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Changes of Land Biota and Their Importance for the Carbon Cycle

The increase of atmospheric carbon dioxide may partly be due to the expansion of forestry and agriculture.

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It is well established that the carbon dioxide content of the atmosphere is increasing. Observations at the South Pole, on Hawaii (*1*), and in the upper troposphere of the Northern Hemisphere (*2*) are available for almost 20 years. The increase has been about 16 parts per million (ppm)—from 311 ppm in 1957 to 327 ppm in 1975—that is, about 5 percent (*3*). Attempts to estimate the probable increase since the beginning of the industrial revolution have yielded a value between 30 and 35 ppm—more than 10 percent. The major cause of this increase is undoubtedly emission of carbon dioxide into the atmosphere from the combustion of fossil fuels. An accurate compilation of the total output of carbon dioxide from burning fossil fuels and also from the cement industry has been made by Keeling (*4*). Keeling defines the airborne fraction as the ratio of the annual increase of carbon dioxide in the atmosphere to the annual output, which has varied between 20 and 80 percent during the last 20 years, the average being close to 50 percent. A considerable transfer of carbon dioxide therefore must have occurred into other natural reservoirs, and it seems likely that the oceans have played the most important role in this regard (*5*). Increased assimilation by land biota cannot be excluded, however, since it is well established that plants grow faster in atmospheres richer in carbon dioxide. Keeling (*6*) analyzed this question carefully and also concluded that land biota may have served as a sink, but this cannot be proved by direct measurements. It is possible that the slightly more acid seawater now present in the surface layers of the sea due to a net transfer of carbon dioxide into the oceans may have brought some calcium carbonate into solution. The sea may thus have been a more effective sink for carbon dioxide than previously considered. This problem remains unresolved.

Humans are, however, intervening in the carbon cycle in more ways than by burning fossil fuels. Deforestation and the cultivation of land for agricultural purposes are examples of major changes in the land biota that may well have had significant implications for the global carbon cycle. Data on these changes are few, and it is difficult to assess precisely what may have happened during the last decades or centuries. I will therefore limit myself to some rather rough estimates, which will show, however, that these changes imply a significant decrease of the amount of carbon in organic matter on land during the last century. Thus humans have also been adding carbon dioxide to the atmosphere in this way.

As a background, the present (that is, 1975) carbon dioxide concentration in the atmosphere, 327 ppm, corresponds to a carbon content of about 690 $\times$ 10^9 tons. The corresponding figure at the beginning of the industrial revolution has been estimated as 610 to 620 $\times$ 10^9 tons. Thus, the amount of carbon in the atmosphere has probably increased by 70 to 80 $\times$ 10^9 tons. These values should be compared with an accumulated output due to fossil fuel combustion and cement production of about 140 $\times$ 10^9 tons, of which about half has been emitted during the last two decades.

Changes in the World's Forests

In recent years several attempts have been made to assess the net primary production and the total mass of land biota. Table 1 is an extract of a summary presented by Whittaker and Likens (*7*), which is probably the best estimate available so far. The figures refer to the year 1950. For comparison, Bazilevich *et al.* (*8*) give about 50 percent larger figures. I will use the values in Table 1, but keep in mind the uncertainty of the estimates.

Even though dense forests cover only about 30 percent of the land surface, about 90 percent of the living biomass is found there. Any significant change in the amount of carbon in land biota would be observed in the atmosphere if it were not masked by the steady increase due to the emission of carbon dioxide from burning fossil fuels. It has long been realized that significant changes of the land biota may have occurred in the past, but because of lack of data no serious attempts have been made to assess quantitatively what may have happened on a global scale during the last century or two. The area of cultivated land has increased considerably during this time. If 25 percent of this area was previously covered by forests, the extension of agriculture has meant a net return of carbon to the atmosphere of 30 to 55 $\times$ 10^9 tons.

Recent changes in forests may be roughly assessed with the aid of studies of world forest resources by the Food and Agriculture Organization (*9–11*). It is, however, important to realize that estimates of forest resources must not be directly interpreted in terms of the total biomass of the forest or the recorded and projected changes, since these only in-

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Table 1. Net primary production and biomass of land biota (*7*).

Type	Area (10^6 km^2)	Total net production (10^9 ton/year)	Total biomass (10^9 tons)
Tropical rain forest	17.0	15.3	340
Tropical seasonal forest	7.5	5.1	120
Temperate forest, evergreen	5.0	2.9	80
Temperate forest, deciduous	7.0	3.8	95
Boreal forest	12.0	4.3	108
Subtotals (forests)	48.5	31.4	743
Woodland and shrubland, savanna	23.0	6.9	49
Temperate grassland	9.0	2.0	6.3
Tundra and alpine	8.0	0.5	2.4
Desert and semidesert	18.0	0.6	5.4
Extreme desert, rock, ice, sand	24.0	0.04	0.2
Cultivated land	14.0	4.1	7.0
Swamp and marsh	2.0	2.2	13.6
Lake and stream	2.5	0.6	0.02
Totals	149.0	48.3	827

clude amounts of timber and pulp for industrial purposes and, with great uncertainties, production of fuel wood. Thus, for boreal (coniferous) forests the FAO estimate of the gross volume of timber is 110×10^9 cubic meters (*9*), about 50×10^9 tons of carbon, which should be compared with 240×10^9 tons of carbon in the biomass as given in Table 1.

In Europe the area covered by forests has increased slightly from 1950 to 1975, while no significant changes seem to have occurred in the United States during this time. Judging from these studies, the net change of the forests in developed countries (including Canada and the Soviet Union) during the last 20 years is probably less than 1 percent, which is insignificant in the present context. It should be realized, however, that the use of forests in some of these countries has changed considerably during the 20th century. Particularly in Europe, they were previously used extensively for cattle grazing. This was especially the case for deciduous forests, but in Sweden, for example, boreal forests were also used in this way. During the last 50 years this practice has been almost completely abandoned, and the forests have grown more dense. As an example, from the middle of the 1920's until about 1970, the total amount of timber in Swedish forests increased by almost 40 percent (*10*). This does not mean that the total biomass has changed by the same percentage, since with modern forestry more of the primary production in the forests has undoubtedly been timber. It is still likely that a significant increase of the biomass has occurred, but it is impossible to assess it more precisely without a detailed investigation. A 10 percent increase of the biomass of Swedish forests represents an increase of the carbon content by 0.5×10^9 tons. For Europe as a whole this figure might be several times larger. On the other hand, when a virgin forest is subjected to regular exploitation its average biomass decreases, since the forest is harvested before the biomass reaches its maximum. To some extent this effect is counteracted by the prevention of forest fire (which is one mechanism for virgin forest renewal) in exploited forests. I conclude that the changes of forests in developed countries at present do not represent a significant net flux of carbon to or from the atmosphere.

Table 2. Production of wood in 1974 (*9*).

Form	Amount (10^6 m^3)
Logs	800
Pulpwood	340
Pitprops, posts, and so on	200
Fuel wood	1170
Total	2510

Table 3. Summary of present net average annual input of carbon (in the form of carbon dioxide) into the atmosphere and accumulated input since the early 19th century due to human modifications of land biota and soils. The basis for the estimates is presented in the text.

Source	Input (10^9 tons) Present average annual	Input (10^9 tons) Accumulated
Reduction of forests		
Developed countries	0 ± 0.1	45 ± 15 (reduction of forests, total)
Developing countries		
Forestation	−0.3 ± 0.1	
Deforestation	0.8 ± 0.4	
Use of fuel wood	0.3 ± 0.2	
Changes of organic matter in soil	0.3 ± 0.2	24 ± 15
Totals	1.0 ± 0.6	70 ± 30

In developing countries major changes are taking place. Forest plantation has increased rapidly. Persson (*9*) estimates that during the last three decades an area of 0.3 to 0.6×10^6 km^2 has been planted in China and about 0.1×10^6 km^2 has been planted in other developing countries. Some of these forests consist of rapidly growing species, particularly *Eucalyptus* and some pine species. Many of these plantations have been on soils that were not recently covered by forests, and not all of them have been successful. I estimate the net amount of carbon being withdrawn from the atmosphere by these forests by assuming an annual net production of 0.5 kilogram per square meter per year, which yields a value of 0.2 to 0.4×10^9 tons per year.

Simultaneously with this forestation, clearing of natural forests for other uses has proceeded at an accelerating rate, particularly in tropical countries. The main reason for this is the need for additional land for agriculture. Persson (*11*) estimates that about 0.02×10^6 km^2 is cleared every year in Africa, and the corresponding figure for Latin America is 0.06×10^6 km^2 (*12*). For the developing countries as a whole about 0.12×10^6 km^2 of natural forest is cleared and burned every year. It is estimated that the areas of closed forests in the developing countries will have decreased by 20 to 25 percent by the turn of the century if this trend continues. If we assume that all of the biomass in these forests burns (20 kg of carbon per square meter) we arrive at an annual input of 1.5×10^9 tons of carbon into the atmosphere in the form of carbon dioxide. This is likely to be an overestimate, partly because not all of the living biomass burns and partly because some of these areas again become covered by vegetation, although usually not forests.

Finally, we should consider the use of wood for industrial purposes and as fuel. Table 2 shows FAO estimates of the production of wood in 1974 (*9*). Measured in amounts of carbon, this production corresponds to 0.4×10^9 tons of carbon in the form of wood, a considerable part (perhaps half) of which goes into long-lasting structures. The paper produced from pulpwood is mostly burned within a year, rapidly returning the carbon to the atmosphere. The estimated production of fuel wood, equivalent to about 0.5×10^9 tons of carbon, is probably considerably too low. In view of the rapidly increasing population in developing countries, it is likely that cutting of wood for fuel has increased appreciably during the last decades and that the present use exceeds the growth of new trees and bushes in these areas. There may be a net input to the atmosphere of 0.2 to 0.4 × 10^9 tons of carbon annually, because of inadequate forest growth for renewal of fuel wood in the developing countries.

Changes of Organic Matter in the Soil

Estimates of the amount of carbon in the form of organic matter in the soil vary widely. The most recent and perhaps the most accurate is Bohn's (*13*) value, about 3000 × 10^9 tons, which is considerably higher than most previous estimates. Since this carbon pool is larger (perhaps four times larger) than the carbon pool of living land biota, the turnover time of carbon in the soil is much longer. The average residence time of carbon in land biota is about 15 years. More than half of the organic matter produced annually—that is, most of what is contained in leaves, grass, and so on—has a short residence time and is decomposed rapidly in the soil. The average turnover time for organic matter in the soil in steady state is longer in the same proportion as the soil reservoir is larger than the reservoir of living organic matter. Under special circumstances—for example, in peat bogs—the turnover time may be many hundred years. Changes of the carbon content of the soil therefore take place rather slowly.

A considerable part of agricultural land originally consisted of bogs and marshes, which have been drained. In Sweden such land constitutes almost 10 percent of the total land area used for agriculture. Cultivation of such areas represents a change in the rate of decomposition of organic matter. Ploughing brings oxygen deeper into the soil, which previously may even have been anaerobic because of high water table. Estimates from the cultivation of such areas on the island of Gotland in the Baltic Sea yield values as high as 0.5 kg of carbon per square meter per year. A similar process occurs when land previously covered by forests is cleared and used for agriculture. Paul (*14*) has shown that the chernozem soils in Canada have lost about 50 percent of their organic matter during 60 to 75 years of cultivation. For the brown soils this corresponds to 2.5 kg/m^2 and for the black soils 6.5 kg/m^2. A comparison of land used for cattle grazing with a nearby forest in southern Sweden shows 5 and 25 kg of carbon per square meter, respectively, indicating an even more marked change of the organic content of the soil due to human utilization of the land (*15*).

If we assume that 25 to 50 percent of the land cultivated today has lost 2.5 to 6 kg of carbon per square meter since the early 19th century, a total of 10 to 40 × 10^9 tons of carbon has been added to the atmospheric pool during this time. The annual input to the atmosphere today may be similarly assessed as 0.1 to 0.5 × 10^9 tons per year. This problem warrants further consideration.

Discussion

The data compilation presented above is incomplete and a much more detailed review of available information should be made. Nevertheless, it is possible to give some overall limits on the way in which humans are modifying the exchange of carbon dioxide between land biota, soil, and the atmosphere. Table 3 is a summary of the estimates, including rough uncertainties. The accumulated input of carbon to the atmosphere is 50 ± 25 percent of the amount transferred to the atmosphere from fossil fuel combustion, and the present annual input is 10 to 35 percent of the present emission from the use of fossil fuels. Possible compensation through more rapid growth of land biota in other parts of the world due to increasing amounts of carbon dioxide in the atmosphere might reduce these figures somewhat, but it seems unlikely that such compensation would be complete. If nutrients are growth-limiting increased assimilation would be unlikely, but if water supply is the important factor assimilation would proceed more rapidly during periods of moist weather, as the flux of carbon dioxide through the open stomata would be enhanced while evapotranspiration remained unchanged.

Even if our understanding of the magnitude of man's effect on the exchange of carbon between the plants, the soil, and the atmosphere is incomplete, it is interesting to carry the discussion one step further. First, during the last decade the average input of carbon to the atmosphere from fossil fuel combustion has been 4.0 × 10^9 ton/year, of which 2.0 × 10^9 ton/year has remained airborne. The total input due to human activities has thus been 5.0 ± 0.6 × 10^9 ton/year. The airborne fraction has been 40 ± 5 percent, rather than 50 percent as estimated previously. Furthermore, the total accumulated input since the early 19th century has been 210 ± 30 × 10^9 tons. Assuming that the airborne fraction has remained unchanged throughout this period, the amount of carbon in the atmosphere has increased by 90 ± 15 × 10^9 tons; that is, the carbon dioxide concentration has increased by 35 to 50 ppm. The concentration may have been as low as 275 ppm during the early 19th century.

It follows that the oceans must have served as a more effective sink for carbon dioxide than previously considered. This result is difficult to reconcile with present models of the role of the oceans in the carbon cycle, and the problem warrants further study [see also (*16*)].

Attempts to predict the future increase in the carbon dioxide content of the atmosphere have been based on the assumption that the airborne fraction of the net output due to human activities has been about 50 percent during the last 20 years. If, instead, it is 40 ± 5 percent, the future increase might be slower and possible secondary effects such as climatic changes might be delayed, provided depletion of the world's forests is stopped. There are other and more immediate reasons why we need to take great care in dealing with the global ecosystem, but the modifications of the global carbon cycle described here are another and in the long run also an important reason (*17*).

References and Notes

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17. The essence of this article was presented at the Dahlem Workshop on Global Chemical Cycles and Their Alteration by Man, Berlin, November 1976. Similar conclusions were advanced by M. Woodwell and R. A. Houghton and by W. A. Reiners and H. Wright, Jr. The discussions at the workshop revealed that a detailed and thorough study of all possible changes of carbon in organic form, not least in the oceans, is urgently needed to obtain more accurate estimates of fluxes in the carbon cycle. Even though the available data are meager it was generally concluded that man's direct interference with land vegetation, particularly forests, most likely decreases the amount of carbon in land plants and the soil.