The Role of Terrestrial Vegetation in the Global Carbon Cycle:
Measurement by Remote Sensing
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CHAPTER 9
Measurement of Changes in the Vegetation of the Earth by Satellite Imagery

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ABSTRACT

Substantial progress has been made recently in use of LANDSAT imagery for measuring the changes in the vegetation of the earth that must be recognized to resolve questions about the global carbon cycle. Progress has required the use of a mathematical model designed around the principles of succession. The data for the model are of two types: basic ecological information about succession, including especially rates of storage of carbon, and information on changes in land use such as rates of transformation of forests to non-forests and non-forests to forests. These latter data are most easily obtained by comparison of images taken sequentially. Primary reliance is placed on detection of change, not on classification and inventory. An example is given of how such data are used to determine the net exchange of carbon for a region such as the State of Maine. A global sampling plan designed to reduce the current uncertainty in the rate of deforestation from sixfold to less than 25 per cent would require a sample of less than one-tenth of the 12 000 scenes required to cover the total land surface of the earth.

9.1 INTRODUCTION

Pictures of the entire earth are now available as imagery from space. No corner of the earth has escaped the probing eye of LANDSAT or any of several other satellites, each arranged to record portions of the electromagnetic spectrum. And the imagery can be repeated, daily in some instances, almost twice monthly in others. The techniques are sufficiently versatile that new methods of investigation are possible using existing data to make further improvements in analysis of details of the earth's surface.

Despite this achievement, supported by hundreds of millions of dollars from the public trust, there is no clearly defined, simple method for obtaining global estimates of such attributes of the earth as the area of forests and changes in that area year-by-year. The need for the information is well-defined. It has been recorded in this book as information basic to resolving a series of uncertainties with respect to the global carbon cycle. But it might have been set forth with equal power as a need for information about changes in albedo, or rates of transpiration, or rates of runoff of water from once forested lands, or about areas in agriculture, or simply as an inventory of wood or energy or the potential for fixing energy biotically, all fundamental to life.

It is possible now to prepare a map of the vegetation of the entire earth from LANDSAT imagery. The problem is cost. Despite the millions available for the hardware, the money available for applications, even to fill fundamental human needs, is small. How can the specific information needed at any moment be extracted with elegance and economy from the wealth of information, equipment and opportunity available now?

Answers to such questions are never simple. Some of the complexity is indicated in the foregoing analyses: the enormous amount of scholarship that has been devoted to the interpretation and mapping of vegetation; the uncertainties inherent in interpreting the status of the carbon retained in soils; the bewildering intricacies of the film and other equipment used for remote sensing by aircraft and satellite; and for the problems of knowing, not assuming on tenuous evidence, what the image shows.

But there is simplicity and clarity emerging, too. Objectives are being narrowed. A new array of global problems is emerging with the CO_2 problem seen as central. The progress is both in narrowing objectives and in limiting the approaches to those that are most promising.

The existence of continuous coverage of the earth with several different types of imagery leads to the assumption that many comprehensive questions can be answered by some type of map. The promise is great. The four spectral bands recorded by LANDSAT offer a wide array of possibilities for developing and testing 'signatures' and it is easy to believe that unique signatures can be found for virtually any objective. This apparent versatility encourages the natural tendency toward classification and mapping, but it is misleading in that it encourages an expectation of great detail at small expense. Satellite imagery does not replace aerial photography. The need for critical choices, a winnowing of objectives, persists. Nowhere is this need for simplicity more clear than in the application addressed in this book.

9.2 DETECTION OF CHANGES IN VEGETATION

The summary of those aspects of the CO_2 problem presented above (Chapter 1), drawn from more detailed analyses (Woodwell *et al.*, 1978; Woodwell, 1978;

Moore *et al.*, 1981; Houghton *et al.*, 1983; Woodwell *et al.*, 1983a,b), suggests that the largest advance in determining the role of the biota in the global carbon cycle at present can be made by improved information on rates of deforestation, especially in the tropics. There is, of course, the possibility that in certain areas, such as the northeastern United States, the abandonment of agriculture has led to extensive reforestation (Woodwell *et al.*, 1978; Houghton *et al.*, 1983); any system for estimating net release from the biota must be capable of detecting reforestation as well. Changes such as these, from forest to non-forest or the reverse, commonly involve large changes in reflectance that are easily detected; the number of classes is limited to those that are most easily identified. Subtleties of elaborate classification schemes can be avoided and emphasis placed on detecting a small number of transitions, each of which can be recognized accurately over large areas.

There is a further advantage in avoiding classification in so far as possible. A complex classification or mapping system opens the possibility of errors due solely to the classification, not to errors in measurement of change. A misclassification of a forest that had not changed over the period considered, for example, would appear as a change in the inventory. There is no need to measure areas that are not changing with respect to their carbon content. Attention can be focused exclusively on areas that have been changed recently.

Despite the simplification, the avoidance of complex classification of vegetation, and the focus on change itself, identification of the types of change may require several years if the only source of information is satellite imagery (Figure 9.1). The forest to non-forest change is recognizable immediately, but

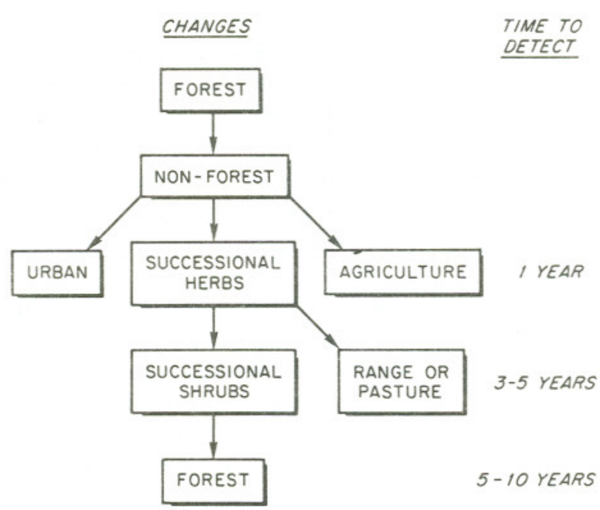

Figure 9.1 The use of satellite imagery for detection of types of changes may require successive images over several years

clear evidence that agriculture has replaced forest or that forest has been allowed to recover may not be available from satellite imagery for several years.

Such information, once available, must be tabulated to be useful in interpretation of the carbon cycle. The tabulation requires a model of some sort. The model used at present is based on succession. All sources of information are used to provide detailed analyses of the stocks of carbon in the vegetation and soils regionally and globally (Moore *et al.*, 1981; Houghton, *et al.*, 1983). The system is well suited for use with information from LANDSAT, especially if the data are derived as outlined here from an emphasis on detection of change as opposed to much more elaborate classification of the vegetation.

These two processes, the development of new data on changes in the vegetation of the earth, and development of a model capable of providing summaries of the net flux of carbon between the land and the atmosphere, are linked; neither can proceed with precision alone. A model that has been developed for this purpose is described in the pages that follow, and one application of it using satellite data from Maine is outlined. The experience suggests that the uncertainty surrounding current estimates of global deforestation can be reduced inexpensively to between one-half and one-tenth of the current level by a satellite-based survey.

9.3 A GLOBAL MODEL

Interpretation of how changes in vegetation and soils affect the amount of CO_2 requires knowledge of natural vegetation, knowledge of patterns of succession, and an understanding of patterns of disturbance over recent centuries. If the interpretation is to be global, a careful accounting will be needed to allow for the complexity of the transformations and to tabulate them over time for each of the various types of vegetation in different regions. It is necessary to know how the carbon in vegetation and soils changes as a result of disturbance and how much land is exposed to different kinds of disturbance each year.

To meet these needs, to provide a systematic and objective appraisal, and to keep a record of the changes over years to a century or so, a simple bookkeeping model has been developed (Moore *et al.*, 1981; Houghton *et al.*, 1983; Woodwell *et al.*, 1983a). The central principle was plant succession. Succession occurs following the harvesting of forest or the abandonment of agricultural or grazing land (Figure 9.2). At the time of harvest the stature of a forest is reduced by some fractional amount, and succession starts. At the same time there is a transfer of additional organic debris into the humus, insolation increases at the surface of the soil, soil temperature rises, and decay is

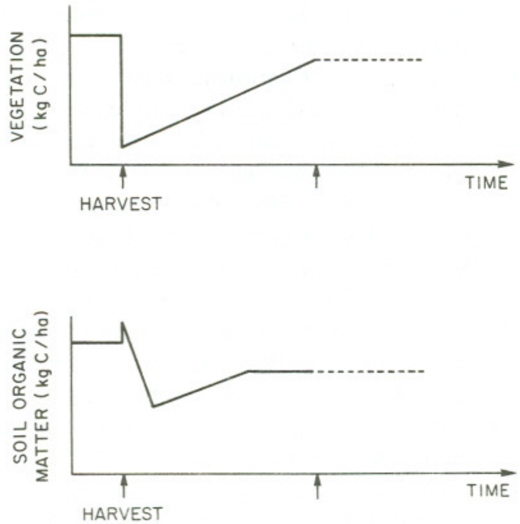

Figure 9.2 Idealized curves describing the changes per unit area in biomass and soil carbon that take place during the regrowth of a harvested forest

stimulated. Enhanced decay continues for several years, reducing the organic content of the soil below the amount that originally occurred in the forest (Covington, 1981). Changes following conversion of forest to agriculture are discussed in this volume in the chapters by Buringh and Schlesinger. When the carbon accumulating in the successional community more than balances the loss of carbon that occurs through respiration, the organic content of the soil begins to rise. Transfers of carbon into the harvested products, where the mean residence time varies between 1 and 1000 years, also were incorporated into the model.

Ten geographic regions were recognized in the model and twelve plant communities (ecosystems) were accommodated. The curves were modified for different initial stocks of carbon, different periods of succession, different degrees of recovery prior to further harvest, and different intensities of harvest. The transfer of carbon from the plant community into soils was modified to correspond to the magnitude of the transfer and the rate of decay. Details of the construction of the model were drawn from the literature and the experience of the authors (Moore *et al.*, 1981; Houghton *et al.*, 1983).

Two kinds of data are needed to operate such a model. One is the amount of carbon held in the vegetation and soils before and after disturbance; the other is the rate of disturbance. These data must be estimated if they are not available from field studies.

Information on the amount of carbon held in the vegetation and soils of the earth is limited. The tabulation prepared by Whittaker and Likens (1973) was used as the primary reference for the amount of carbon in vegetation and Schlesinger's (1977) tabulation was used for carbon in soils. These data were modified to accommodate other information, such as recent analyses of Brown and Lugo (1980). Earlier reports and the authors' experience were used to describe the changes in biomass and soil carbon that accompany succession and other transformations of forests (Houghton *et al.*, 1983).

The main source of information in 1980 on the changes in forest areas over time for the period following 1945 was the series of tabulations compiled by the UN Food and Agriculture Organization (FAO *Production Yearbooks* and *Yearbooks of Forest Products*, 1946–present). These tabulations include the amount of land used in agriculture, the amount of land in forests, and sales of forest products. All such data are subject to error, sometimes substantial (Persson, 1974), because the FAO reports the numbers as they are provided by the reporting nations. Methods of appraisal vary among the nations, and the data are occasionally affected by political considerations.

Other sources included summaries such as those prepared for tropical forests by Myers (1980) and earlier reports for other regions of the world. These records do not cover the entire world, however, and a comprehensive set of contemporary data obtained independently through objective methods is needed.

9.4 APPLICATION OF SATELLITE IMAGERY

The greatest simplicity in use of satellite imagery for the purpose outlined here appears to be in a system designed around detection of change using paired images. Various approaches have been used previously (Robinson, 1979; Riordan, 1982). One of the simplest is based on subtracting the spectral information of one LANDSAT scene from the information of a second scene of another date. The two images are brought into precise coincidence, one over the other, a process called registration. One image is subtracted from the other, both images being in digital form within the computer. Areas that have the same position and spectral information are nullified; areas that are different become part of the new, third image. The greatest difficulty is in obtaining accurate registration of one image on the other. Various techniques have been developed for facilitating the process (Woodwell *et al.*, 1983a).

The advantages of the approach based on detection of change as opposed to any system of classification are several:

(a) The paired image change detection technique avoids most classification.
(b) It eliminates errors associated with classification, a major potential source of error in estimating change.
(c) It measures the area of change directly.
(d) It focuses on the large, easily seen and readily measured areas of dramatic change (forest to non-forest, non-forest to forest) while relying

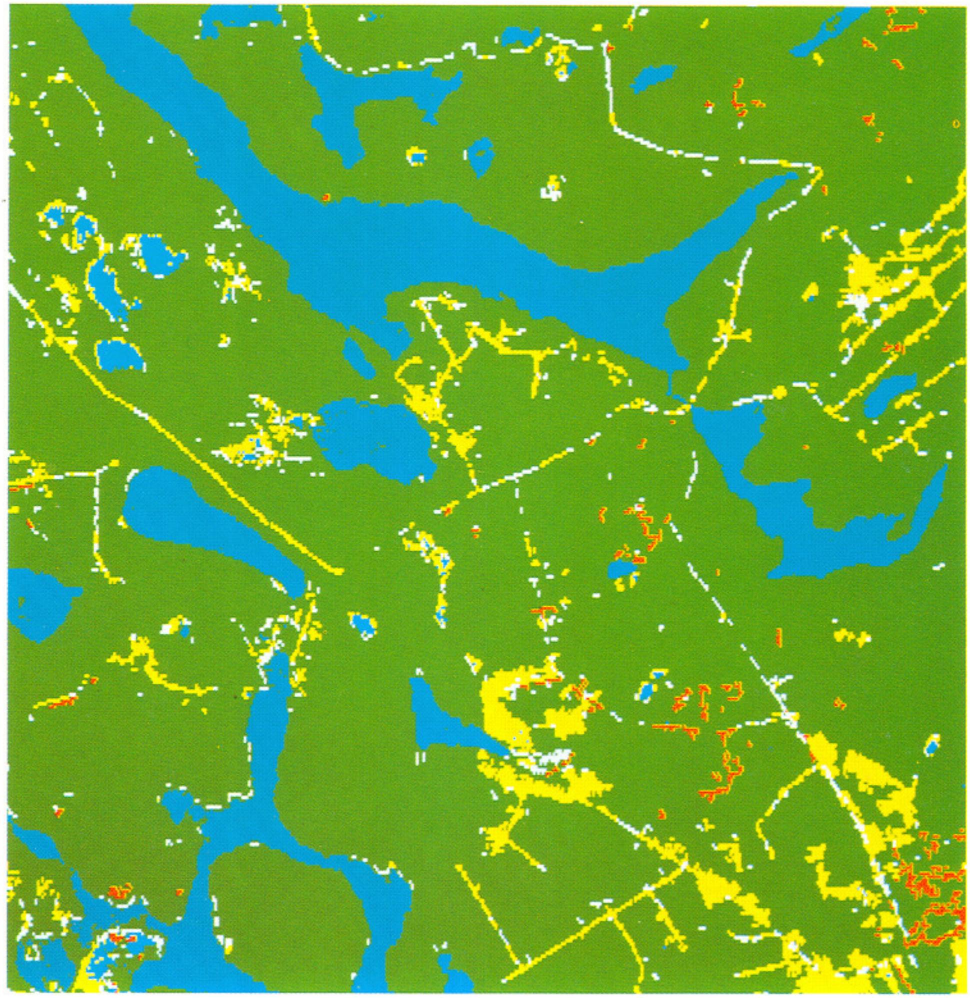

Figure 9.3 Mud Pond subscene, north central Maine. The changes are shown here in yellow for forest to non-forest and in red for non-forest to forest. (For key see Table 9.1)

on a model to compute the more subtle, easily misclassified successional changes in biomass over time.

(e) It estimates efficiently the most uncertain term (clearing and harvest rates) in the terrestrial carbon balance while relying on gound-based data for the terms most difficult to measure via satellite (carbon in biomass and soils of various types of vegetation).

The technique requires, however, certain systematic corrections and much care in application. Registration is usually accurate within ± 1 pixel. A systematic error of one pixel introduces errors into the residual image. The margins of ponds or forest stands may appear as changes. Roads, for instance, are approximately one pixel wide and appear as change if the images are not aligned perfectly. A special algorithm was prepared for this work to eliminate this edge effect (Woodwell *et al.*, 1983a). The correction was based on recognition that:

(a) errors of misregistration occur at boundaries; and
(b) these errors appear as lines one pixel in width.

The algorithm is a filter that eliminates single-pixel lines otherwise recorded as changes.

9.4.1 Implementation of the Method in Maine

The change-detection system has been tested in northern Maine and in the State of Washington using LANDSAT imagery. Figure 9.3 shows one application of the technique in a segment of a scene near Mud Pond in north central Maine. For convenience in presentation the changes have been superimposed on the LANDSAT image, which has been classified as shown (Table 9.1).

The accuracy of such tests was estimated for selected plots in Maine by use of aerial photographs at much larger scale. The same change detection procedure was followed in the photography as for the satellite imagery. The experience revealed that reliance on detection of high-contrast changes, such as

Table 9.1 The Mud Pond subscenes, north central Maine. See Figure 9.3

	Total area (%)	Colour
Water	13.6	Dark blue
Forest	78.4	Green
Bogs	0.6	Light blue
Roads and clear-cuts	1.7	White
Forest to non-forest	4.9	Yellow
Non-forest to forest	0.7	Red

the change from forest to bare ground, may introduce a systematic exaggeration of change beyond the single pixel lines discussed above. The problem arises because pixels on the borders of changes often cover an area that was only partially cleared but the entire pixel was recorded as changed because of the sharp contrast. The bias was corrected by subtracting half of the border pixels from the area recorded as changed. This correction was, of course, most important in areas where there were many small or long-narrow areas that had been changed in some way.

The change detection technique as outlined here was applied to three areas in northern Maine. The areas were selected for convenience in analysis, not because they were representative of Maine. Nonetheless, they provide an example of how data from satellite imagery, once accumulated, can be used with other data and experience to determine details of flux of carbon from changes in forest area.

9.4.2 Estimates of Forest Biomass and the Release of Carbon from Deforestation

The data from three subscenes in northern Maine indicated that 6.88 per cent of the area in forest was cut between September 1972 and July 1977, about 1.38 per cent annually. The total area of forests in Maine, according to Ferguson and Kingsley (1972), was 16 894 000 acres (6.837×10^6 ha) in 1971. If the annual cutting rate obtained from the three subscenes is representative for the state, timber was harvested over 233 000 acres (94 000 ha) annually.

According to US Forest Service studies, the 'growing stock' in Maine forests averaged 1258 cu ft of wood/acre (99 m^3/ha) in 1971 (Ferguson and Kingsley, 1972), or 28 metric tons (MT) C/ha (2.8 kg/m^2) (average density of wood is 700 kg/m^3 according to the FAO, 1979; average carbon content of wood is 45 per cent). Such estimates do not include leaves, branches, bark or roots. The crudest estimate of the net removal of carbon from the forests of Maine in 1975 is the product of area cut (94 000 ha) $\times$ biomass (28 MT C/ha), or 2.63×10^{12} g C.

This estimate can be refined considerably. First, growing stock is not equivalent to biomass. Growing stock volume includes only commercial species 5.0 inches of dbh (diameter breast height) or greater, and only the stem wood from stump to a top diameter of 4.0 inches. The rest of the tree above- and below-ground, smaller trees, non-commercial trees and other species may contribute to a biomass 2.7 times greater than growing stock (Johnson and Sharpe, 1982). With this conversion factor the mass of carbon in the trees would be 75.6 MT/ha or 7.5 kg/m^2 and the net release of carbon for the entire State in 1975 was 7.10×10^{12} g, about three times the crude estimate above.

A direct estimate of biomass based on field measurement of 376 samples from Elm Stream Township, taken by H. E. Young (1976) and colleagues, was 7.93 kg/m^2.

A small part of the total biomass is oxidized and released as CO_2 during harvest or immediately after harvest. Most of the wood is used to produce paper, lumber or other products that decay over a longer period. Paper products are usually oxidized in 10 years and lumber in 100 years. The delay in decay makes the records of earlier harvests important in estimating the flux for the current year.

The history of the harvest of forests in Maine from 1860 to 1970 was obtained from Wood (1971), Ferguson and Kingsley (1972), and Smith (1972).* The fraction of the harvest that was paper, lumber, and other products was estimated from reports of the Forest Service.

These data were used with the assumption that the fraction of the harvest in the 1-, 10- and 100-year decay pools has always been as it was in 1971 (6, 65 and 29 per cent) (Ferguson and Kingsley, 1972), to provide an estimate of the net release of carbon from Maine forests in 1975 of 2.36×10^{12} g. This estimate included the flux from wood harvested and burned in 1975 (0.16×10^{12} g C) and the flux from the oxidation of residual products from the last 100 years (2.20×10^{12} g) (Table 9.2).

Much of the original biomass is left on site at the time of harvest. For this analysis we started with a forest biomass of 75 MT C/ha (2.7 × growing stock of 28 MT C/ha), harvested 28 MT C/ha, and left on site 46 MT C/ha, of which only 5 MT C/ha was assumed alive and 42 MT C/ha was dead. Decay of logging residues from harvests over the past century contributed 4.38×10^{12} g to the net release of carbon in 1975 (Table 9.3). This was the largest single factor in the net flux.

Regrowth of forests following harvest removes carbon from the atmosphere and stores it in growing vegetation. Using harvest rates derived from the literature and from satellite imagery, the model calculated that regrowing forests accumulated 3.58×10^{12} g C in vegetation in 1975 (Table 9.2). We assumed that a harvested forest returns to its original biomass in 72 years, the time required to support a sustained yield of 1.38 per cent of the standing stock annually.

Disturbance of the forest floor during harvest results in oxidation of soil organic matter over several years (Tamm and Petterson, 1969; Covington,

* One of the problems of reconstructing this history is that certain units of measurement are not strictly comparable through time. For example there are not 12 board feet in a cubic foot (cu ft) because the International 1/4 in rule specifies that a board foot is $0.904762 \times (0.22\,D^2 - 0.71\,D)$, where D is the inside bark diameter at the small end of a four foot length of stem. Thus, the smaller the stem, the fewer the number of board feet per cu ft. For the sawlogs harvested from Maine in 1970 there were only six board feet per cu ft. The difference represents slash, sawdust and other residues which may be used for pulp or other industrial products, may be burned, or may decay over time. Other conversions subject to variability are the number of cubic feet of wood in a 128-cu ft cord (usually 80) and the density of wood itself (FAO, 1979).

Table 9.2 Factors contributing to the net release of carbon from forests of Maine in 1975

Factor	Net flux of carbon in 1975 ($\times 10^{12}$ g)
Oxidation of wood harvested in 1975	0.16
Oxidation of wood products harvested previous to 1975	2.20
Oxidation of logging residues from the 1975 harvests	0.26
Oxidation of logging residues from harvests prior to 1975	4.38
Storage of carbon in forests regrowing after previous harvests	−3.58
Net flux of carbon from soils (includes oxidation and build-up of organic matter)	2.89
Total net release of carbon in 1975 from harvest of forests	6.31

Table 9.3 A comparison of aircraft- and satellite-based estimates of deforestation in Washington

	Aircraft (ha)	Satellite (ha)	Error (%)
	68	68	0
	32	34	6
	50	49	−2
	23	26	13
	6	6	0
	45	36	−20
	40	36	−10
	26	24	−8
	34	29	−15
	8	4	−50
	6	4	−33
	29	35	20
	43	40	−8
	13	10	−23
	15	16	7
	9	9	0
Sum	445	425	4.5

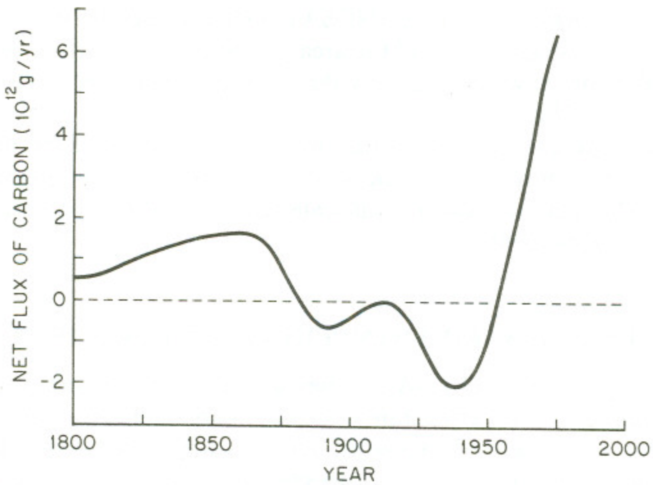

Figure 9.4 Net flux of carbon between the forests of Maine and the atmosphere from 1800 to present. The flux was positive for most of the period but became negative (atmosphere to biota and soils) between 1880 and 1950

1977). The assumption was made for this analysis that 20 per cent of the soil carbon in the top 1.0 m of soil is lost during the 15 years following harvest, and that the carbon content gradually recovers to its original level. Schlesinger's (this volume) estimate of the carbon content of boreal forest soils after 50 years of recovery is 200 MT/ha (20 kg/m^2). The results showed that in 1975 the soils of harvested and regrowing forests were responsible for almost 50 per cent of the computed net flux of carbon from forests (2.89×10^{12} g C) (Table 9.2).

The net annual release of 6.31×10^{12} g C from forests in Maine is a recent phenomenon (Figure 9.4). The increased release of carbon since about 1950 is the result of increased rates of harvests (Ferguson and Kingsley, 1972; Smith, 1972). During the period 1885 to 1950 regrowing forests were responsible for a net accumulation of carbon on land.

The experience, recorded here, in measurement of changes in forests shows part of the process by which remote sensing can be used to provide new, objective data on changes. The results demonstrate how those data can be applied with other data through use of a model to determine fluxes of carbon between the biota and the atmosphere. The combination of techniques developed in Maine and applied later in Washington shows how well satellite imagery can be used routinely to detect and measure changes in the area of forests. Tracts of 400–500 ha can be measured within $\pm$1–2 per cent; small areas, usually within about 10 per cent. Results of a test of the technique in forested areas of Washington appear in Table 9.3. As would be expected from all previous experience with LANDSAT imagery, errors in estimates of individual plots rise as the size of the area diminishes to one or a few hectares. The overall error, however, was less than five per cent over 16 plots whose total area was 445 ha.

The important questions as to the size of the sample and the design of a sampling plan appropriate for the globe have been left unresolved. While details of such a plan will await a full-scale test of the techniques, certain limits can be set at the moment.

9.5 STEPS TOWARD A SAMPLING PLAN FOR THE GLOBE

Approximately 12 000 LANDSAT scenes are required for one image of the total land surface of the earth. Handling such a large number of images would be expensive and awkward; a system for sampling is required. How much improvement in accuracy can be expected from sampling programmes of various intensities and designs? A detailed, quantitative answer will require experience with the sampling programme adopted, but data and experience available now show that the approach is practical.

Any sampling programme will be stratified to assure that the density of samples is higher in places where change is occurring. A knowledge of the areas of intensive change is needed. There is also a need to define the relationship between the intensity of sampling and the improvement in accuracy. In the following appraisal the ultimate sampling unit is the LANDSAT scene, a large unit (3.4×10^4 km^2 or 3.4×10^6 ha). Scenes will be subsampled in any final programme.

The objective is to use resources most effectively in improving information about rates of change in the area of forests globally. One criterion for the allocation of sampling effort is the uncertainty that exists among current estimates of changes for a region. Sampling might emphasize those regions now marked by uncertainty.

9.5.1 Identifying Critical Regions

Table 9.4 lists the rates of deforestation for 10 regions covering the entire earth. The estimates for tropical and subtropical regions were derived from FAO *Production Yearbooks* (1949–1977) (low estimate) and from Myers (1980) (high estimate). The ranges of carbon fluxes for temperate and boreal regions (non-tropics) were obtained from Armentano and Ralston (1980) and Houghton *et al.* (1983). Restricting the use of LANDSAT to forest reduces the number of scenes from 12 000 to 4200 globally (Table 9.5).

Ninety per cent of the uncertainty in the estimated global carbon flux for 1980 was attributable to five regions (listed in order of least to most certain):

Table 9.4 Range of estimates of deforestation and of carbon flux for the regions of the world

	Deforestation (10^6 ha/yr) Low	Deforestation (10^6 ha/yr) High	Flux of carbon (10^{15} g/yr) Low	Flux of carbon (10^{15} g/yr) High	Number of LANDSAT scenes containing forest
World	27.1	41.5	0	4.5	4260
Tropics	9.3	24.2	1.2	4.1	2128
Non-tropics	17.8		−1.2[b]	0.4	2132
North America[a]	5.7		−0.41[b]	0.003	604
Europe	1.6		−0.075[b]	−0.044	238
USSR[a]	7.8		−0.48[b]	0.5	1040
Pacific developed	0.5		−0.045[b]	0.003	185
China	1.3		0.13		65
Latin America[a]	4.0	7.6	0.73	1.38	847
North America and Middle East	0.26	0.34	0.038	0.056	55
Tropical Africa[a]	2.3	5.7	0.22	0.92	888
South Asia	1.9	2.8	0.17	0.46	114
Southeast Asia[a]	1.6	8.1	0.20	1.47	224

[a] Five regions that account for 90 per cent of the uncertainty in the global flux of carbon.
[b] Armentano and Ralston (1980).

Table 9.5 Number of LANDSAT scenes required for different levels of stratification

	Maximum Number of LANDSAT scenes[a]: with 100% sample	with 25% error acceptable
Global areas:		
Total vegetated	12 000	
Total forested	4 200	
Forest areas:		
Five critical regions	3 600	
Total tropical	2 100	360
90 per cent of tropical deforestation	1 200	
Highest rates of tropical deforestation	500	75

[a] Number of scenes calculated by summing, country by country, the scenes containing forest. Because scenes overlap at the edges of countries, some scenes were counted twice and the estimates are high.

Southeast Asia, USSR, Tropical Africa, Latin America, North America (Table 9.4). The forests of these regions are 85 per cent of the world's forests.

It is important to recognize the uncertainties inherent in individual estimates of deforestation such as those based on data from the FAO (1981a,b,c). The recent FAO Tropical Forest Assessment (1981c) estimated deforestation in Burma by two methods. Comparison of aerial photographs from the 1950s with LANDSAT imagery gave an annual estimate of 23 320 ha deforested. An estimate based on numbers of people practising shifting cultivation yielded an estimate of 92 000 ha. The FAO chose the second value as more realistic (FAO, 1981c).

Deforestation is not distributed randomly within regions. Certain countries and areas within countries have particularly high rates of deforestation, and a knowledge of these differences provides the basis for another level of stratification. The FAO Tropical Forest Assessment (1982) gives the rates of deforestation for 76 countries. Countries with rates of deforestation of 15 000 ha per year or higher are listed in Table 9.6. Deforestation in Brazil was divided among the Brazilian states according to data given by Hecht (1982). Thirty-four countries (or states within countries) account for 90 per cent of the FAO estimates of tropical deforestation. The number of LANDSAT scenes required to cover the forests of these countries once is about 1200.

Even within countries there is considerable geographic variation in the rates of deforestation. Myers (personal comm.) claims that the majority of deforestation occurs in zones of intense activity, or fronts (Figure 9.5). About 500 LANDSAT scenes would be required to view these areas. When countries or states are ranked by the rate of deforestation (FAO, 1981a,b,c) per unit area (Table 9.6), the sequence allows one to see the relationship between information and cost. Figure 9.6 shows the number of LANDSAT scenes required to document up to as much as 90 per cent of the total deforestation for the tropics and subtropics (FAO, 1981a,b,c).

9.5.2 The Number of Scenes Required for Accuracy

The discussion of numbers of LANDSAT scenes has been based on the assumption of a 100 per cent sample; that is, a complete analysis of the scenes covering the areas in question. Such a complete analysis would not be carried out; each area would be sampled. The number of samples ordinarily depends on the variance of the population, as shown in the following equation:

$$n = \frac{4\sigma^2}{L^2}$$

where n = the required sample size, σ^2 = the variance of the population (in this case the variance of the area deforested per LANDSAT scene) and L = the

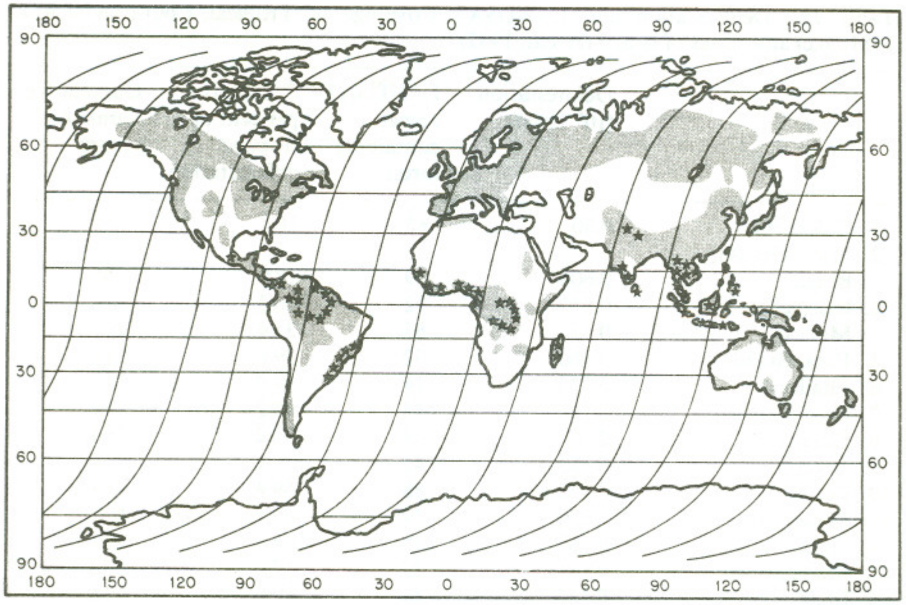

Figure 9.5 Regions of the world containing forests (shaded areas) and regions of intense tropical deforestation (stars). Horizontal lines are latitude: s-shaped lines are the paths (orbits) of LANDSAT in one day. Total coverage of the earth requires 18 days and, hence, 18 times as many orbits. There are 198 LANDSAT scenes in a cell bordered by 0° and 15° latitude and by two of the orbits shown. Data from Myers (personal communication) and the experience of the authors

acceptable error (expressed as a deviation from the mean area deforested per LANDSAT scene).

If an estimate of variance were available, the equation would give the number of scenes required for a 95 per cent probability that the measured rate of deforestation was within the acceptable error (L) of the true rate. To our knowledge an estimate of the variance of deforestation per scene does not exist. We were able to construct a crude estimate, however, by calculating for each of the countries included in the FAO Tropical Forest Assessment (1981a,b,c) the mean rate of deforestation per LANDSAT scene containing forest. The number of forested LANDSAT scenes per country was developed by creating a series of templates of LANDSAT scenes as overlay maps in the *World Atlas of Agriculture* (1969). Thus, for each of the 76 countries an average rate of deforestation per scene was estimated. The variance calculated from these 76 rates is an underestimate because it is based on averages. Nevertheless, we used it to evaluate the equation. We assumed that a 10 per cent error was acceptable; that is, $L = 0.10 \times \text{mean} = 9072$ ha/scene. Thus a sample size of 2250 scenes should give an estimate with 95 per cent probability

Table 9.6 Deforestation and LANDSAT Coverage of Tropical Countries (FAO, 1981a,b,c) and states of Brazil (Hecht, 1982)

	Deforestation (10^6 ha/yr)	LANDSAT scenes containing forest	Cumulative per cent of tropical deforestation	Cumulative number of scenes
1. Colombia	0.80	65	10.7	65
2. Mato Grosso, Brazil	0.608	39	18.9	104
3. Indonesia	0.550	92	26.3	196
4. Mexico	0.53	65	33.4	261
5. Para, Brazil	0.460	52	39.6	313
6. Thailand	0.333	24	44.0	337
7. Ivory Coast	0.310	15	48.2	352
8. Ecuador	0.30	14	52.2	366
9. Nigeria	0.285	45	56.1	411
10. Peru	0.253	68	59.4	479
11. Malaysia	0.230	21	62.5	500
12. Zaire	0.167	110	64.8	610
13. Madagascar	0.165	22	67.0	632
14. India	0.147	86	69.0	718
15. Maranhão, Brazil	0.146	20	70.9	738
16. Laos	0.125	11	72.6	749
17. Venezuela	0.125	46	74.3	795
18. Nicaragua	0.111	9	75.8	804
19. Philippines	0.101	40	77.1	844
20. Rondonia, Brazil	0.099	17	78.5	861
21. Burma	0.0955	31	79.9	892
22. Honduras	0.095	11	81.0	903
23. Nepal	0.084	8	82.1	911
24. Guatemala	0.080	9	83.2	920
25. Cameroon	0.08	31	84.3	951
26. Vietnam	0.065	19	85.2	970
27. Bolivia	0.065	56	86.0	1020
28. Costa Rica	0.060	6	86.8	1032
29. Acre, Brazil	0.043	10	87.4	1042
30. Liberia	0.041	8	88.0	1050
31. Angola	0.04	56	88.5	1106
32. Guinea	0.036	21	89.0	1127
33. Amazonas, Brazil	0.034	69	89.4	1196
34. Panama	0.031	10	89.9	1206
35. Ghana	0.027	20	90.2	1226
36. Sri Lanka	0.025	6	90.6	1232
37. Congo	0.022	13	90.9	1245
38. Papua New Guinea	0.021	26	91.1	1271
39. Kampuchea	0.015	11	91.3	1282

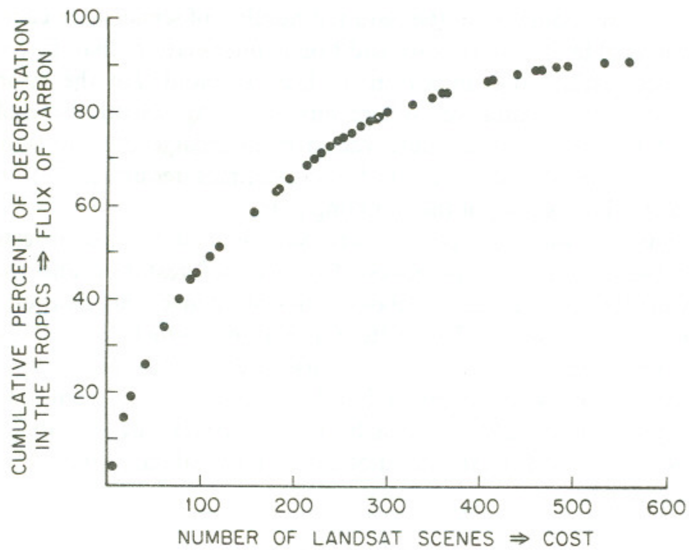

Figure 9.6 Per cent of deforestation observed as a function of LANDSAT scenes analysed. All of the deforestation (rate given by FAO, 1981a,b,c) is assumed to occur in fronts of intense activity

of being within 10 per cent of the true rate. The total number of LANDSAT scenes containing forests in the tropics is less than the required sample size, indicating that the variance is so large as to require use of 100 per cent of the scenes. When the sample size was calculated for the zones of intense deforestation, the required number of scenes was less than that calculated for the 76 tropical countries ($n=475$ scenes), but was, again, of the same magnitude as the total number of scenes for those zones (i.e., about 500) (Table 9.5). Complete coverage appears to be required for an error of 10 per cent or less.

Inasmuch as current estimates of deforestation in the tropics vary by 600 per cent (Houghton *et al.*, 1983), a reduction of the uncertainty to ± 10 per cent may be a greater improvement than is appropriate, at least immediately. If an uncertainty of ± 25 per cent were acceptable, the required sample size for all tropical and subtropical forests and for the zones of intense activity would be 360 and 75 scenes, respectively (Table 9.5). These values are equivalent to a sample of 17 and 15 per cent of the total number of scenes for these levels of stratification. The number of scenes might be reduced still further if subsampling within scenes were to be a part of the overall design. These numbers are small relative to the number of scenes containing forest worldwide. The samples may provide an acceptable estimate of deforestation for the moment, however, because other factors in the flux calculations are of similar uncertainty.

The progressive reduction in the required number of scenes with each step of this analysis (Table 9.5) is due to additional information that provides the basis for stratification. It is important to keep in mind that the information currently available is tentative. Where any sampling scheme is applied, its results must be used to recalculate variance, to change the location of the samples, and to recompute the number of samples required. This iterative process is a continuing part of the sampling plan.

On the basis of what is reported here, sampling of tropical forests might begin with two strata: one, the zones of intense deforestation and the other, the rest of the forest. Information about zones of intense deforestation may be obtainable from the NOAA 7 satellite, for example, which has demonstrated its ability to locate areas of current large-scale disturbance rapidly and inexpensively (Tucker *et al.* in press). Similarly, recent results from the shuttle-based imaging radar (SIR-A) (Elachi *et al.*, 1982) suggest that several approaches may complement one another in a global sampling effort of the type presented here.

9.6 CONCLUSIONS

Satellite imagery can be used effectively to measure current rates of change in the areas of forests globally. The basis of such use, however, must lie in direct measurement of changes, not in indirect analyses based on a comparison of inventories. Such an emphasis enables simplification to the point of avoiding most, but not all, classification of vegetation. The reliance on classification is replaced by detection of change, a much simpler process amenable to routine use of machine techniques.

The use of such data requires a model that incorporates the fundamental principles of ecological succession and the basic data on the carbon content of major types of vegetation. One such model, the MBL-TCM, is used at present. There is always a need for further refinements of the data and assumptions of such models.

Preliminary analyses suggest that a LANDSAT-based appraisal of current changes in the area of forests would be useful if based on a sample of 10 per cent or less of the approximately 12 000 scenes required to cover the land area of the globe.

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