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Carbon Dioxide Effects Research and Assessment Program

Measurement of Changes in Terrestrial Carbon Using Remote Sensing

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Carbon Dioxide Effects Research and Assessment Program

Measurement of Changes in Terrestrial Carbon Using Remote Sensing

Reports of Panel Discussions at a Conference
held at The Ecosystems Center
Marine Biological Laboratory
Woods Hole, Massachusetts

May 1979

G. M. Woodwell, *Editor*

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I. REPORTS OF THE CONFERENCE

A. The Problem

The increase in the CO_2 content of the atmosphere, observed over the past 70-100 years, is the result of human activities. The major sources of CO_2 are the combustion of fossil fuels and the acceleration of decay of carbon compounds in the terrestrial biota and in soils. The relative importance of these two sources of CO_2 is in question. A major component of the uncertainty is the question of the rate at which the area of forests is changing worldwide. The objective of this conference was to examine the potential of remote sensing for resolving the uncertainty.

The role of the terrestrial biota and soils in affecting the CO_2 content of the atmosphere has appeared uncertain in part because of confusion over two processes. First, there is the possibility that the increase in carbon dioxide in the atmosphere has stimulated photosynthesis worldwide and resulted in additional accumulation of carbon in terrestrial systems. The process under which such an accumulation might occur is complex and is not discussed in detail here. Most ecologists believe at present that the extent of any such stimulation of carbon storage must be small because of the limitations on rates of photosynthesis commonly imposed by the availability of water and nutrients and the ease with which respiration and the decay of organic matter are stimulated by disturbance. Nonetheless, the need to measure any increase in carbon storage, sometimes called the beta factor after Bacastow and Keeling (1973), remains important and appeared in various forms in the discussions at this symposium.

The second factor that affects the exchanges of carbon between the land and the atmospnere is the various transformations of forests, either into successional forests as a result of harvest, or into agricultural lands or other impoverished plant communities. Preliminary analyses of the importance of these transformations have suggested that the net flux of carbon is from the forests into the atmosphere and that the magnitude of the net flux may be of the same order as the release through the combustion of fossil fuels, 5-6 billion metric tons annually. Obviously, the question of whether this appraisal is accurate is important. If so, the models used currently to describe the world cycle of carbon and to predict the future CO_2-content of the atmosphere are incomplete and may be misleading.

This conference was arranged with the objective of determining whether and how remote sensing might be used to

measure changes in the total amount of carbon stored in the vegetation and soils of the earth as a whole. Early in the conference participants agreed that satellite imagery is appropriate for this purpose. The uncertainties are how to do it most efficiently, what collateral information is required, and the precision that can be obtained.

Measurement of changes in the amount of carbon held in the vegetation and soils requires two kinds of information: (a) measurement of the area of each type of vegetation and (b) measurement of the amount of carbon within each. The first of these, measurement of area and change in area, is readily obtained from analysis of satellite imagery. The second requires ground-based techniques that were discussed but not developed in detail in this conference.

The most difficult aspect of measuring changes in area is the series of problems inherent in identifying a particular type of vegetation from satellite imagery. How consistently can similar categories of vegetation be identified? How similar is the carbon content of sites from within the same community? The experience of several participants was that remotely sensed imagery will offer many more possibilities for recognizing classes of vegetation than can in fact be used and the first major hurdle will be reduction of this number of potential classes to a small group that can be recognized on the ground as well as from the imagery. This observation alone constituted a major advance for many of the scientists at the conference because it demonstrated the potential of satellite imagery for use in ecology.

The procedure for measuring changes in carbon content of terrestrial communities requires that the classes of vegetation distinguishable through imagery have carbon values assigned to them either from previous work or through new studies carried out on the ground. Field studies will provide both confirmation of the classification of areas, and information on the standing crop of carbon in the vegetation and soils when these data are not available from other sources. Additional studies will be required to measure changes in that carbon stock with time and to determine whether such changes can be detected from satellite or aerial imagery. The requirement for ground stations remains vague in that the need for new data will depend heavily on the amount of experience and data available now and applicable to this work. The topic was discussed at length and no agreement was reached, or could be reached, on the intensity of sampling required from ground sites; it will vary from place to place with several factors, outlined below.

B. The World Carbon Cycle: Analysis by Modelling (Panel 1)

Models are tools. Prediction of the future CO_2 content of the atmosphere requires modelling because the interactions that affect the amount of CO_2 in circulation are too complex to be interpreted in any other way. The most satisfactory approach in the longer term will be based on well defined physical, chemical and biotic processes incorporated into models, but much progress is possible in the short-term through simpler approaches in which the processes are generalized.

We can account roughly for the present rate of increase in atmospheric CO_2 by calculating the oceanic response to the increase using models that incorporate data on the carbon content of the oceans, the oceanic circulation, and the rate of release of carbon into the atmosphere from combustion of fossil fuels. The CO_2 that is neither absorbed into the oceans nor residual in the atmosphere has been thought to be accumulating in the standing crop of carbon on land through the stimulation of photosynthesis . However, appraisals of the carbon held in the biota on land and in soils suggest that there has been in the past and continues to be a substantial net release into the atmosphere from terrestrial sources. The difficulty is that at the moment neither extreme, the possibility of a significant release from terrestrial sources nor the possibility of storage of carbon on land, can be eliminated on the basis of current data. Although the issues cannot be resolved in toto by an application of remote sensing, significant segments of the problem can and should be resolved.

The most important topics are:

1. The net effect of the harvest and regrowth of forests over time on the CO_2 content of the atmosphere.
2. The net effect of the transformation of forested land into other types of use, including agriculture, grazing land, impoverished plant communities, or others.
3. The net effect, if any, of the increase in carbon dioxide in the atmosphere on the storage of carbon on land.

Remote sensing techniques can provide information critical to evaluating the first two topics but will probably not prove directly useful in measuring the effect of increased CO_2 in air on the net ecosystem production of terrestrial communities (the beta factor of Bacastow and Keeling, 1973). On the other hand, if the oceanographic models that contain the assumption that the pool of carbon in the biota is increasing

are correct, and if the analyses of land-use changes that show the biota to be decreasing in carbon are also correct, then the beta factor can be evaluated, as the difference between the two. The topic was discussed at length during the conference, but no conclusion was reached as to a method of measuring the potential effect of CO_2 enhancement directly in nature beyond the observation that any such measurement will require very careful field studies over a period of years.

In the meantime an analysis of changes in carbon storage resulting from forest harvesting and the clearing of land for agriculture can do much to improve our understanding of the global cycle. Simple models can be written to describe the changes in carbon content of forests, including soils, following harvest. The models can be designed on the basis of existing data, can incorporate generalizations of physiological processes without relying on the details of those processes, which may be difficult to obtain for most vegetation types, and can provide a summation for the earth as a whole. Specific suggestions were offered in the papers submitted to the conference. The models can also be written to incorporate the transformations of forests to agricultural or other types of vegetation. Sources of data for such models are (1) the literature and (2) new data from remote sensing.

The most important question addressed by the modelling panel was the precision of the analysis that would be required to improve knowledge of the current role of the biota in the global carbon budget. The precision is dependent on the data available, not on intrinsic limitations in modelling or any obvious intellectual lacunae. The uncertainties at the moment arise because we are attempting to measure very small differences in large fluxes of carbon. Precision can be improved by integrating changes over several years. The procedure is appropriate as long as the magnitude and direction of the changes do not themselves change appreciably over the period measured. Such an assumption appears reasonable for changes in the vegetation of the earth. There is uncertainty at the moment as to whether the biota and soils have been releasing or accumulating carbon relative to the atmosphere over the past one to two decades. The magnitude of the uncertainty is of the order of 1-10 billion metric tons of carbon annually, possibly 20.

An improvement in the current estimates of the flux of carbon between the atmosphere and the terrestrial biota and soils would have to reduce the uncertainty by a factor of ten to approximately one billion metric tons of carbon annually. Such an improvement can be approached through several methods but one is through direct measurement using remote sensing in combination with other techniques.

Conclusions:

1. The next step in interpretation of the world carbon budget is development of the ability to measure changes brought by human activities.

2. The greatest uncertainties are:
   a. The net effect of the harvest and regrowth of forests over time on atmospheric CO_2.
   b. The effects of the transformation of forests into agricultural, grazing or other plant communities.
   c. Whether the increase in CO_2 in the atmosphere affects net ecosystem production.

3. While eventually the most satisfactory analysis will be based on detailed mechanisms incorporated into a model or series of models, for the next several years analyses will be based on more generalized models that use simplified schemes for classifying the vegetation of the earth and for describing its changes over time.

4. The precision in prediction possible at the moment is limited by the quality of the data available, especially the information on exchanges and storage within the oceans and on the transition in the terrestrial vegetation and soils of the earth as a whole.

5. A ten-fold improvement in the precision of prediction is required to the point where the biotic fluxes are known within $\pm$ 1 billion metric tons of carbon annually or less. Remote sensing using a combination of satellite and aircraft imagery appears to have the potential for making such an improvement in the data on terrestrial carbon pools.

Panel Chairman: C. D. Keeling
Rapporteur: R. A. Houghton

C. The Vegetation of the Earth: Measurement of Changes (Panel 2)

Two types of changes in the vegetation are important in improving knowledge of the role of the vegetation in the global carbon cycle:

1. changes in the area of major types of vegetation due to harvest or transformation to agricultural or to other plant communities; and

2. changes in carbon content within an area, including those caused by succession, and those resulting from differences in the availability of water, nutrients, or CO_2.

Changes in area of plant communities can be measured by comparison of measurements of area carried out at different times. Satellite imagery is available beginning in 1972 and observations that span 5-8 years may be available after 1980 for many segments of the earth. The emphasis should be on change and areas in which changes are occurring. Such an emphasis implies a sampling plan that is stratified to reflect the emphasis on change.

Successional changes are important because they define the rate of storage of carbon in secondary forests. In well-known vegetations, such as the forests of the Temperate Zone or the Boreal Forests, the major stages of succession are known and can be identified in the field. Identification of these stages on satellite imagery may be possible, but will require a substantial effort. In less well-known vegetation, such as the tropical forests, much more experience will be necessary than is available at present to identify successional stages in the field. Their recognition on satellite imagery may not be possible, at least immediately. Efforts in defining details of succession and the ages of tropical forests should be intensified.

The first step in measurement of changes in terrestrial carbon storage is to choose a classification scheme that includes major successional patterns. The next step is to attempt to identify on the imagery the classes that can be seen on the ground. Most current remote sensing techniques will offer more potential classes than can be used in practice. The difficulty is to determine which of the large array of classes are appropriate.

For the first phase a simple physiognomic breakdown should be used such as that used by UNESCO. The UNESCO system includes such categories as closed forests, open forest, scrub and shrubland, dwarf scrub, and herbaceous vegetation. Such a classification can of course be refined further in a later phase when and where the vegetation is better known. The classification will distinguish between the extremes of aboveground biomass within most regions. There is obvious need for simplicity, at least in the initial stages.

Two kinds of maps are important for this work: a map of potential natural vegetation (a description of what the natural vegetation would be if all sites were allowed to develop in the absence of disturbance); and a map of the actual vegetation, including agricultural areas, forests, successional stands, and other communities. The map of actual vegetation identifies discrete stages in succession and would be used to estimate the current standing stocks of carbon. The maps of potential vegetation describe the standing stock before disturbance and after succession has run its course.

One of the major difficulties is the high probability that sites that have been disturbed repeatedly lose some of their potential for supporting secondary forests with the same standing crop and diversity of species as the primary forests. The problem will have to be kept in mind in each location and corrections entered.

The importance of experience with the specific types of vegetation in question cannot be over-emphasized. The complexities of succession, partial harvest, grazing and other types of disturbance are familiar to local students of the vegetation, not to others. These and other factors emphasize the importance of a regional approach to the remote sensing of vegetation. The approach would place major reliance on regional experts, centers of scholarship, and existing sites where data have been, continue to be, or could be gathered in support of this work. Many such sites exist now and are well known to the scientific community.

Conclusions:

1. The emphasis should be on changes in the vegetation, not on inventory per se.

2. A stratified sampling plan is appropriate to emphasize those areas undergoing greatest change.

3. Change can be measured by:
   (a) successive inventory where change is probable, and
   (b) knowledge of the successional status of the vegetation.

4. A classification scheme that is simple is most appropriate for the first phase of the work. The UNESCO system was proposed.

5. The first step in any program depends on what can be recognized from satellite imagery. The number of potential classes is usually much greater than can be used.

6. A regional approach is appropriate to take advantage of local specialists in phytogeography, existing data and sites where studies are currently underway.

Panel Chairman: M. Kassas
Rapporteur: G. Shaver

D. The Soils: Measurement of Changes in Organic Carbon Content of Soils (Panel 3)

The total amount of organic carbon retained in soils is 2-3 times the amount held in the biota (see papers, this conference*). Small changes in this total have the capacity for affecting the CO_2 content of the atmosphere appreciably. While we wish to improve knowledge of the total amount of carbon held in soils, the improvement is less important than clear evidence of the direction and magnitude of changes in the pool as a result of human activities. Discussions therefore were focussed on improvement of knowledge of (1)the changes in soil carbon that follow disturbance, and (2) the carbon content of soils, especially the fraction that decays rapidly following disturbance.

The following definitions have been accepted widely and are important in this work.

a) Soil Organic Matter (SOM): All organic material in the soil is usually considered as SOM except living roots. Dead organic matter aboveground is included as long as it is in direct contact with the soil. This dead organic matter is often called litter.

b) The Standard Profile has a depth of 1.5 m and is divided into two units: 0-30 cm, to include the densely rooted or plowed horizon that contains easily exchangeable SOM, and the potentially less reactive fraction 30-150 cm deep.

Soils are intimately coupled with vegetation and the carbon content of soils is predictable from knowledge of the vegetation. The linkage of these relationships is close enough to encourage use of remote sensing in interpreting changes in soils following disturbance of the vegetation.

* In press, John Wiley and Sons.

The first classification of soils and their carbon content will be based on the classes of vegetation. The classification can be refined on the basis of well-known soil classifications within each major unit of vegetation. The most comprehensive sources of data on soil carbon content are the U.S. Department of Agriculture soil survey system and the FAO/UNESCO Soil Map of the World. There is a large variation in SOM content within each soil type in both systems and further data on climate and land use history are necessary. Special studies will be required to cover peat bogs and other formations such as caliche.

Changes in soil carbon will follow changes in plant growth, vegetation and land use. Among the changes likely to affect soil carbon are the following:

a) conversion of forest (or other natural vegetation) to agriculture;
b) reversion of former agricultural land to forest;
c) conversion of land to non-agricultural uses such as urban use;
d) harvesting of trees.

Woodland clearing for agriculture took place in Europe starting in Neolithic times, in North America from 1600-1900, and has occurred mainly in the tropics recently. The transformation of forest is invariably accompanied by a decline in soil carbon. Soils in the tropical rainforest may have a carbon content of 2-5 %, or 6-15 kg C m^{-2}. Under agricultural use the carbon content may fall by 50% or more. Soils in the savannah zone may also lose half of their carbon on conversion to agriculture. These changes are caused by loss of the vegetation, which is the source of the influx of carbon, by increased temperatures and increased rates of respiration associated with the rise in temperature, and, in some cases, by erosion. The change in carbon content under similar circumstances in the temperate zone is parallel but less. The decreases apply to tilled land; soils under pasture may have carbon contents either above or below the level in the original soils. The expansion of agriculture in the tropics is a major contemporary transition and there is every indication that it will continue.

Reversion of farmland through succession to woodland and forest is taking place, especially in North America. It may be accompanied by a build-up of soil carbon, thus counteracting the losses from the tropics. The magnitude of the increase is unknown but is open to estimation through remote sensing supplemented by systematic field studies.

Conversion of land to non-agricultural use is well-documented in Europe and of unknown but probably substantial magnitude in developing countries. Effects on the

soil are complex, ranging from quasi-permanent "sealing" in asphalt to carbon enrichment in gardens.

Felling of trees for forestry purposes, if followed by replanting or natural regeneration, has different effects on the soil from those of forest clearing for agriculture. The topsoil is greatly disturbed by earthmoving machinery and there may be accelerated erosion. Some carbon may be restored as slash decays.

The changes in soil carbon will be correlated with changes in the vegetation and a program based on remotely sensed measurements of the vegetation can be developed to interpret changes in soil carbon as well.

Conclusions:

1. Soil and vegetation are linked, both as to carbon content and changes in carbon content with time.

2. The separation of long-term refractory carbon held at greater depths from carbon that is available for decay in the short-term is important.

3. The first criterion for classification of soils is vegetation; the second, the soils themselves within the vegetation types. Maps showing classes of soils exist for most of the world.

4. Major changes in soil carbon follow changes in land use.

5. Any study of the inventory of soil carbon and changes with time will require field studies of selected plots plus more extensive surveys to measure changes following disturbance and recovery. Many such sites already exist.

6. An effort should be started soon to determine where data are adequate, where field studies now underway can be used, and where new field studies should be developed.

Panel Chairman: A. Young
Rapporteur: J. M. Melillo

E. Remote Sensing by Aircraft: Usefulness in Measuring Changes in the Vegetation and Soils of the Earth (Panel 4)

Remote sensing from aircraft can be used to supply supplemental information in a satellite-based program of

measurement of changes in the vegetation of the earth. The specific role of aircraft remote sensing includes the following.

1. Supporting "ground truth": Conventional black and white aerial photographs provide background information for interpretation of satellite imagery. A global study would involve aerial photographs of approximately 1,000 sites of 100 km^2 each.

2. Filling in of data gaps: Significant areas of the earth's surface will be missed by LANDSAT due to cloud cover. An appropriate sampling scheme using aircraft photography or aircraft mounted radar should be used whenever possible in these cases. The level of activity required is uncertain without further study of satellite imagery.

3. Detailed studies of certain sites: Detailed maps of field sites will be needed to test the satellite imagery. Aerial surveys in conjunction with existing data can be used for estimates of biomass at these sites. The basic descriptive maps needed for a global survey with stratified sampling would involve conventional mapping techniques for 1,000 10 km^2 sites.

Aerial remote sensing will provide special, supplementary information to two groups. First, the LANDSAT data processing group will obtain "ground truth" maps of certain areas at a scale of 1:12,000. Second, modellers will obtain the following from aerial sensors: 1) base maps of intensively studied sites: 2) vegetation type maps of intensively studied sites (1:24,000 scale; 10 m^2 potential minimum mapping resolution; 5-year periodicity); 3) field maps of 100 hectare subsections of intensively studied sites (1:4,800 scale; photographic enlargements of vegetation type maps); 4) biomass estimates from selected photographs within intensively studied sites.

The imagery used will include the following:

1. Existing imagery--A comprehensive inventory of existing imagery is needed to be used to fill data gaps, to use in selection of study sites and for training. These data would serve as the historical record of the intensively studied sites.

2. Specially acquired imagery--Small scale (1:60,000) aerial black and white and color infrared photography would be sufficient for the mapping of intensively studied sites.

Analysis will be by interpretation of stereo pairs. Machine assisted enhancement techniques such as video density slicing may be appropriate. The approaches necessary are conventional, well developed and routine. They are:

1. Conventional methods of aerial remote sensing. It is recommended that local personnel and aircraft be used when appropriate to take greatest advantage of experience.

2. Conventional methods of mapping from aerial imagery. Interpretation and map preparation activities should be centralized at one location with the products readily available to all who need them.

3. The sequence of activities commonly applied in such studies is:

   a. Compilation of catalogues of existing imagery;
   b. Preparation of intensive site maps;
   c. Preparation of "ground truth" imagery;
   d. Feasibility studies on vegetation volume (biomass) estimates from aerial interpretation;
   e. Determination of biomass in subsamples of intensive study sites;
   f. Continued service of "ground truth" and intensive study sites;
   g. Education of users and indigenous parties;
   h. Establishment of central storage and processing facility.

Conclusions:

1. Aircraft remote sensing will play an important supporting role in any program for measurement of changes in the carbon content of the vegetation and soils of the earth.

2. Role:

   a. To support "ground truth" for LANDSAT processing .
   b. To supply data in the sampling scheme for areas where excessive cloud cover prevents use of satellite imagery and to provide historical records from existing photography of intensively studied sites.
   c. To support modelling efforts by providing base and field maps, detailed vegetation cover maps, and remotely made estimations of biomass on certain plots.

3. Process:

   a. Use existing imagery.
   b. Make routine flights of selected test sites every five years at medium scale for mapping; make large-scale flights of sites for biomass where appropriate.

4. Precision:

   a. Vegetation cover and base maps of intensive study sites will be at 1:24,000 and 10 m^2 minimum mapping resolution. Field maps will be "blow-ups" of vegetation map at a scale of 1:4,800.
   b. "Ground truth" maps will be at 1:24,000 and 10 m^2 minimum mapping resolutions.
   c. Historical maps when prepared will be at 1:24,000.
   d. Radar coverage will be used in a sampling scheme to estimate aerial coverage of vegetation types. Sample site maps will be produced but no comprehensive mapping will be attempted.

Panel Chairman: E. Hardy
Rapporteur: J. Berry

F. Remote Sensing by Satellites: Usefulness in Measuring Changes in the Vegetation and Soils of the Earth (Panel 5)

Purpose

Satellite sensors collect reflected and emitted energy across a wide portion of the electromagnetic spectrum (~0.2 μm to > 1 m wave lengths) and convert the energy into a series of signals that can be used to produce many different images of the earth's surface. Such images have been used effectively to determine the distribution of various types of vegetation and to infer other details of the plant cover. Effective use of this type of information to measure the area and other more subtle characteristics of the plant cover will require substantial collateral information (see above and papers in the symposium), including some aerial photography and data taken on the ground. There is, however, no question as to the usefulness of satellite imagery for the purpose addressed by the conference. The only questions involve (1) details of the approach and (2) the accuracy possible. The report addresses these two topics.

Is Complete Coverage of the Earth Possible?

The total area of land that is vegetated is approximately 147×10^6 km^2. Each LANDSAT scene covers about 2.19×10^4 km^2 without overlapping other scenes. Worldwide coverage of land would require about 6700 frames, if no frame contained any coastal water or large areas of lakes. A more realistic estimate is 12,000 frames just to include all the land. Clouds and failures of equipment, difficulties in reception, and the fact that the satellites do not operate continuously would probably increase the total number of frames needed by a factor of 2 to 24,000. If changes in the vegetation are to be detected, the total would probably be doubled again to ~ 50,000 frames, a number that is clearly impractical. The Panel judged that there is no alternative to use of a stratified sampling system, despite the advances in automation or interpretation of imagery and in handling of data.

Additional limitations intrinsic to the satellite system make a sampling program, as opposed to an inventory, appropriate. For instance, receiving stations cover less than 50% of the earth's surface at present and tape recording of data over areas not covered by receiving stations is limited. The satellites do not operate continuously and cloud cover limits the usefulness of many images. Finally, imagery must be obtained from certain types of vegetation at a particular season and special attention must be given to seeing that the imagery is in fact obtained at that time and is useful. The probability is small of obtaining appropriate imagery for the entire earth over any period of less than several years.

Sampling for Measurement of Changes in the Vegetation of the Earth

The objective is measurement of the pattern and magnitude of changes in the storage of carbon in the biota and soils worldwide. The method is use of satellite imagery with collateral data applied through a stratified sampling plan. The criteria for stratification should be (1) the magnitude of the carbon pool available for change, (2) the probability of change, and (3) the size of the change. If it is possible to isolate the majority of change ($> 90\%$) in a small area ($< 5\%$ of total area), then the accuracy can be enhanced appreciably without a large increase in effort.

The measurement of changes in the vegetation and soils will require data that span at least a year. Accuracy will increase as the period increases and the extent of the changes measured becomes greater.

The work must consider successional change, the changes

over time following disturbance. Succession is especially important in forests because of their large carbon content. The ability to recognize successional communities will hinge on their spectral characteristics, the precision with which the changes can be recognized on the ground, and knowledge of the patterns and rates of succession for major vegetations. There is little experience with this topic and special attention to it in research is appropriate. The topic is important because a detailed approach to it will enhance substantially the accuracy of any appraisal of changes in carbon storage of any site.

Classification of Vegetation

The usefulness of floristic, physiognomic and economic classifications of vegetation based on LANDSAT data is open to question. The most successful use of LANDSAT data has been with economic classifications used in forestry. Physiognomic classifications such as Ellenberg's of 1973 and the UNESCO scheme of 1973 have also been used effectively. The Panel considered that the classification used by Whittaker and Likens (1973) is an appropriate system for the first approach and is useful here as an example of the degree of simplicity required in the first plan of a world study (Table 1).

The Panel emphasized the dearth of experience with tropical forests and urged the early establishment of a test site on the ground in the Amazon.

International Organization

With the possible exception of LACIE, no other remote sensing project of this size has been undertaken. The Panel considered that the best approach might be through an explicit attempt to develop regional interest in the project by encouraging development of regional centers. Centers for study of applications of remote sensing already exist in Kenya, Zaire, Upper Volta, in Bolivia, Brazil, and in Thailand. U.N. sponsorship might be desirable.

Implementation: A Five Year Plan

The discussion has been restricted to existing remote sensing systems. Improvements are underway. By 1985 several new sensors should be operating. These include 1) NASA's LANDSAT D with a 7-channel ($\simeq$ .4 μm to 14 μm) multispectral scanner with 30 m resolution (LANDSAT has 80 m); 2) the French SPOT satellite with reported 15 m resolution; 3) an ESRO "push broom" scanner with both high spatial and spectral resolution; and 4) Multiple Linear Array (MLA) systems now under

Vegetation	Area (10^6 ha)
Tropical Forest	
lowland	22.0
montane	2.5
Temperate Forest	12.0
Boreal Forest	12.0
Woodland	8.5
Tropical Grassland	15.0
Temperate Grassland	9.0
Tundra	8.0
Desert Scrub	18.0
Rock and Ice	24.0
Cultivated Lands	14.0
Swamp and Marsh	2.0
	147.0

Table 1. Areas of major vegetation types according to Whittaker and Likens (1973).

consideration by NASA. These systems would increase the availability of data and probably reduce problems of acquiring coverage for tropical regions.

A five-year plan has been outlined (Appendix A)

Conclusions:

1. Satellite-based remote sensing using conventional, existing equipment is appropriate for measurement of changes in the carbon content of the vegetation and soils of the earth.

2. The satellite-based approach will require:
   (a) a stratified sampling program;
   (b) collateral information from specially selected plots, from aerial imagery, and from the experience of specialists in the local vegetation.

3. A simple classification scheme is important, especially in the beginning. That scheme can become more complex as the work proceeds.

4. An emphasis on regional centers and regional experts is necessary to assure the best information and access to sites. A systematic effort in development of these centers is appropriate now.

Panel Chairman: J. Coiner
Rapporteur: C. Tucker

G. Selected References

Bacastow, R. and C. D. Keeling. Atmospheric Carbon Dioxide and Radiocarbon in the Natural Carbon Cycle: II. Changes from A.D. 1700 to 2070 as Deduced from a Geochemical Model. In Carbon and the Biosphere, G. M. Woodwell and E. V. Pecan, eds. Technical Information Center, Office of Information Services, U.S. Atomic Energy Commission, pp. 86-135, 1973.

Bolin, B. Changes of Land Biota and their Importance for the Carbon Cycle. Science 196, 613 (1977).

Bowden, L. and E. Pruitt, Manual of Remote Sensing, Vol. 2(American Society of Photogrametry, Falls Church, Va., 1975).

Ellenburg, H. "Die Okosysteme der Erde: Versuch einer Klassifikation der Okosysteme nach funktionalen Gesichtspunkten" in Okosystemforschung, H. Ellenberg, ed. (Springer-Verlag, Berlin, 1973).

Lieth, H. The Role of Vegetation in the Carbon Dioxide Content of the Atmosphere. J. Geophys Res. 68, 3887 (1963).

Moore, P. Atmospheric Carbon Dioxide and Forest Clearance. Nature 268, 269 (1977).

Morain, S., Interpretation and Mapping of Natural vegetation, in Remote Sensing, J. E. Estes and L. W. Senger, eds. (Hamilton, Santa Barbara, CA, 1974).

Stuiver, M. Atmospheric Carbon Dioxide and Carbon Reservoir Changes. Science 199, 253 (1978).

Tucker, C. Red and Photographic Infrared Linear Combinations for Monitoring Vegetation. Remote Sensing of Environment 8, 127 (1979).

_____, Hand-held Radiometer Studies on Vegetation in Situ: A New and Promising Approach: NASA Tech, Memo 80273 (NASA, Greenbelt, MD, 1979).

_____, Remote Sensing of Leaf Water Content in the Infrared, NAS ech. Memo 80291 (NASA, Greenbelt, MD, 1979).

_____, et al., Relationship of Red and Photographic Infrared Spectral Radiances to Alfalfa Biomass, Forage Water Content, Percentage Canopy Cover, and Severity of Drought Stress, NASA Tech. Memo 80272 (NASA, Greenbelt, MD, 1979).

UNESCO, International Classification and Mapping of Vegetation. UNESCO Ecology and Conservation Series No. 6, 1973).

Whittaker, R. and G. Likens, in Primary Productivity of the Biosphere, H. Lieth and R. Whittaker, eds. (Springer-Verlag, N.Y. 1973).

Williams, D. and J. Coiner, Utilization of Landsat Imagery for Mapping Vegetation on the Millionth Scale, in Proceedings of the NASA Earth Resources Survey Symposium (NASA, Houston, TX, 1975).

Woodwell, G. M., et al. The Biota and the World Carbon Budget. Science 199, 141 (1978).

II. SUMMARY AND RECOMMENDATIONS (Panel 6)

Changes in the area of forests as well as changes in the storage of carbon within forest stands have large potential effects on atmospheric CO_2. This conference addressed the challenge of measuring changes in the area of forests globally through use of satellite remote sensing. The conclusion of the approximately seventy participants from around the world was that a program based on LANDSAT imagery supplemented by aerial photography is both possible and appropriate. The following additional major points were made in the conference:

1. The primary objective should be measurement of changes in the vegetation of the earth because it is these changes that will affect the atmospheric CO_2. Measurement of the total carbon held in various types of vegetation should be the secondary objective.

2. The storage of carbon within soils is sufficiently closely correlated with the vegetation that the program can include estimation of the effects of changes in soil carbon stocks on atmospheric CO_2.

3. The emphasis on change as opposed to inventory makes a stratified sampling program appropriate. This step will reduce the size and the total cost of the program considerably below what would be required if successive world inventories were attempted.

4. The information required in addition to what satellite imagery is available since 1972 will include:

    (a) new imagery for segments of the earth for which imagery may not now be available because no imagery has been requested.
    (b) aerial photography, synthetic aperture radar (SAR) imagery, and side looking airborne radar (SLAR) imagery of limited areas to offer control data for interpretation of the satellite imagery. Much of the imagery probably exists.
    (c) data taken on the ground from specially selected plots to aid in development of the signatures for the interpretation of the satellite imagery and to provide information on the standing crop of carbon held in the vegetation and soils.
    (d) collateral information from existing maps, records of land use, soil surveys and the experience of regional specialists.

5. The work will be based heavily on data from intensive studies of limited areas around the globe. These studies will provide both tests of the interpretation of the satellite imagery and the data on the standing crop of carbon held in the vegetation and soils. The ground studies will also provide the information on succession needed to interpret rates of change in the vegetation following various types of disturbance. The number of such plots is indeterminate. The data will probably come from regional centers of research where long-term studies of forests and agriculture have been focussed over many years. There are many such centers around the world.

6. The data from this work will have wide application in interpretation of the role of the biota in major global nutrient cycles and will bear heavily on the management of these resources over the next years.

   The first steps in development of the study might be a pair of pilot studies, one in a heavily studied segment of the Temperate Zone Forest and a second in the Amazon with the objective of developing methods and estimating costs.

   Simultaneously steps should be taken to identify research centers that would collaborate on regional segments of the global study. The Brazilian Institute for Research in the Amazon (INPA) in Manaus is one such center.

   The importance of the work in resolving details of the global cycle and the potential of the analysis for supplying basic data for other global studies gives urgency to an early start. There is special need to start the process of accumulating background data including satellite imagery for critical areas around the globe. There is equal urgency in attracting able, thoughtful analysts of vegetation to address the problems inherent in such a large but important program. The program is necessarily international and will require international support. Such support develops slowly at best.

The Conference could not develop all the details of a global study. Various aspects of the work were considered in detail, however. These details appear in the papers of participants, published as a part of this report, and in the reports of the panels, above.

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IV. Appendix A
A Five Year Plan

FIRST YEAR

Collection of available data

- Landsat - from EROS Data Center (EDC) and other sources, including foreign ones.
- Photography - fom EDC, Defense Mapping Agency (DMA), and other private and foreign sources.
- Demographic and ancillary information- e.g., topographic maps, population distributions, climate data, vegetation maps.
- Radar - domestic and foreign (X-band or K-band mandatory) where available.

Identification of Test Sites

- Forest type - variety of cover, changed areas, available coverage.
- Change detection - clear cutting, successional response.

Identification of possible solution to problems (test site and extrapolation).

- Multiseasonal? (changes with season)
- Interpretation of SAR
- Registration - change detection, different scale data
- Appropriate classification scheme
- Recognition of floristic, physiognomic, and/or economic classes.

Development of Initial Methodology

- Photointerpretation and computer, including ancillary data
- Data base structure
- Conversion of ancillary data to usable form
- Digitization
- Manual collateral files.

SECOND YEAR

Initiation of pilot studies at forest remote sensing test sites

- Tropical forest sites (Puerto Rico and Brazil?)
- Multistage remote sensing studies
- Interfacing of remote sensing outputs to vegetation classifications
- Creation of detailed data base.

Collection of missing data necessary to complete ancillary data and remote sensing data

- Sensitivity of outputs to missing data
- Mission requirements - SAR and Shuttle
- Cloud cover studies of existing Landsat
- Identification of new collateral data needs

Initiation of sampling approach to areas not covered by detailed pilot studies

- Total area
- Choose a sample method

Initiation of change detection studies on pilot study sites

- Coordination with modelling effort
- Identification of areas of change - large, contiguous areas; scattered areas
- Identification of cover type changes
- Identification of change in vigor (density)

Initiation of biomass studies using ground or aircraft collected spectral data

- Accuracy required for success: 70+ percent
- Possible extension to other instrumented study sites (e.g., International Biome Program and Man in the Biosphere Program)
- Extension of biomass measurements to satellites

Planning of training program for Third Year

- Selection of an international training cadre - research staff, internal investigators
- Preparation of manuals and systems documentation

THIRD YEAR

Initiation of training personnel for international full-scale program

- Operational adaptation of procedures
- Training of local personnel
- Analysis of data by local personnel
- Coordination of regional operations by central directorate
- Selection of international participants for research teams
- Definition of equipment required for international sites

Initiation of sampling for non-pilot study sites

- Drawing of sampling frames
- Investigation of bias

Initiation of change detection for pilot study sites

- Computation of change data
- Evaluation of change data in relation to modelling effort

Case study of historical land cover change - 1972 on using Landsat, 1946 on using aerial photography

Establishment of ancillary data base on line

- Digitization of maps for high priority areas
- Extrapolation of climate data from specific stations to areas
- Digitization of other data as required

Analysis of two (2) years worth of pilot study-site data

- Accuracy - area, type, biomass
- Sensitivity to missing data
- Verification by airphoto, ground, and collateral sources
- Design review

FOURTH YEAR

Collection of data for missing remote sensing data as required

- SAR
- Shuttle
- Airphoto
- Non-U.S. satellites

Verification/validation evaluation of sampling approach to non-study site areas (i.e., balance of world)

- Estimation of sampling error
- Additional sampling as necessary

Establishment of the majority (70+ percent) of worldwide ancillary and remote sensing data base for modelling effort

- Access of on-line data base to users on limited areas
- Initial transfer of output data
- Evaluation of accuracy of operational product

FIFTH YEAR

Conclusion of change detection feasibility studies

- Assessment of how to operationalize

Conclusion of biomass studies using spectral data

- Assessment of future research direction

Establishment of global (i.e., worldwide) vegetation groupings using broad (to be determined) criteria

- 90 percent accuracy
- Flexibility for additional groupings as required

Completion of follow-on work recommendations

- Monitoring - area, type, change, state
- Base line data refinement.

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