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BIOTIC CONTRIBUTIONS TO THE GLOBAL CARBON CYCLE: THE ROLE OF REMOTE SENSING

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ABSTRACT

The CO_2 content of the atmosphere is increasing currently as a result of the combustion of fossil fuels and the oxidation of vegetation and soils associated with changes in the use of land. Prediction of the atmospheric CO_2 concentration in the future requires a better understanding of how important these land-use changes are currently and how important they have been in the past. In this paper we present an analysis of past changes in the terrestrial biota and soils of the earth. The analysis is based on rates of forest harvest and regrowth, rates of land conversion to agriculture, and on the changes in biomass and soil carbon that accompany these uses of land. The results of the analysis show that changes in land use have caused a net release of carbon to the atmosphere that until recently was larger than the release from combustion of fossil fuels. There is still a large uncertainty in the analysis, however, largely because of conflicting reports as to the current rate of disappearance of tropical forests. We outline the kinds of information needed to improve the analysis and believe that remote sensing is of use immediately in reducing the range of uncertainty by a factor of two to four.

I. INTRODUCTION: THE GLOBAL CO_2 PROBLEM

The atmospheric CO_2 concentration is rising as a result of the combustion of fossil fuels and the destruction of forests. The importance of the destruction of forests as a source of CO_2 is uncertain within a factor of five or more. The amount of CO_2 from fossil fuels is known within less than 50%. Existing tabulations of data on the harvest and transformation of forests to agricultural and grazing land, changes that are important in the global CO_2 flux, could be improved greatly by use of satellite imagery. In this paper we examine methods currently being developed for this purpose.

The atmosphere contains about 0.03% CO_2, little more than a trace. The concentration has been increasing at an accelerating rate since the beginning of the century, possibly much longer. The best evidence for the increase has been produced at Mauna Loa in the Hawaiian Islands beginning in 1958 (Fig. 1), when C. D. Keeling started his famous program of measurements there and in the Antarctic.[9,10] These measurements and many other more recent data show an increase in CO_2 concentration that appears to assure a doubling of the preindustrial concentration by 2040, possibly earlier.

The increase in CO_2 is important because CO_2, in contrast to the other major gases of the atmosphere, O_2 and N_2, absorbs infra-red energy. An increase in the amount of CO_2 will result in greater retention in the atmosphere of radiant heat from the sun and a higher equilibrium temperature for the earth as a whole. The rise in temperature is expected to be important, 2-4° C averaged for the earth as a whole for a doubling of the CO_2 in the atmosphere.[19,22] The increase at the poles will be greater, as much as 10° C, or more.[12,13] The transition threatens rapid changes in climate that will affect agricultural productivity globally. The problem is serious. A clearer definition of the problem requires better data and more detailed analysis, especially of the biotic segments of the cycle, which appear to be less well known than other segments.

The release of carbon annually from the combustion of fossil fuels is about 6×10^{15} g C. The accumulation in the

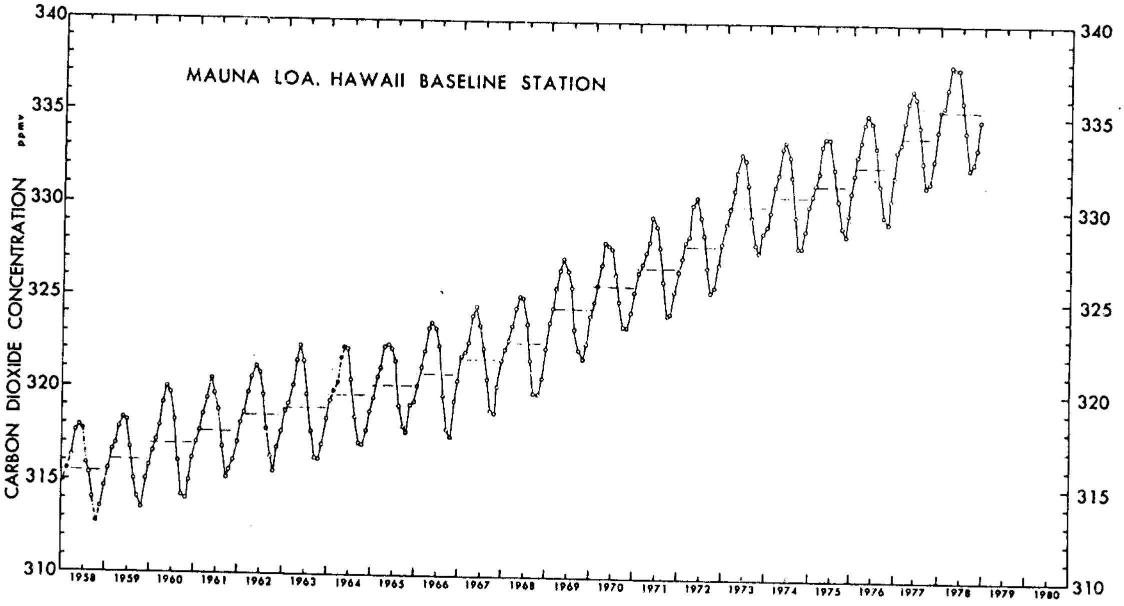

Figure 1. Record of the concentration of CO_2 in air (ppmv) at Mauna Loa, Hawaii (L. Machta, NOAA Air Resources Laboratories, 1979).

atmosphere is equivalent to about half of this release. Analyses based on oceanographic models suggest that most of the rest of the release is absorbed by the oceans, while a small remainder accumulates in the world's terrestrial biota.[2,11,20,5] Analyses based on changes in the use of land worldwide suggest that the earth's biota, far from taking up a small amount of carbon per year, is responsible for a net release of between 1 and 8 x 10^{15} g C annually.[1,3,24,25,8,14] The release of carbon from the terrestrial biota is a result of deforestation and other changes in land use. If this net release is even slightly greater than zero, the estimates of oceanic uptake are low, for the terms in the carbon equation are not balanced. The total release to the atmosphere from the biota and from combustion of fossil fuel is greater than the amount that is retained in the atmosphere plus the amount thought to be transferred to the oceans. If future concentrations of CO_2 in the atmosphere are to be predicted, enough must be known to balance the budget.

II. CHANGES IN THE CARBON CONTENT OF THE BIOTA AND SOILS

Our work at the Marine Biological Laboratory has been to determine the changes in the carbon content of the terrestrial biota and soils of the world. The changes we have considered are those related to changing uses of land. Forests contain much more carbon in the vegetation and soil both globally and per unit area than cultivated land. If more land is under cultivation now and less of it is forested than 100 years ago, the carbon content of terrestrial ecosystems is now less. The difference must have been a release of CO_2 to the atmosphere. How much has the carbon content of the earth's terrestrial ecosystems changed in the last decades? What are the changes currently?

The emphasis is on change. We are not attempting to determine the area and carbon content of the major vegetation types of the earth. Rather we are documenting the rate of harvest of forests, the rate of decay of wood products, the rate of land clearing for agriculture, and the rate of reforestation. We have developed a simple model[14] that breaks the world into 10 geographic regions and 14 vegetation types, including cultivated lands and pastures. The data we use to compute the annual change in the carbon content of the vegetation and soils in each of these ecosystems are of two types: (1) ecological information on the response of vegetation and soils to a change in land use, and (2) statistical information on areas of harvest or areas of land transformation.

Figure 2 is an idealized curve showing an example of the first kind of information we use. The curve shows the changes in carbon (metric tons/hectare) that occur in vegetation (top) and soils (bottom) following harvest of a forest.

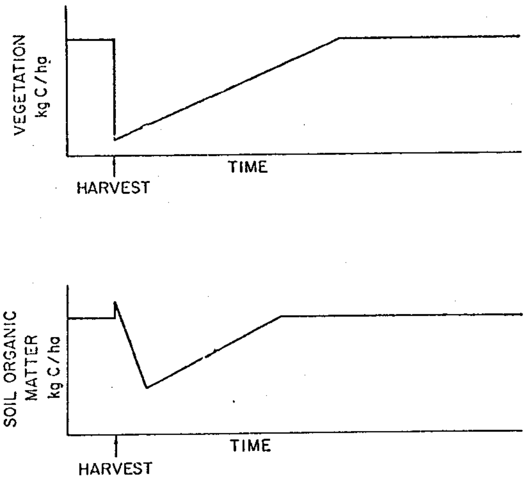

Figure 2. Idealized curves describing the changes in carbon per unit area that take place during the regrowth of a harvested forest.

In the year of harvest some of the carbon originally held in vegetation is removed from the forest to become fuelwood, paper, timber, or some other product. These products are assigned to one of several decay constants to account for their oxidation over periods of 1 to 100 years. Some of the vegetation on the harvested site is killed (e.g., slash, leaves, roots). This dead organic matter is transferred to the soil (initial peak on the bottom curve in Fig. 2) where it decays over time. The vegetation that was neither harvested nor killed on site begins to regrow the year following harvest. If one considers only the vegetation of a harvested forest (top curve), its regrowth removes carbon from the atmosphere and stores it in the regrowing forest. The carbon content of soils following harvest first declines, releasing carbon to the atmosphere as the organic matter decays, and then increases, reducing the carbon content of the atmosphere, as the soils of the regrowing forest develop. The slopes of the curves determine the annual net flux to or from the atmosphere for each hectare of harvested forest. Curves are defined for each of five forest types in the 10 regions of the world.

A similar pair of curves defines the changes in the carbon of vegetation and soil following the clearing of land for agriculture (Fig. 3) and the abandonment of agricultural land. Clearing and abandonment together transfer carbon between the atmosphere and terrestrial ecosystems in much the same way that wood harvest does. Without abandonment, however, the clearing of land reduces the carbon content of vegetation and soils permanently. Such changes have led to the increase in atmospheric CO_2.

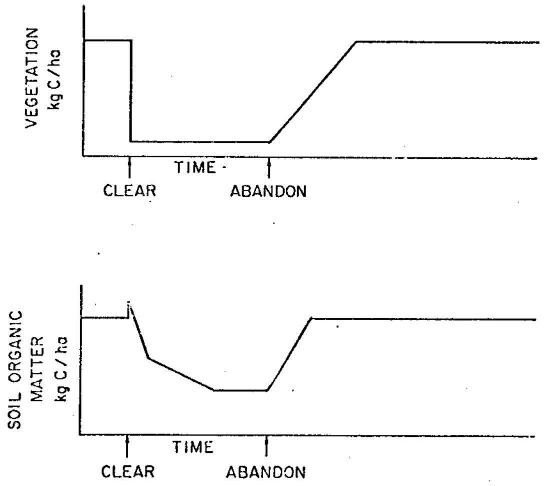

Figure 3. Idealized curves describing the changes in carbon per unit area that take place during the clearing of land for agriculture, during cultivation, and after abandonment.

The second broad type of information required in this analysis is the rate at which areas of forests are harvested or areas of natural systems cleared or forested. It is important to recognize that with this approach it is not sufficient to obtain the rates of land-use change for a single year. The calculation of the net carbon flux in 1981, for example, requires a knowledge of the cutting and clearing rates for at least 50 years prior to 1981 because forests cut less than 50 years ago are still regrowing and removing carbon from the atmosphere. Decay of organic matter and wood products also introduce time lags into the analysis. In this analysis we have attempted to document changes in the use of land since 1700. We have used the reports of agricultural historians, geographers, and economists for the years prior to 1945 and regional and global surveys conducted by various organizations in more recent years. A more thorough discussion of the model, the data and sources used, and the results are given in Moore et al.[14] We report here some of the major results.

The results show that there has been a net release of carbon from terrestrial systems worldwide for as long as we have documented changes in land use (Fig. 4). Individual regions, Europe and North America, for example, do not show this sustained release, but the global results are what concern us here. The major reason for the release of carbon through history has been the clearing of lands for permanent agriculture (Fig. 4). Although the area of forests harvested has been greater than the area permanently cleared during this time interval, the regrowth of harvested forests stores carbon, and the net flux from both harvest and regrowth is less than from harvest itself.

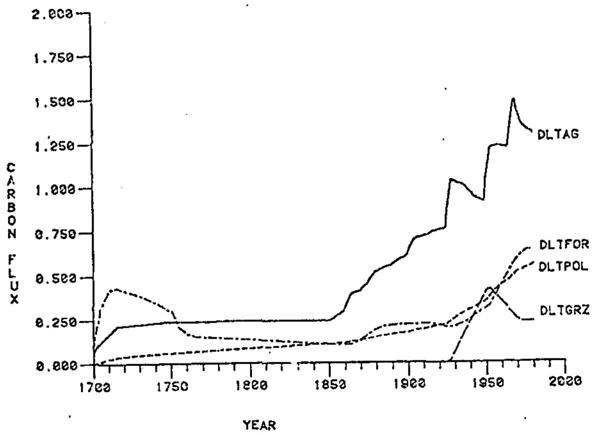

Figure 4. Net annual flux of carbon to the atmosphere as a result of clearing and cultivation of agricultural land (DLTAG), harvest and regrowth of forests (DLTFOR), oxidation of wood harvested or cleared from a site (DLTPOL), and clearing of land for pasture (DLTGRZ).

When the net fluxes of carbon from all land-use changes are summed, the net release in 1980 was 2.6×10^{15} g C. The carbon released from the combustion of fossil fuels was about 6×10^{15} g C in the same year, but appears until recently to have been less of an annual release than the release from the biota and soils (Fig. 5).

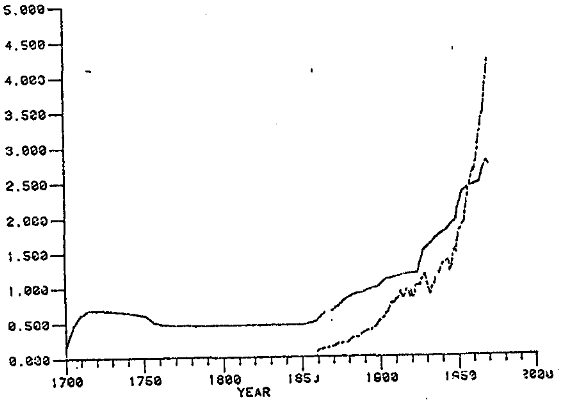

Figure 5. Net annual flux of carbon to he atmosphere as a result of changes in land use (solid curve) and as a result of the combustion of fossil fuels and production of cement.

The net flux of 2.6×10^{15} g C from terrestrial systems in 1980 is an estimate based on what appear to us to be the most reasonable sources of information. It may be more appropriate, however, to express the 1980 flux of carbon as a range of $1\text{-}5 \times 10^{15}$ g C. This range results from use of different assumptions and different sources of information in alternative analyses with the model. The widest range occurred as a result of one uncertainty: the rate at which tropical forests were converted to agriculture between 1950 and 1980. The low value of the range (Fig. 6) (1.0×10^{15} g C released in 1980) was obtained using changes in agricultural area reported by the Production Yearbook of the Food and Agricultural Organization of the United Nations. Several authors have pointed out the problems inherent in such an approach[17] and it may be that the rates of agricultural expansion are greater than reported. For the high end of the range we used rates of tropical

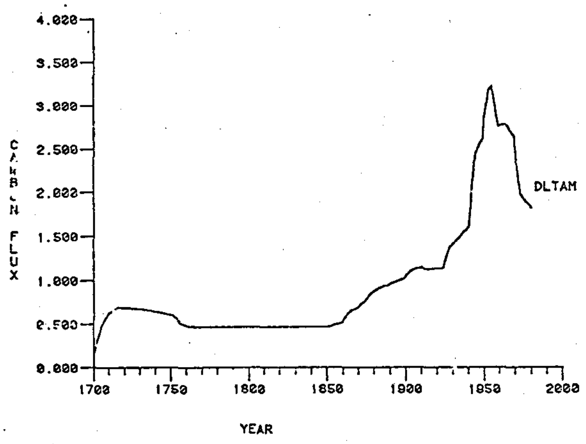

Figure 6. Net annual flux of carbon to the atmosphere calculated from agricultural information obtained from FAO Production Yearbooks.

forest destruction reported by Myers (Fig. 7).[15,16] It is not always clear from Myers' reports whether or not the forests grow back.

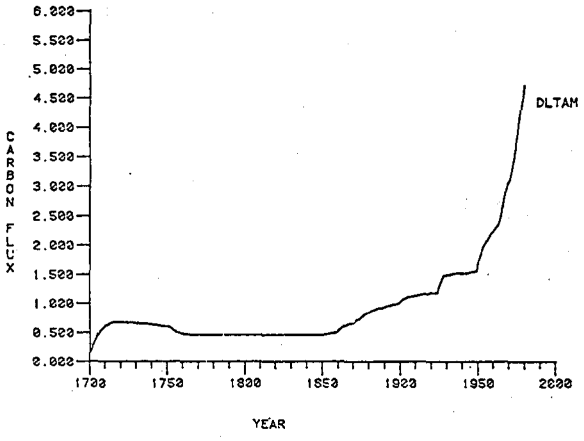

Figure 7. Net annual flux of carbon to the atmosphere calculated with information from Myers (1980a, b) on deforestation rates in the tropics.

If we are to understand the global carbon cycle, we must continue to narrow the range of uncertainty in the magnitudes of fluxes. We have reached the point in our analyses where the largest uncertainty (1-5 x 10^{15} g C yr^{-1}) is caused by conflicting reports as to the area of tropical forests cleared for agriculture between 1950 and 1980. Were these areas converted to permanent agriculture or to shifting cultivation? How large an area was cleared? We need an objective method for measuring changes in area. Can remote sensing supply that need?

III. THE CHALLENGE FOR REMOTE SENSING

It is important to recall that the emphasis is on change; change in carbon stocks, change in area, and change in land use. Is it likely that we can use remote sensing to obtain these changes? Before answering the question it is useful to distinguish two different kinds of change: change in carbon per unit area and change in area. The annual rate of change we are interested in is of the order of 1.0 x 10^{15} g C. The carbon content of the world's vegetation and soils is about 1500 x 10^{15} g C. Thus we are looking for a change of 1 part in 1500, or 1-2 parts per thousand. The average carbon content of forests worldwide, including soils, is about 300 metric tons/ha (Table 1). If the annual change of 1 in 1500 were distributed equally over the forests of the earth, we would be looking for a change of about 0.2 mt C/ha in 300. There is no hope that remote sensing would detect such a change in less than 100 years. Direct sampling of forest biomass on the ground is unlikely to reveal the change either; the variability of plots measured within the same forest type is of the order of tens of mt/ha.[7,21]

On the other hand if the change in the storage of terrestrial carbon is concentrated in areas where, say, all of the carbon in a forested hectare is released to the atmosphere, 1 part in 1500 amounts to an annual change of about 3.5 x 10^6 ha of forest (world forests occupy about 5000 x 10^6 ha). Actually the minimum area is 5-7 x 10^6 ha since the carbon lost in the transformation of forests to cultivated land is about 50% of the carbon originally held in the forest. Thus the change in area sufficient to release 1 x 10^{15} g C is a change that can be measured with remote sensing. In fact the transformation of forests to agriculture and the reverse transformation are the kinds of change responsible for the major

Table 1. Average amount of carbon (mt/ha) in different forest types.

	Tropical moist forests	Tropical seasonal forests	Temperate evergreen forests	Temperate deciduous forests	Boreal forests
Vegetation[23]	200	160	160	135	90
Soil[18]	117	117	134	134	206
Total	317	277	294	269	296

uncertainty in our current analysis of net carbon flux. The changes include the clearing of forest for agriculture, abandonment of agricultural land, and reforestation.

The current resolution of the carbon problem is such that a direct measure of the transformations of forests is sufficient to decrease our uncertainty by a factor of 2 to 4 - from a range of 1-5 x 10^{15} g C yr^{-1} to one of 1.5-3.0 x 10^{15} g C yr^{-1}. At this point in the analyses, therefore, we need not classify cover types or land uses into more than two categories. Differences in carbon content between forest types, for example, is of the order of 10-50 mt/ha (Table 1) as opposed to 100-200 mt C/ha for forest to non-forest differences. The former differences are of secondary importance at this stage of our analysis. Furthermore, to the extent the techniques exist for detecting change between two satellite images without prior classification, the task of classification will be made still easier. Only those pixels, or groups of pixels, that register a change need classification. This approach requires that the registration of two images be to within several pixels at least; but to the extent that registration is a simpler problem to deal with than classification, the approach seems justified.

If LANDSAT is used in the detection of change, there are several kinds of information it will provide. As long as images are analyzed frequently enough to detect a clearing before it is covered again, imagery will yield <u>when</u> a change has occurred. As long as the registration of images is to within several pixels, the approach will provide <u>where</u> a change has occurred and <u>how much area</u> was changed. But will image analysis reveal <u>what kind of change</u> took place? Hopefully forest to non-forest and non-forest to forest transformations will be evident. But the response of vegetation and soils to logging is different from their response to clearing and cultivation. The analysis of two images may reveal a cleared forest, but without a third image at a later date the analysis will not reveal whether the clearing was permanent or not. Neither will it be clear what exchanges of carbon should be assigned to that area of change. Our analysis, thus, has a further requirement.

We need to know and to remember where a change has occurred. There are two reasons why we need to be able to return to the same group of pixels with a subsequent image. First, we need to establish what the change was. Was it a harvest with regrowth or was it a more permanent clearing? Second, we want to know the carbon content of a forest when it is harvested or cleared a second time in the record of the imagery. If satellite imagery could be used to obtain values of biomass and soil carbon directly, the model would be unnecessary. But the development of a forest canopy, or leaf area index, (spectral response) is not proportional to the development of biomass and soil carbon (carbon content).[6,4] Seven year-old pine stands look spectrally similar to 50 year-old stands (Barker, this symposium), yet their carbon contents are clearly different. As long as remote sensing cannot distinguish carbon differences associated with succession (Hicks and Park, this symposium), our analysis requires an independent source of data. We do not require that satellite imagery yield information on the biomass and soil carbon of a forest but only that it detect when and where a change has occurred. The model, based on ecological information, predicts how carbon in a hectare of regrowing forest will change with time. Imagery will provide the information to start the regrowing process; the model will calculate the changes in carbon per unit area. To be useful for our purpose, remote sensing must indicate when and where a change has occurred, and the methodology must provide a means of returning to that changed area on subsequent dates.

As this discussion represents work

in progress it is appropriate to end with a question. The global carbon problem requires a global approach and, hence, a global sampling scheme. The area of forests is approximately 5000 x 10^6 ha; the total area of land, about three times that. One satellite image covers about 2.2 x 10^6 ha, so complete coverage of the total land area once would require over 6000 frames. Including the frames required to cover land-water boundaries and the frames necessary to account for equipment failures, cloudiness, and other problems, the total number of frames is probably about 24,000 for one look. Change detection requires a minimum of two images for each time interval. Clearly there is a need for stratification, but on what basis? How many scenes must be analyzed to reduce our uncertainty to 1 x 10^{15} g C yr^{-1}? The questions are difficult, the task of sampling is formidable. But the development and practice of such a scheme would have countless uses in managing the resources of the earth.

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