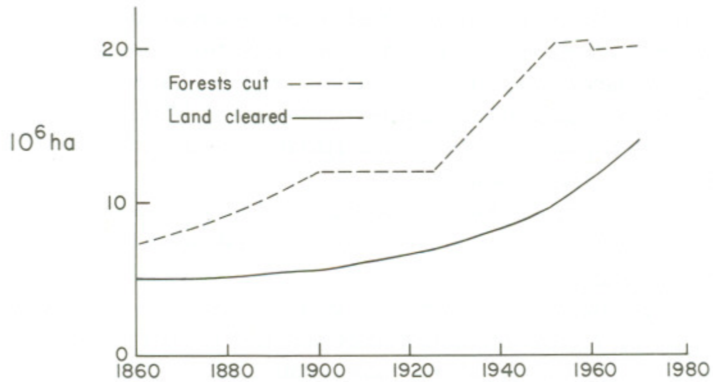

Figure 9: The total area of forest cut annually for wood products and the total area of land cleared for agriculture in the reference scenario.

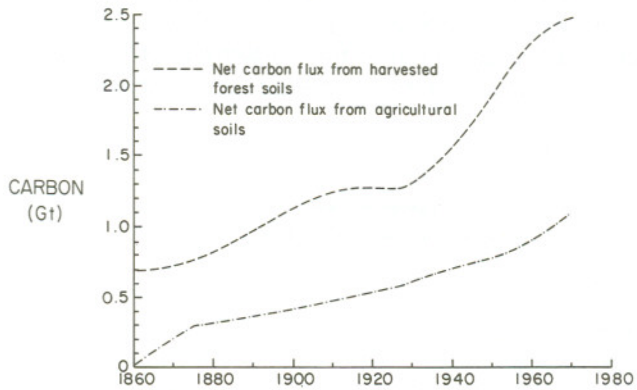

Figure 10: The annual, net carbon flux from harvested forest soils and from agricultural soils.

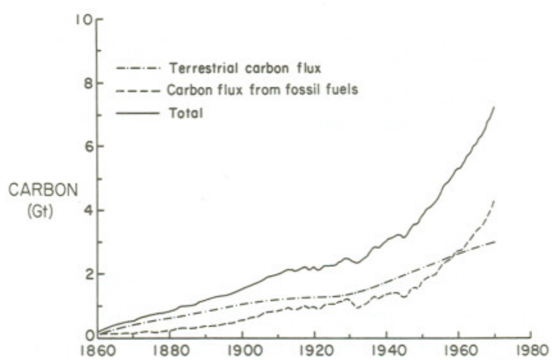

Figure 11: The annual, net, terrestrial carbon flux to the atmosphere in the reference scenario compared to the carbon flux from fossil fuel consumption and cement production (Keeling 1973; Rotty 1973, 1974). The top curve is the sum of the two curves.

The net release of carbon from terrestrial systems as a result of forest harvest and transformation was large in comparison to the release from fossil fuel combustion and cement production during the same period (Figure 11). Between 1860 and 1970 the cumulative net release from vegetation and soils was 148 Gt carbon, while the release from industrial CO_2 production was 116 Gt (Keeling 1973; Rotty 1973, 1974).

The reference scenario shows:

1) Accelerating rates of harvest and transformation of natural systems have caused a continuous net transfer from these systems to the atmosphere between 1860 and 1970.
2) The net release of carbon from lands cleared for agriculture has been greater than the net release from forests harvested and allowed to regrow.
3) The time course of harvest and transformation rates is important because the time for recovery is long.
4) A complete determination of the net exchange of carbon between terrestrial ecosystems and the atmosphere requires an analysis not only of living vegetation but of soil carbon and wood products as well.
5) The net annual release of carbon from disturbance of vegetation and soils has until recently been greater than the release from the combustion of fossil fuels.

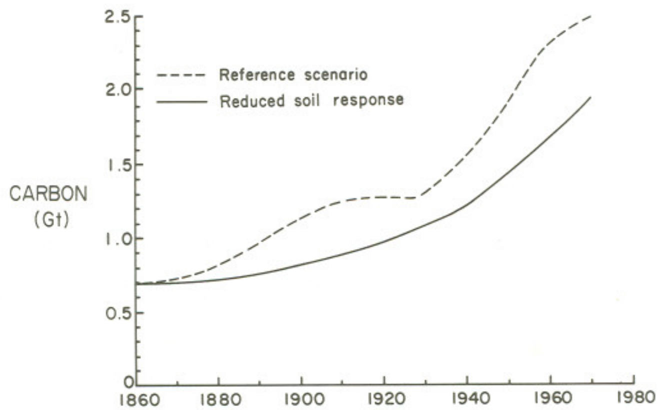

Figure 12: The net carbon flux from forest soils following harvest in the reference scenario compared with the net carbon flux from forest soils following harvest in the reduced soil response scenario.

OTHER SCENARIOS

One important question that cannot be addressed with the reference scenario alone is how sensitive are the results to uncertainties in the data. In this section we begin to test this question by use of additional scenarios. The tests fall into two categories: those that alter the shape of the response curves and those that change the rates of harvest and clearing. Table 1 gives the net transfer of terrestrial carbon to the atmosphere in 1970 for each of the tests.

1. *Reduced Soil Response.* In the first two tests we have examined the effect of changes in the soil curve. In the first test no soil carbon but only the dead vegetation left on the site at the time of harvest was allowed to decay. The soil carbon was not reduced below its original level as it was in the reference scenario (Figure 3). In other words the "dip" in the soil curve of the reference run was replaced with a single linear slope to describe the decay of dead vegetaion not removed during harvest. Under this assumption there was neither the large annual release of carbon from soil in the early years of recovery nor the accumulation of carbon in later years. The curves for agriculture were not altered. The result was a reduction in the amount of carbon released from harvested systems. The difference in the response of forest soils between this scenario and the reference scenario is shown in Figure 12. Overall, less carbon was released; however, the soil carbon of the harvested system became a continuously increasing source of CO_2. So significant was the difference that the exchanges in the forest were less important than the releases from the decay pools until about 1930 (Figure 13). In 1970 the forest exchange was about 50 percent smaller than the exchange in the reference run (Table 1).

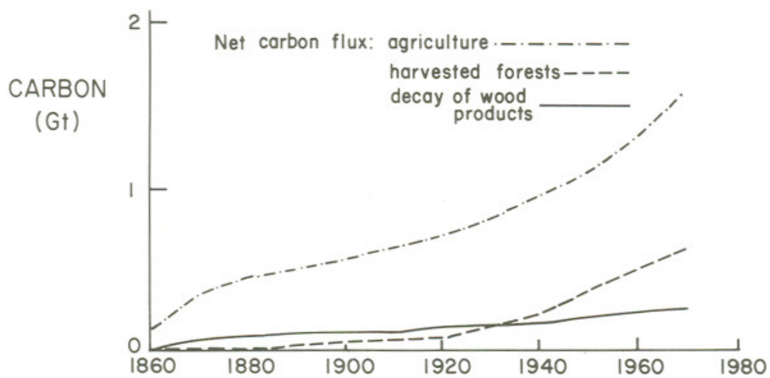

Figure 13: The components of the net terrestrial carbon flux to the atmosphere under the assumption that soil carbon levels do not fall below their pre-cut levels following forest harvest.

2. *Exaggerated Soil Response.* The possibility remains that the rate of release of carbon from disturbed soils is greater than that assumed in the reference scenario. In this test we have modified the soil response curve to give a residual carbon content equal to 1/2 of the reference value (Figure 3). Since we have held the level of carbon in undisturbed and regrown systems constant, and have not changed the soil recovery times, the regrowth curves for the soil have become steeper. Thus, there is a more precipitous drop in soil carbon in the first few years following a cut, but thereafter a more rapid build-up. The curve describing soil changes during agricultural clearing was not modified from the reference scenario.

The result was that the exchanges of carbon from forests became larger (Figure 14). During certain years the annual rate of carbon release from forests exceeded the rate given in the reference scenario by more than 50%. In 1970 the flux was 25%

Table 1. Summary of net carbon transfers (Gt).

Scenarios/ Compartments	Reference	Reduced Soil Response	Exaggerated Soil Response	Greater Harvests from Reference Area	Greater Harvests from Greater Area	Agricultural Expansion Doubled	Agricultural Expansion Halved
Total net loss of carbon from terrestrial eco-systems during the period 1860–1970	148	114	169	143	168	235	104
Net loss of carbon from terrestrial ecosystems and decay pools in 1970	3.0	2.4	3.3	2.8	3.0	4.7	2.2
Net loss of carbon from harvested forest ecosystems in 1970	1.2	0.6	1.5	0.9	1.2	1.2	1.2
Net loss of carbon from agricultural systems in 1970	1.2	1.2	1.5	1.5	1.5	3.1	0.8
Net loss of carbon from 10, 100, and 1000–year decay pools in 1970	0.3	0.3	0.3	0.4	0.3	0.4	0.2

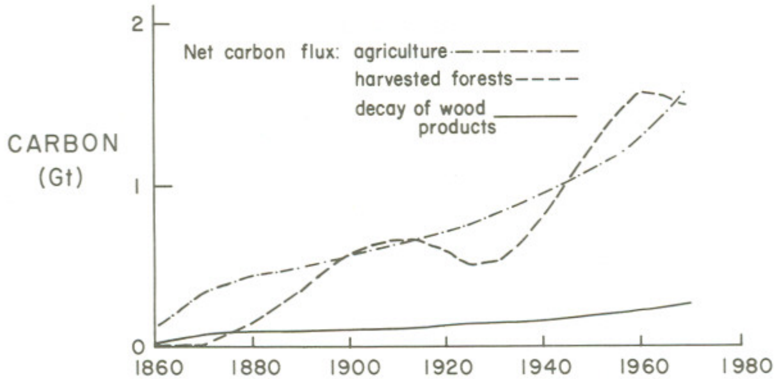

Figure 14: The components of the net terrestrial carbon flux to the atmosphere under the assumption that there is a large decrease in soil carbon after forest harvest.

greater. The reason for the greater net release of carbon in this scenario is that with an increasing rate of harvest a proportionately greater fraction of recovering forests are in the early stages of succession, where the release of carbon from soils has now been increased.

3. *Greater Harvest from Same Area.* Several authors have pointed out that tallies of roundwood production reported to the FAO are often too low (Openshaw, 1978; Earl, 1979; Palmedo *et al.,* 1979). FAO statistics include wood products that flow through commercial markets; they do not include harvest of fuelwood by individuals or small companies not licensed by the local governments. Fuelwood, which accounts for 80% of wood removal in the Third World (Eckholm 1979), seems most seriously underestimated. Openshaw (1979), for example, estimated that the world use of fuelwood in 1976 was $305 \cdot 10^6$ m^3 out of a total wood use of $480 \cdot 10^6$ m^3. The corresponding values from FAO are $118 \cdot 10^6$ m^3 and $252 \cdot 10^6$ m^3. In the third and fourth tests we have increased the annual harvest of wood products above the data used as reference by a factor of two.

Doubling the amount of wood removed from forests can be simulated by either doubling the forest area harvested or doubling the volume of wood removed from the same area. In the third scenario the area harvested was the same as in the reference run but the harvest itself was doubled. The result was only slightly different from the reference results. The increase in the release of carbon from the oxidizing harvested products was balanced by a decrease in the releases of carbon from the forests themselves (Table 1). The net loss of carbon from terrestrial systems in 1970 was within 4% of the reference value.

4. *Greater Harvest from a Greater Area.* In the fourth scenario we assumed that the timber harvested per hectare remained at the reference values (Weck and Wiebecke 1961), and that twice as much area was harvested. The increased area of harvest worldwide can be seen by comparing the area harvested in this scenario (Figure 15) with the reference (Figure 9). The abrupt reductions in harvest rates around 1918 and

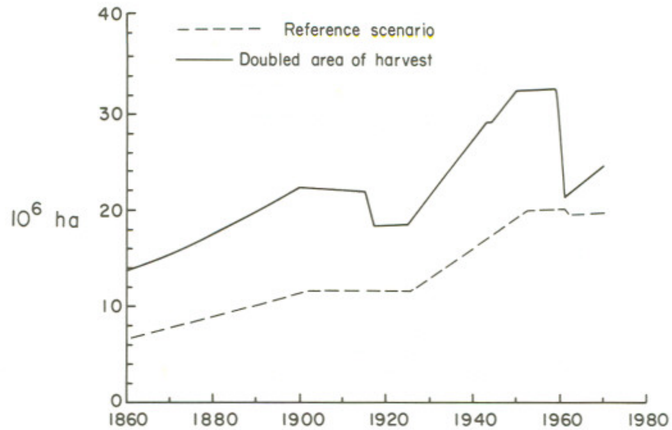

Figure 15: Total area of forest cut annually in the greater harvest−greater area scenario.

1960 (Figure 15) did not reflect the doubled rates but resulted from the fact that under the high rates of cutting in this scenario all of the available forests had already been harvested in some regions of the world. In this version of the model the harvest of regrowing forests was not permitted, and the specified area of harvest could not be applied.

The effect of the abrupt changes in annual rates of harvest on the flux of carbon is shown in Figure 16. The release of carbon from harvested forests reflected the rates of harvest but contained a time lag that smoothed the curve. After 1960, for example, harvest rates were increasing again while the release of carbon from harvested forests was decreasing. While it cannot be seen from these results, if the rate of harvest were to become constant worldwide, the net release of carbon from forests would decrease to zero as a new steady state was attained. If the rates were to decrease worldwide, the net exchange between forests and the atmosphere would be from the atmosphere as regrowing forests accumulated carbon.

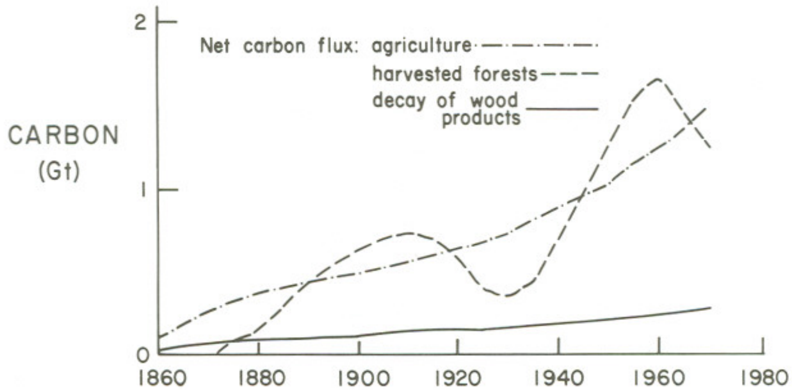

Figure 16: The components of the net terrestrial carbon flux to the atmosphere where a doubling of the forest products harvested is achieved by doubling the area cut.

5. *Rate of Agricultural Expansion Doubled.* For the final two scenarios, the rates of land transformation to agriculture were doubled and halved relative to the reference scenario. At the doubled rate the release of carbon from agricultural systems gave generally the same shape as it had in the reference run but was elevated by a factor of two as might be expected. The doubled clearing rate had the effect of raising the annual exchange between terrestrial systems and the atmosphere by approximately 50% throughout the 111-year period. Table 1 shows that this scenario gave the greatest release of terrestrial carbon both in 1970 (4.7 Gt) and overall (235 Gt).

6. *Rate of Agricultural Expansion Halved.* The net transfer of carbon from lands cleared for agriculture under this scenario was one-half the magnitude of the value in the reference run. The harvest of forests and the clearing of land for agriculture released approximately equal amounts of carbon until 1940. The total annual carbon flux to the atmosphere in 1970 was 2.2 Gt in this scenario, the smallest net release of any scenario (Table 1). The total released over 111 years was also the smallest, 104 Gt. The fact that variations in the rate of agricultural expansion gave the largest and smallest carbon releases of all the tests presented here reaffirms the importance of land transformation to agriculture in the global carbon cycle.

DISCUSSION AND CONCLUSIONS

The model we have developed and tested here is simple and yet incorporates the well-known patterns of change in terrestrial ecosystems that occur following disturbance. The model is also predictive to the extent that future rates of forest harvest and land clearing can be predicted. Finally, the model is flexible: it is easily modified to incorporate new data and to examine different assumptions about the data and about the model's own structure and operation.

The most important test, however, is whether the model is accurate and useful. The structure of the model (its vegetation and soil curves) is sufficiently simple to be easily examined. Validation depends on development of independent tests of the entire procedure including both details of the model's structure and the data used.

Our analyses to date have been based on data that are far from comprehensive. The most satisfactory contemporary data will probably come from satellite studies of changes in the vegetation of the earth as a whole. Meanwhile,we are encouraged that based upon our initial data set and six different sensitivity tests the range of net releases of carbon from vegetation and soils in 1970 was 2.2 to 4.7 Gt, and these values are similar to rates reported by others (Table 2). In fact, all previous estimates of net global carbon flux based on worldwide forestry and agricultural statistics have indicated that terrestrial ecosystems as a whole release carbon, although specific regions may show a net accumulation of carbon (Armentano and Hett 1979, and a regional analysis of the reference scenario presented here).

The estimates that appear in Table 2 are not all directly comparable. The values given by Woodwell *et al.* (1978) and Hampicke (1979), for example, include estimates of a β-factor. Other analyses, including this one, do not consider explicitly a β-factor. This analysis includes the exchanges of carbon between the atmosphere

Table 2. Estimates of annual net carbon exchange between terrestrial ecosystems and the atmosphere in or about 1970.
Positive values indicate net terrestrial releases to the atmosphere.

Authors	Gt C yr^{-1}
Woodwell et al. 1978	2 to 18
Hampicke 1979	1.5 to 4.5
Adams et al. 1977	0.4 to 4
Bolin 1977	0.4 to 1.6
Wong 1978	1.9
This analysis	2.2 to 4.7

and land that result from succession and recovery of soils in previously cut systems. It is not enough to consider the net rate of change in the area of natural systems at any time; the historical sequence of forest harvests and recoveries, and the past sequence of disturbance and succession determines the net flux in any region. To the extent that other studies have not incorporated the time lags associated with succession and decay, they have probably overestimated the current net release of carbon from terrestrial systems. Such lags may operate for decades or centuries. The similarity of the values reported here to those reported by other investigators is probably a result of the information that has been available for analysis rather than a result of the methods of analysis. This analysis is more comprehensive than other analyses we have seen and establishes a systematic basis for incorporation of additional data as they become available.

Carbon isotopes have also been used extensively in attempts to isolate the biotic contribution to the atmospheric CO_2 burden. In Table 3 we have summarized these data. Estimates range from about 70 to 200 Gt carbon released over a period of about 100 years or an average of 0.7 to 2 Gt per year. The isotope techniques require considerable refinement, but the total net release reported here of 148 Gt between 1860 and 1970 is consistent with the majority of the estimates based upon isotopic ratios.

Table 3. Estimates of the net release of carbon from terrestrial biota and humus to the atmosphere during the last century based on models using carbon isotope ratios in tree rings.

Author	Interval	Release of carbon from terrestrial biota and humus to atmosphere during interval (Gt)
Stuiver 1978	1850–1950	120
Wagener 1978	1800–1935	170
Freyer 1978	1860–1974	70
Siegenthaler et al. 1978	1860–1974	133–195
Tans 1978	1850–1950	150

Although the similarity of these results to those obtained by other analyses lends credence to the approach, the actual net flux between terrestrial ecosystems and the atmosphere may be outside the range determined by these few scenarios. There is a need to examine additional assumptions and to incorporate far more comprehensive data. Further work must include an analysis of such activities as shifting agriculture, afforestation, the transformation of natural systems to pasture, and the production of charcoal during fires. We must incorporate an analysis of the β-factor in subsequent analyses. The model is easily modified to incorporate these additions and appears to be a valuable research tool.

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