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The Carbon Dioxide Question

Human activities are clearly increasing the carbon dioxide content of the earth's atmosphere. The question is: Will enough carbon be stored in forests and the ocean to avert a major change in climate?

by George M. Woodwell

In the century and a quarter since 1850 human activities have increased the amount of carbon dioxide in the atmosphere of the earth from 290 parts per million or less to slightly more than 330 parts per million. Perhaps a fourth of the total increase has come within the past decade. By the year 2020, if present trends continue, the amount of carbon dioxide in the atmosphere could approach twice the current value. Until recently the increase was commonly attributed to the burning of fossil fuels. Now there is evidence that it may be due in equal degree to another source: the worldwide destruction of forests.

Although carbon dioxide is only a trace gas in the atmosphere of the earth, present at a concentration of about .03 percent by volume, it plays a possibly critical role in controlling the climate of the earth because it absorbs radiant energy at infrared wavelengths. Heat trapped in this way has a large potential for altering the world climate substantially. And quite apart from possible effects on the climate, the carbon dioxide in the atmosphere also plays a critical role as the source of the carbon that is fixed in photosynthesis by green plants and therefore provides the basis for all plant and animal life.

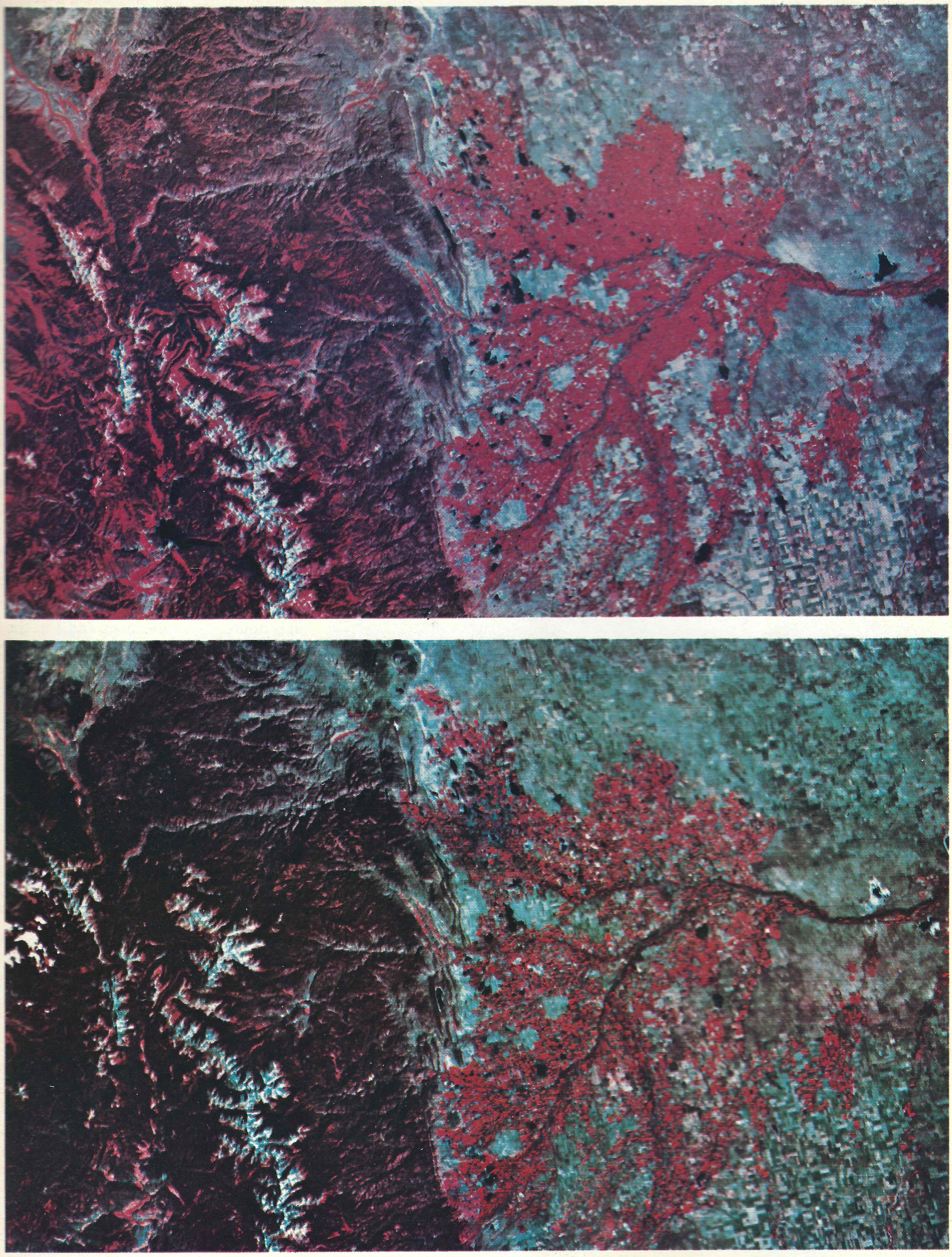
Mankind therefore faces a historic dilemma. The human activities that are increasing the carbon dioxide content of the atmosphere promise to bring a general warming of the climate over the next several decades. Although one cannot be certain of how much the climate will change, or of the precise mechanisms that will be involved, the results of a steadily rising amount of carbon dioxide in the atmosphere will almost certainly be destabilizing. An increase in the average world temperatures will probably enlarge the area of the arid zones and significantly affect agricultural production.

The other horn of the dilemma is that the kinds of corrective action that might be contemplated would surely have effects that would be equally destabilizing. The most obvious corrective action would be a major reduction in the consumption of fossil fuels. Equally important would be measures to lower the rate at which the forests of the world are being reduced or cleared by logging, by the expansion of agricultural and grazing lands, by toxification and by other consequences of industrial development. A major effort to change the balance of land use between agriculture and forest, in addition to an effort to restrict the burning of fossil fuels, would so upset established patterns of social and economic development as to be equivalent to the drastic changes in the human condition that a warming of the climate might lead to.

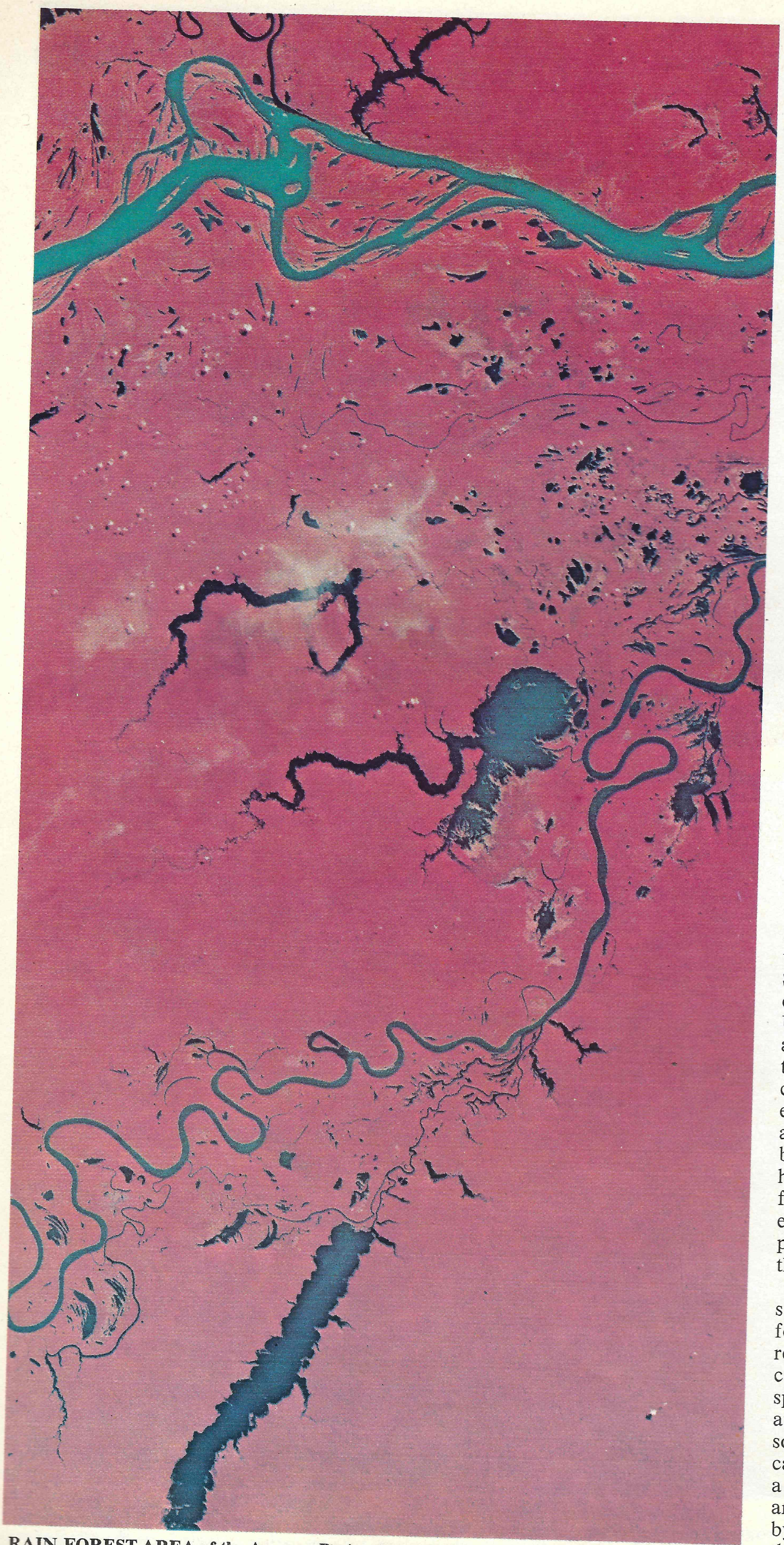
Although the carbon dioxide problem has been with us for more than a century, unambiguous data on changes in the carbon dioxide content of the atmosphere have been available only since 1958. In that year Charles D. Keeling of the Scripps Institution of Oceanography established a continuous carbon dioxide monitoring station on the volcano Mauna Loa on the island of Hawaii. Mauna Loa was chosen because it offered an opportunity to study the carbon dioxide content of the mixed air of the troposphere, or lower atmosphere, in the middle latitudes. The records now available from Mauna Loa and other stations show two clear patterns. First, there has been throughout the period since 1958 a regular upward trend in the carbon dioxide content of the atmosphere. The amount of the increase at Mauna Loa has been about .8 part per million per year, although there have been obvious variations in the rate of increase. Second, there is a systematic oscillation in the carbon dioxide content of the atmosphere correlated with the seasons. The carbon dioxide content rises to a peak in late winter, usually April in the Northern Hemisphere, and falls to a minimum at the end of the northern summer, in late September or October. The data from Mauna Loa are the longest and most accurate continuous record of carbon dioxide concentration ever made anywhere in the world.

Records of carbon dioxide concentration have been kept for various periods at the South Pole, in Australia, at Point Barrow in Alaska, on Long Island in New York and at other locations. Investigators in the U.S., Sweden, Australia and elsewhere have also sampled the atmosphere extensively from airplanes. The data all show a winter-summer oscillation with a minimum in late summer and a maximum in late winter. The oscillation follows the seasons of each hemisphere. The data also show a more or less continuous increase in the carbon dioxide content of the atmosphere, with the amount varying with time and place between about .5 part and 1.5 parts per million annually.

The seasonal change in atmospheric carbon dioxide reflects one of the most important factors affecting the atmosphere: the metabolism of the biota, or the totality of living matter. The seasonal change in carbon dioxide concentration in the atmosphere is correlated with the "pulse" of photosynthesis that occurs during the summer in middle latitudes of both hemispheres. Recently it has been recognized that the primary cause of the seasonal change is most probably the pulse of photosynthesis in forests of the middle latitudes. The emphasis is on the forests because they are extensive



SUMMER AND FALL Landsat satellite images of an area along the eastern edge of the Rockies near Boulder, Colo., show the annual "pulse" of carbon dioxide fixation characteristic of the temperate zones. In this type of imagery the green of vegetation comes out red. In the top image, made in August, the intense red of the area to the right of the mountains at left reflects a peak of photosynthetic activity, in which plants take up carbon dioxide from the atmosphere to build themselves. In the bottom image, made in October, red has substantially faded, reflecting a diminution of the photosynthetic activity. In this area the activity is that of both forest and crop plants.



RAIN-FOREST AREA of the Amazon Basin of northwestern Brazil that appears in this Landsat image is almost uniformly red, reflecting the intense year-round photosynthetic activity that is characteristic of tropical rain forests. Natural forest communities fix more carbon per unit area than most agricultural cropland. The area of such forests, however, is being reduced.

in area, conduct more photosynthesis worldwide than any other type of vegetation and have the potential for storing carbon in quantities that are sufficiently large to affect the carbon dioxide content of the atmosphere.

The variation in the amplitude of the difference between the winter concentration of carbon dioxide and the late-summer concentration is consistent with this hypothesis. The difference ranges from about five parts per million at Mauna Loa to more than 15 parts per million in central Long Island. The difference drops toward the Tropics, where the seasonal pulse of metabolism is either less pronounced or absent; the difference is also less at higher elevations at all latitudes. The amplitude is substantially less in the Southern Hemisphere, apparently because the smaller continental land mass limits the area of forests. The clear conclusion is that the forests of the earth have a pronounced influence on the short-term carbon dioxide content of the atmosphere.

The cause of the long-term increase in the carbon dioxide content of the air, an increase of 10 to 15 percent since 1850, has usually been ascribed to the accelerating release of carbon dioxide through the combustion of fossil fuels. Recent analyses have thrown this assumption into doubt. My colleagues and I at the Ecosystems Center of the Marine Biological Laboratory in Woods Hole, Mass., in collaboration with R. H. Whittaker and Gene E. Likens of Cornell University, W. A. Reiners of Dartmouth College and C. C. Delwiche of the University of California at Davis, have shown that there is probably a substantial additional release from the biota. Similar findings have been published by other workers, notably Bert Bolin of the University of Stockholm and J. R. Adams and his colleagues at Rice University. The release from the biota has been chiefly through the destruction of forests and the oxidation of humus. The assumption that the increase in the carbon dioxide content of the atmosphere has been a consequence of burning fossil fuels, without regard to possible changes in the biota, has led to what now appears to be a serious miscalculation of the world carbon budget.

The difficulty has arisen from the assumption that the biota has been a sink for atmospheric carbon dioxide when in reality it has probably been a source of carbon dioxide released to the atmosphere. This probable error means that at the moment it is not possible to resolve major questions about the world carbon budget. If the biota has not been a sink for atmospheric carbon dioxide, and if the absorption of carbon dioxide by the oceans of the world is no greater than we have thought, then the amount of carbon dioxide in the atmosphere should be increasing even faster than the observations show. Obviously the estimates are wrong. But where does the error lie?

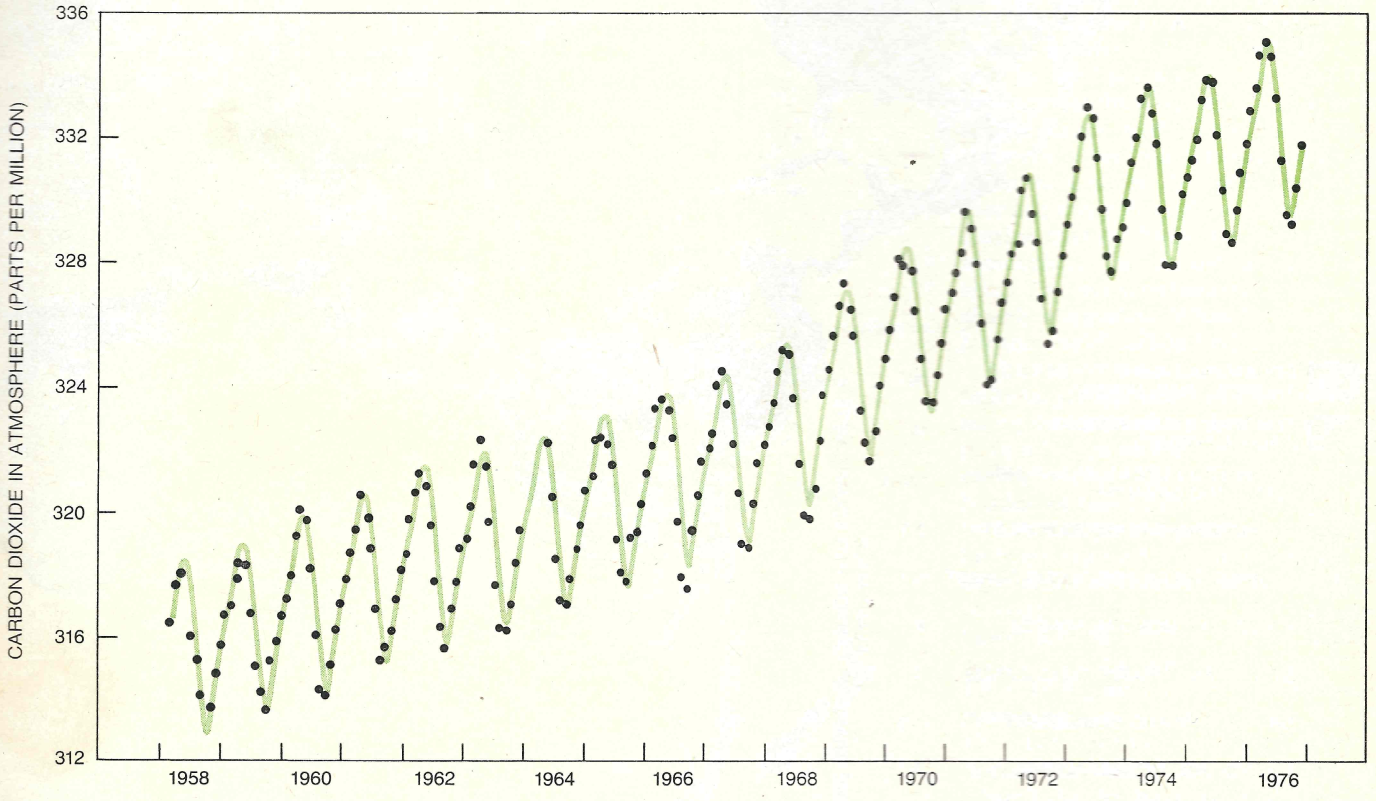
The issue can be seen more clearly by comparing the magnitudes of the pools that are more or less continuously exchanging carbon with one another. The atmosphere holds at present about 700×10^{15} grams of carbon in the form of carbon dioxide, which is continuously being exchanged with the biota and with the surface waters of the ocean. The amount of carbon held in the total worldwide biota is about 800×10^{15} grams, or somewhat more than is held in the atmosphere. A still larger pool of carbon, variously estimated at between $1,000 \times 10^{15}$ and $3,000 \times 10^{15}$ grams, is held in the organic matter of the soil, mainly humus and peat. The harvest of the forests, the extension of agriculture onto soils that contain large amounts of organic matter and the destruction of wetlands all speed the decay of humus, which is transformed into carbon dioxide, water and heat. The carbon dioxide released enters the atmospheric pool.

Although these three pools of carbon in continuous interaction are all roughly the same size, the total amount of carbon held in the oceans is much larger. The largest part of the carbon is in the form of dissolved carbon dioxide, which is a part of the carbonate-bicarbonate system. The total in this pool approaches $40,000 \times 10^{15}$ grams when the waters of the great oceanic basins are included. On a time scale measured in thousands of years the carbon dioxide content of the atmosphere may well be determined by the equilibrium established with the inorganic carbon of the deep ocean. The rate of exchange between the atmosphere and the ocean as a whole, however, is low. The most rapid exchanges are between the atmosphere and the mixed surface layer, roughly the top 100 meters above the colder abyssal waters. The surface layer contains about 600×10^{15} grams of inorganic carbon. The second-largest reservoir in the ocean is in the form of dissolved organic matter (the "humus" of the ocean), which seems to be everywhere about one part per million and may total as much as $3,000 \times 10^{15}$ grams in the oceans as a whole.

The deep waters of the ocean vastly exceed in volume the waters of the mixed layer and hold by far the largest pool of carbon that is in exchange with the atmosphere: from $35,000 \times 10^{15}$ to $38,000 \times 10^{15}$ grams. (Excluded from this pool is the carbon in the carbonaceous sediments, which contain a far larger amount.) The capacity of the abyssal regions for absorbing carbon is virtually unlimited. The problem is that the carbon appears to move from the atmosphere through the mixed layer of the ocean into the oceanic depths very slowly.

When one tries to construct a flow chart showing the net transport of carbon from one pool to another, one finds that the available estimates vary widely in quality. The most accurately known figures are for the carbon dioxide released by the worldwide combustion of fossil fuels, currently about 5×10^{15} grams of carbon per year, and the increase in the carbon dioxide content of the air, equivalent to about 2.3×10^{15} grams of carbon per year. That leaves 2.7×10^{15} grams of fossil-fuel carbon to be removed by some combination of terrestrial and oceanic processes. Let us assume for the moment that the terrestrial biota represents a stable pool of carbon, neither augmenting nor reducing the amount of carbon dioxide in the atmosphere. In that case (which I shall argue is unlikely) the ocean must provide the sink for 2.7×10^{15} grams of carbon per year. Is that rate of removal supported by the evidence?

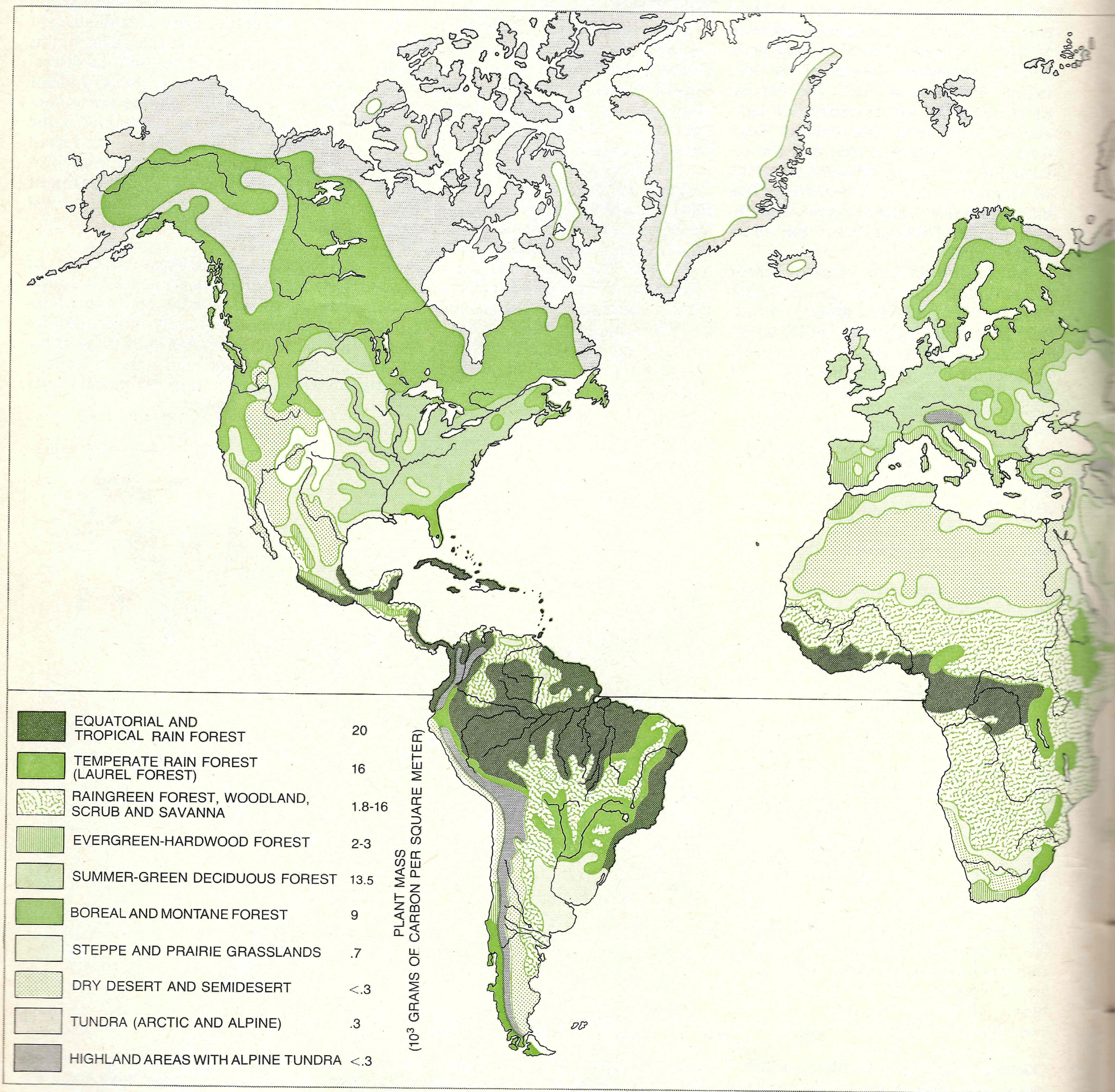
According to the best estimates of chemical oceanographers, it is difficult to explain how the ocean could absorb that much annually. Their analyses are based on a detailed knowledge of the amount of carbon held in the carbonate-bicarbonate system of the surface layer



TREND IN ATMOSPHERIC CARBON DIOXIDE has been measured since 1958 at the Mauna Loa Observatory on the island of Hawaii by Charles D. Keeling of the Scripps Institution of Oceanography. The dots indicate the monthly average concentration of carbon dioxide. The seasonal oscillations are caused by the removal of carbon dioxide by photosynthesis during the growing season in the Northern Hemisphere and the subsequent release during the fall and winter months. The Mauna Loa measurements and those made elsewhere show that the average carbon dioxide content of the atmosphere has risen more than 5 percent since 1958. Rate of increase has varied from year to year from causes not yet known. Current rate is one part per million per year, equivalent to 2.3×10^{15} grams of carbon.

combined with carefully constructed models of the mechanisms of mixing in the oceans. The radioactive isotopes carbon 14 and tritium (hydrogen 3), both produced in large quantities by the atomic bomb tests of the 1950's and early 1960's, have been exploited as tracers to examine the rates at which water of the mixed layer is exchanged with the water of the oceanic depths. The studies seem to show that the mixing rate is very low indeed. The transfer of carbon from the atmosphere through the surface layer and into abyssal waters, according to some calculations, is unlikely to exceed 2.5×10^{15} grams per year. In sum, according to these studies, the oceans seem to be barely adequate as a sink for the difference between the 5×10^{15} grams per year of carbon currently being released into the atmosphere by the burning of fossil fuels and the 2.3×10^{15} grams that the atmosphere actually retains.

This balance of flows has to be completely reexamined if the biotic pool of carbon, instead of either expanding or being in net balance with the carbon in the atmosphere, is actually a net source of atmospheric carbon dioxide. Whittaker and Likens have recently provided a tabulation of current information about the size of various segments of the biota. Their work shows that the largest pools of carbon in the biota are in forests. It also shows that the largest amount of net photosynthesis is on land, not in the ocean as had been assumed previously on the basis of earlier guesses about the rates of net primary production in the oceans. (Net primary production is the net amount of fixed carbon, or



CARBON STORED IN PLANTS is distributed as is shown in this world map based on the work of H. Brockmann Jerosch. The total amount of carbon stored in terrestrial biomass is about 830×10^{15} grams. In comparison the carbon in the total oceanic biomass is negligible: less than 2×10^{15} grams. About 40 percent of all plant carbon is stored in the tropical rain forests. Another 14 percent is held

organic matter, left from photosynthesis after the needs of the plant for respiration have been met. It is the organic matter available for the growth of the plant and is ultimately available for storage or for consumer organisms such as animals or organisms of decay.)

Perhaps the most significant finding of the Whittaker-Likens study is that the tropical rain forests, with their big trees, represent the largest single pool of carbon in the biota and also have the highest total net primary production. This observation emphasizes the importance of the tropical forests in the earth's carbon budget. If these and other forests are harvested rapidly and the stored carbon is released, they have the potential for contributing significantly to the amount of carbon dioxide in the atmosphere. Conversely, if deforested lands are allowed to become forested again, the forests will absorb some of the carbon dioxide from the atmosphere, retarding the rate of increase.

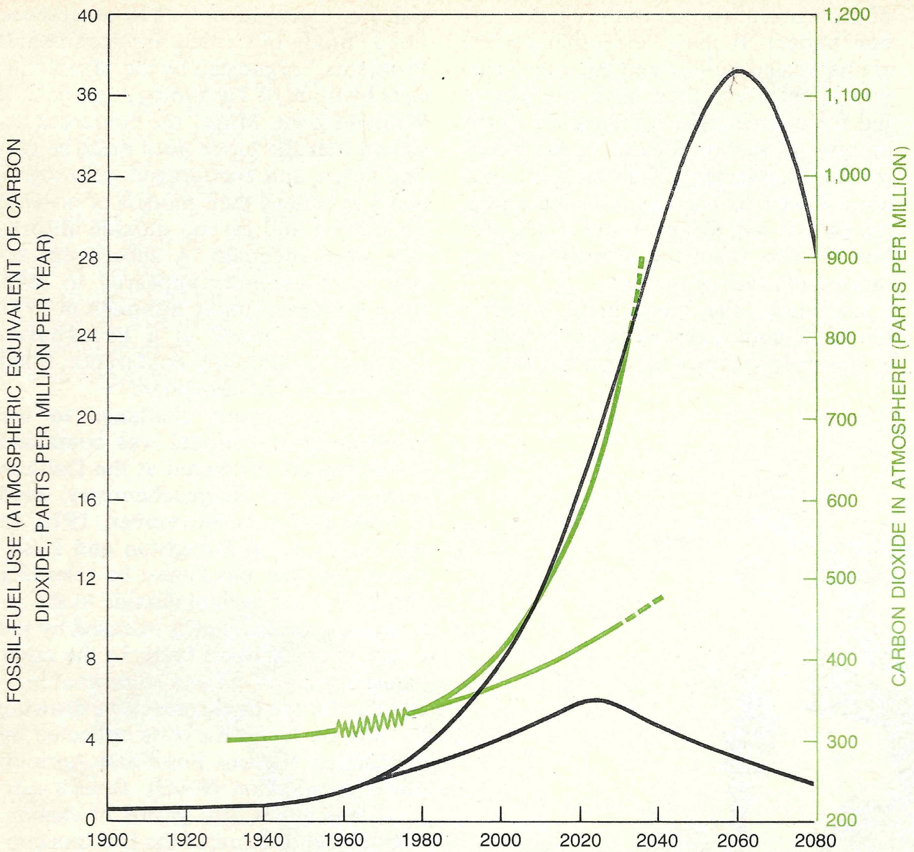
Curiously, the question of whether the biotic pool is getting larger or smaller has only recently become controversial. For example, at a 1970 conference titled "Study of Critical Environmental Problems," organized by the Massachusetts Institute of Technology and held in Williamstown, Mass., the conferees assumed that the biotic pool must be getting larger and encouraged oceanographers to believe their models of oceanic circulation and carbon dioxide absorption were adequate. A subsequent series of conferences appeared to reinforce this assumption, although in 1972 doubts were raised at a Brookhaven National Laboratory conference titled "Carbon and the Biosphere."

The first serious challenge to the oceanographers' model was contained in two papers presented at the Dahlem Conference on Biogeochemistry, held in West Berlin in November, 1976. In one paper R. A. Houghton and I estimated that the biota may be releasing about as much carbon dioxide to the atmosphere annually as is released by the combustion of fossil fuels. In the other paper Bolin arrived at a somewhat lower value for the biotic release by drawing on data on forest harvests collected by the United Nations Food and Agriculture Organization (FAO). Bolin's estimate was about 10^{15} grams of carbon. The subject dominated the Dahlem conference, stimulating much discussion.

The possibility of a significant release of carbon dioxide from the biota also dominated two subsequent conferences, one arranged by the Department of Energy (formerly the Energy Research and Development Administration) last March in Miami Beach and the other held in April at Ratzeburg in West Germany under the auspices of the Scientific Committee on Problems of the Environment of the International Council of Scientific Unions. Recent papers in *Science* and other journals support the conclusion that the biota is a net source of atmospheric carbon dioxide and not a sink. The oceanographers' models are clearly in question. What does this mean for the world carbon budget?

The answer is far from clear. Substantially larger quantities of carbon are entering the atmosphere than are stored in it. In addition to the 5×10^{15} grams of carbon released annually from the combustion of fossil fuels, another 4×10^{15} to 8×10^{15} grams, possibly more, may be being released currently through the destruction of forests and the accelerated oxidation of humus. Of this combined amount, 9×10^{15} to 13×10^{15} grams of carbon per year, only 2.3×10^{15} grams accumulate in the atmosphere. The remainder, 7×10^{15} to 11×10^{15} grams, perhaps more, is stored somewhere on the earth. But where? As we have seen, the present models of oceanic uptake provide for the removal of less than 3×10^{15} grams of carbon per year. Oceanographers are now reviewing their assumptions to see if they have overlooked mechanisms

in tropical seasonal forests. Forests at all latitudes hold nearly 90 percent of all the carbon stored in the world's ecosystems, both terrestrial and marine. Author believes reduction in the area of forests has contributed significantly to increase of carbon dioxide in the atmosphere.



PROJECTIONS OF FOSSIL-FUEL CONSUMPTION (*black curves*) **and carbon dioxide content of the atmosphere** (*color*) **are shown for minimum and maximum plausible rates of increase. The fuel-consumption rates are taken from a recent study done at the Oak Ridge National Laboratory. The minimum projection assumes an annual increase of 2 percent per year until 2025, followed by a symmetrical decrease. The maximum projection assumes a growth rate of 4.3 percent per year until the rate is limited by the depletion of resources in the middle of the next century. The uncertainty of such predictions makes estimates of the future carbon dioxide content of the atmosphere extremely risky. The uncertainty is greatly aggravated by the newly recognized possibility that the destruction of forests may also be releasing large amounts of carbon dioxide to the atmosphere. The sawtooth part of the curve represents the Mauna Loa measurements that were begun in 1958. At present the fossil fuel burned each year releases to the atmosphere an amount of carbon dioxide equivalent to about two parts per million. About half of that amount of carbon dioxide is actually retained in the atmosphere.**

that would be able to sequester additional amounts of carbon.

Because the issue is so important those who are familiar with terrestrial ecosystems are closely examining their own data, particularly the data covering changes in forest mass. How certain can we be that terrestrial communities are indeed a net source and not a sink? The problem has been addressed in several ways in recent months. The data are not as good as one might hope, but they seem compelling to those who are familiar with them.

The analysis is based first on knowledge of the relative magnitudes of the pools of carbon held within the biota and on the net primary production for each of the major plant communities on the earth. For example, the Whittaker-Likens study shows that tropical rain forests hold about 42 percent of all the carbon locked up in terrestrial vegetation and account for about 32 percent of the total net primary production. Forested areas of all kinds—tropical, temperate and boreal—hold 90 percent of all the carbon held in vegetation and contribute more than 60 percent of the net primary production. The only other large single contributor to the net primary production is the savannas, or grasslands, which account for about 12 percent of it and for only about 3 percent of the standing mass of carbon. All the cultivated land on the earth accounts for about 8 percent of the total net primary production and for less than 1 percent of the standing mass of carbon. The Whittaker-Likens estimates lie about midway between the extremes of other analyses that were carried out under the direction of P. Duvigneaud of the University of Brussels at the Ratzeburg conference. Since the various studies all confirm the importance of forests, particularly the tropical forests, it is essential to establish whether or not these ecosystems are changing in size and, if they are, at what rate.

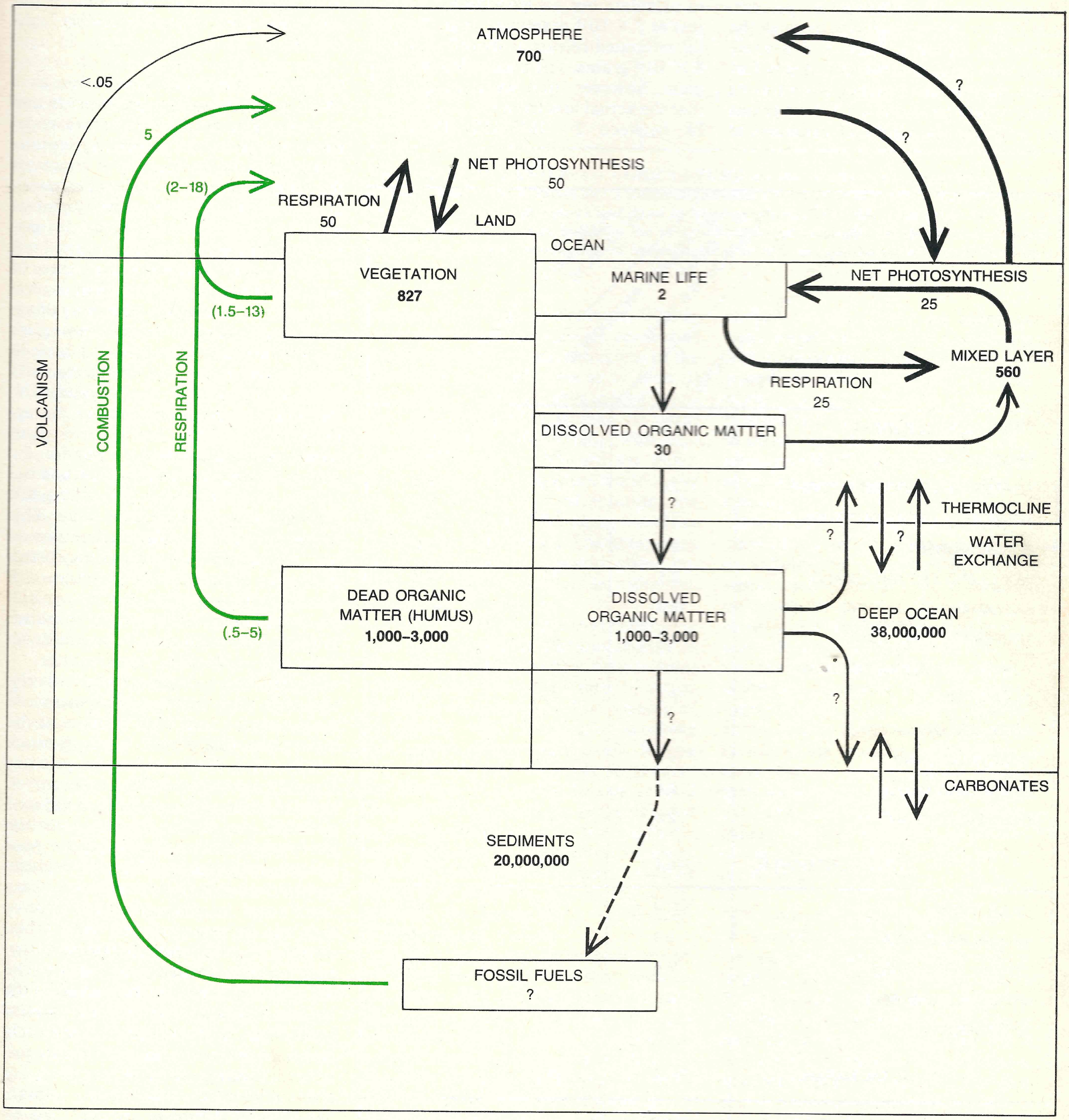
The data are scarce. We have the experience of Henry C. Darby, a British geographer, who in 1954 published an appraisal of the changes in the forest vegetation of Europe spanning the millennium from A.D. 900 to 1900. In that period the forest cover of western Europe was reduced from about 90 percent to about 20 percent. A similar change took place earlier in the lands of the Mediterranean, particularly the Levant. This great reduction in forest area released a quantity of carbon that was a significant fraction of the total previously held in the atmosphere. It is reasonable to assume that since 1900 continued industrialization and population growth have resulted in similar changes in the forests elsewhere.

Timothy Wood and Daniel B. Botkin of the Ecosystems Center at Woods Hole recently conducted a study of the changes in the forest area of New England over the period since the arrival of European settlers. They found that up to 1900 there was a continuous reduction in the total standing crop of forests but that since then there has been a period of recovery owing to the abandonment of agriculture and the expansion of forests into the former agricultural land. The recovery, however, has not resulted in a pool of carbon equivalent to that of the original forests. The forests have been harvested regularly and have never reached the stature or extent of the original ones; the standing crop of carbon today is no more than half the original one. The newest data indicate that the increase in the forested area has now ended, probably because of a renewed expansion of agriculture and an intensified harvest of trees.

The Wood-Botkin study shows that in a Temperate Zone forest that was allowed to recover from intensive harvest the storage of carbon amounted to 3 or 4 percent per year of the net primary production over the entire period of recovery, about 70 years. If a similar fraction of the net primary production of other Temperate Zone forests were stored and an equal additional quantity were stored in humus, the amount of carbon accumulated in all the Temperate Zone forests of the earth would come to about $.5 \times 10^{15}$ grams per year. The experience with New England forests suggests the regrowth of forests in the temperate zones probably does not at present provide a large sink for atmospheric carbon dioxide.

Meanwhile there has been a continuous expansion of agriculture into other forested lands, a continuous harvesting of primary forests elsewhere and a general toxification of the earth as a result of human activities. The most conspicuous inroads into the forests have been in the Tropics. The largest remaining forested area on the earth is the Amazon Basin, and we have sought data on the rate of harvest of Amazonian forests. There is no thoroughly satisfactory survey that can be applied to the entire Amazon Basin without all the hazards associated with any extrapolation. Nevertheless, Lawrence S. Hamilton of Cornell University and his colleagues have recently published a series of reports on changes in Venezuelan forests.

One of the reports, by J. P. Veillon, shows a 33 percent reduction in forest area in the western llanos of Venezuela between 1950 and 1975. Hamilton, in an introduction to the series, cites FAO data that "suggests an estimate of moist forest cleared per year at . . . 0.6 to 1.5 percent of the still existing area." Studies from other sections of the Amazon Basin attest to the high rate of development of highways, the expansion of agriculture at the expense of forests and the failure of revegetation after the forest has been cleared. Virtually no knowledgeable investigator with experi-



GLOBAL BALANCE SHEET shows major carbon repositories and annual exchange rates among depots that are in contact. Quantities are expressed in units of 10^{15} grams, or billions of metric tons. Annual releases to the atmosphere governed by human activities are shown in color. Land plants fix a net of about 50×10^{15} grams of carbon per year. This carbon is either consumed and promptly respired by various terrestrial organisms or stored in the plant mass. The balance between fixation (net photosynthesis) and storage plus the total respiration of all terrestrial organisms determines whether there is a net flux of carbon dioxide to or from the biota. Many biologists now believe that there has been a long-term net flow of carbon dioxide from the biota into the atmosphere and that the flow is continuing. The carbon fixed by marine organisms is either respired or stored. It has been commonly assumed that most of it is respired immediately and recycled. It now seems possible that sinking fecal pellets may carry more carbon into the oceanic depths than had been thought. This transfer would supplement the normally slow diffusion of carbon dioxide into the surface layers of the ocean, where it comes into equilibrium with the carbonate-bicarbonate system. Although the deep ocean provides a virtually unlimited sink for carbon dioxide, gas must enter mixed layer and then penetrate thermocline, a thermally stratified layer that impedes mixing with deeper layers.

ence in the Tropics believes the Amazonian forest will escape substantial inroads from harvest and clearing over the next 30 years.

The best assumptions available to me suggest that the rate of clearing of tropical forests for all purposes is probably in the range of .5 to 1.5 percent of the existing area annually. If the rate is 1 percent, and if most of the clearing is through the expansion of agriculture and grazing lands into areas that were formerly forested, the release of carbon from forests alone would be about 4.5×10^{15} grams per year. By applying such estimates to the entire terrestrial biota, allowing for additional storage through regrowth, my colleagues and I have recently estimated that the net release of carbon dioxide to the atmosphere from the biota is 6×10^{15} grams of carbon annually. The magnitude of an additional release through the decay of soil humus is hard to calculate but we have estimated the loss at 2×10^{15} grams per year. The total estimated release is therefore about 8×10^{15} grams. The uncertainties are so great, however, that we have guessed that the actual loss from the biota might lie between 2×10^{15} and 18×10^{15} grams per year. Although one must always bear in mind the limitations of the data on which such assumptions are based, it is difficult to avoid the conclusion that the destruction of the forests of the earth is adding carbon dioxide to the atmosphere at a rate comparable to the rate of release from the combustion of fossil fuels, and if the oxidation of humus is included, at an appreciably higher rate.

	AREA (10^6 SQUARE KILOMETERS)	NET PRIMARY PRODUCTION (10^{15} GRAMS OF CARBON PER YEAR)	PLANT MASS (10^{15} GRAMS OF CARBON)
TROPICAL RAIN FOREST	17.0	16.8	344.0
TROPICAL SEASONAL FOREST	7.5	5.4	117.0
TEMPERATE EVERGREEN FOREST	5.0	2.9	79.0
TEMPERATE DECIDUOUS FOREST	7.0	3.8	95.0
BOREAL FOREST	12.0	4.3	108.0
WOODLAND AND SHRUBLAND	8.5	2.7	22.0
SAVANNA	15.0	6.1	27.0
TEMPERATE GRASSLAND	9.0	2.4	6.3
TUNDRA AND ALPINE MEADOW	8.0	0.5	2.3
DESERT SCRUB	18.0	0.7	5.9
ROCK, ICE AND SAND	24.0	0.03	0.2
CULTIVATED LAND	14.0	4.1	6.3
SWAMP AND MARSH	2.0	2.7	13.5
LAKE AND STREAM	2.0	0.4	0.02
TOTAL CONTINENTAL	149.0	52.8	826.5
OPEN OCEAN	332.0	18.7	0.45
UPWELLING ZONES	0.4	0.1	0.004
CONTINENTAL SHELF	26.6	4.3	0.12
ALGAL BED AND REEF	0.6	0.7	0.54
ESTUARIES	1.4	1.0	0.63
TOTAL MARINE	361.0	24.8	1.74
WORLD TOTAL	510.0	77.6	828.0

MAJOR PLANT COMMUNITIES of the earth are listed along with their area, their net primary production and the amount of carbon they hold in storage. Net primary production is the amount of carbon a plant community provides annually for harvesting or for the support of various consumer organisms, either wild or domesticated. Although only about 30 percent of the earth's surface is covered by land, the net primary production of terrestrial vegetation is slightly more than twice the primary production of the oceans. The quantity of carbon stored in land plants is some 500 times greater than the quantity stored in marine ecosystems. The carbon stored in trees is roughly equal to the carbon in the atmosphere. The figures in the table were recently compiled by R. H. Whittaker and Gene E. Likens of Cornell University.

These observations have come as a surprise to many agriculturists and foresters. The assumption in their experience has been that modern agricultural and forestry practices have improved the net primary productivity of terrestrial systems under human management and that the improvement of net primary production must have resulted in a faster storage of carbon in the humus of soils under management than in natural soils. But the average productivity of agriculture, measured in the ecologist's units of total organic matter available to man or other animals, is substantially less than the average primary productivity of the natural communities the agriculture replaced. Agricultural plant communities are managed not for the storage of large quantities of carbon but for the rapid turnover of carbon pools through their utilization by man. This means that lands under agriculture do not store as much carbon as the forests that were replaced by agriculture did. Similarly, grasslands turned to agriculture tend both to lose the organic matter in the soil through decay and not to accumulate additional organic matter.

Forests that are managed intensively, although they may produce increased amounts of wood, tend to have at the time of harvest a standing crop much smaller than the stands of the primary forests they replaced. This again means that the turnover time has been reduced and that the standing pool of carbon never achieves the same size as the pool of the original forests. Thus the replacement of primary forests with secondary forests that are managed for lumber or pulp results in a net release of carbon dioxide. There is a further release of carbon through the decay of humus. The decay is stimulated by the harvest of the forests and may continue for several years after the harvest during the early stages of the plant succession that follows the cutting. All these factors lead to a net release of carbon when unmanaged primary forests are replaced by managed ones.

One further line of evidence seems to support the conclusion that the terrestrial biota has for many decades been a net source of carbon dioxide rather than a sink. By comparing the ratios of carbon isotopes in trees Minze Stuiver of the University of Washington has calculated that in the century between 1850 and 1950 the biota appears to have released to the atmosphere 1.2×10^{15} grams of carbon per year. Over the same period the release from fossil fuels averaged $.6 \times 10^{15}$ grams of carbon per year.

Stuiver exploited the fact that the ratio of carbon 12 to carbon 13 varies among the atmosphere, the biota and fossil fuels. The biota and fossil fuels are enriched slightly in the lighter isotope, carbon 12. In addition a third isotope of carbon, carbon 14, is present only in the atmosphere and in the biota. Carbon 14 is produced in the upper atmosphere through the cosmic-ray bombardment of the common isotope of nitrogen, nitrogen 14. It has also been produced in large quantities by atomic bomb tests in the atmosphere. Because carbon 14 has a half-life of some 6,000 years it has long since disappeared from fossil fuels, which were formed millions of years ago. The combustion of fossil fuels therefore releases a pool of carbon that is deficient in carbon 14 and tends to dilute the carbon 14 of the atmosphere. By measuring the concentration of various carbon isotopes in the rings of trees of known age and comparing the ratios with those of the atmosphere and of fossil fuels Stuiver was able to estimate the amount of carbon released from the biota. The measurements are technically difficult; moreover, the ratios of carbon isotopes in trees are affected by various environmental factors that make the results less clear-cut than one might like. Nevertheless, the technique offers an important additional means for testing the magnitude of the release of carbon dioxide from the biota.

FORESTS:	PLANT MASS (10^3 GRAMS OF CARBON PER SQUARE METER)	NET PRIMARY PRODUCTION (GRAMS OF CARBON PER SQUARE METER PER YEAR) RANGE	MEAN
TROPICAL (WET)	3.0–36.0	450–1,600	990
TEMPERATE	3.0–90.0	270–1,125	560
BOREAL	3.0–18.0	180–900	360
SAVANNAS	0.1–7.0	90–900	400
GRASSLANDS	0.1–2.3	90–675	270
CULTIVATED LAND	0.2–5.4	45–2,800	290

TRANSFER OF LAND INTO AGRICULTURE usually results in a sharp reduction in the carbon stored in the biomass and a somewhat smaller reduction in the carbon dioxide removed annually from the atmosphere and fixed by photosynthesis. The table, also based on the work of Whittaker and Likens, indicates the range of published estimates for the standing biomass and the net primary production of major natural ecosystems compared with cultivated land.

In view of the available evidence there seems to be little question that the increase in carbon dioxide content of the atmosphere is due not only to the combustion of fossil fuels but also to the destruction of forests. G. Evelyn Hutchinson of Yale University made this point in a chapter in *The Earth as a Planet,* a book edited by Gerard P. Kuiper in 1954. Hutchinson guessed that the release of carbon from the biota was about equal to the release from fossil fuel. The best evidence we have at present indicates that this relation persists.

There is enough carbon held within the biota for the relation to continue for another decade or two through the expected peak in the worldwide consumption of oil. By that time, if not sooner, the earth will have been committed to climatic change as a result of the accumulation of carbon dioxide in the atmosphere—if indeed such a change is to take place. The question of whether or not it will take place depends on the scale of the carbon dioxide effect, an appraisal that is extremely difficult to make with any certainty. It is now recognized that changes in the output of the sun, changes in the reflectivity of the earth (as it is influenced by the extent of cloud, snow and ice cover) and other factors all influence the climate. Whether or not the carbon dioxide content of the atmosphere is great enough to be the dominant factor remains to be seen. If the carbon dioxide effect is indeed dominant, the probability is that the earth will be warmed differentially, with temperatures increasing toward the poles. Such a change can be expected to move the desert zones poleward, enlarging the areas of aridity and reducing the areas suitable for agriculture. The prospect is not encouraging for a world whose human population may double within the next 30 to 35 years.

If the evidence were overwhelming that the risk of a deleterious change in climate over the next few decades was unacceptably great, the course of action would be clear enough. The burning of fossil fuels would be restricted to reduce that source of carbon dioxide. Strong moves would also be made to prevent the harvest of primary forests around the world, to expand the areas devoted to forests and to allow such areas to develop massive standing crops of trees. Whether such drastic measures could be effected is much in doubt; the social problems that would result would clearly be profound.

Other suggestions have been made, including the suggestion that because the availability of phosphorus is considered by some to limit net primary production in the oceans the advanced nations should apply some of their industrial energy to the mining of phosphorus with the objective of transferring it as rapidly as possible to the relatively infertile oceans, thereby stimulating photosynthesis and the storage of carbon. The scheme is superficially attractive because it seems to offer a way of speeding the storage of carbon in the oceans. The possibility exists, however, that any additional photosynthesis stimulated in the ocean would be offset by an equivalent stimulation of respiration, so that there would be no net increase in carbon storage. There are many questions about the feasibility of such a step, including the basic one of whether phosphorus is indeed critically limiting in oceanic waters. There is a reasonable possibility that nitrogen is also limiting, in which case the stimulation of marine photosynthesis could prove to be substantially more difficult than has been assumed.

Nevertheless, recent experience has emphasized to all of us who work in these fields that important details of the world carbon budget are substantially unknown at present. Some improvement in our knowledge of such details seems feasible through measurement of the changes in the areas and structures of forests worldwide from satellite photographs. Investigations are also under way to see if biotic mechanisms might facilitate the transfer of considerably more carbon into the oceanic depths than we assume is being transferred today. The immediate prospect of establishing with high precision all the details of the world's carbon budget, however, is not bright.

The potential hazards associated with a steady increase in the carbon dioxide content of the atmosphere will loom large in the coming decades and will doubtless bear heavily on such decisions as whether to accelerate the development of power plants based on nuclear fuel instead of those based on coal and whether to preserve forest areas instead of encroaching on them (and, if the forests are to be preserved, how to provide the new lands that are almost certain to be needed for agriculture). There is almost no aspect of national and international policy that can remain unaffected by the prospect of global climatic change. Carbon dioxide, until now an apparently innocuous trace gas in the atmosphere, may be moving rapidly toward a central role as a major threat to the present world order.