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Carbon in Live Vegetation of Major World Ecosystems

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ENVIRONMENTAL SCIENCES DIVISION
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J. S. Olson, J. A. Watts, and L. J. Allison[1]

Environmental Sciences Division
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Data on mass of tropical forests in Table A-3 in Appendix A, and area data reviewed in Appendix A.3, were organized primarily by Yip Hoi Chan while he was a University of Tennessee postdoctoral Fellow at ORNL. We are grateful to Cheryl Palm, R. A. Houghton, and other staff of the Marine Biological Laboratory for advice while those data and other materials were being reviewed and published.

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The responsibility for many judgments, especially in discounting closed forest plot data for obtaining lowered biomass of natural and artificial openings in world landscapes, is mainly that of the senior author. This is U.S. Eastern Deciduous Forest Biome contribution 354 of the Analysis of Ecosystems Program of the International Biological Program and Carbon Dioxide Information Center contribution No. 9.

ABSTRACT

OLSON, J. S., J. A. WATTS, and L. J. ALLISON. 1983.
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Tennessee. 180 pp.

A computerized data base was developed to make a seven-color global ecology map (1:30,000,000 near the equator) of 44 land ecosystem mosaics or subdivisions in seven broad groups: FOREST AND WOODLAND; INTERRUPTED WOODS; MAINLY CROPPED, RESIDENTIAL, COMMERCIAL, PARK; GRASS AND SHRUB COMPLEXES; TUNDRA AND DESERT; MAJOR WETLANDS; and OTHER COASTAL, AQUATIC, AND MISCELLANEOUS.

Our main objectives are to document this computer-based global map of vegetation and carbon density for natural and modified complexes of ecosystems and to illustrate some human influences on the global carbon cycle. The map provides a basis for making improved estimates of vegetation areas and carbon quantities, of natural biological exchanges of CO_2, and eventually of the net historic shifts of carbon between the biosphere and the atmosphere.

Our map of world ecosystems and vegetation carbon is derived independently from: (1) patterns of preagricultural vegetation or potential vegetation types and their relation to carbon content, and (2) modern areal surveys and intensive biomass data from research sites. Ecosystem complexes are defined and located with a 0.5° x 0.5° grid that reflects the major climatic, topographic, and land-use patterns.

Most of the world's plant mass and carbon are in various major regional land systems, especially tree-dominated formations. The latter include FOREST AND WOODLAND of widely varying projected tree crown cover, plant mass and carbon, foliage reflectivity, and seasonality. INTERRUPTED WOODS, with substantial fractions of the landscape mosaic without trees or with stunted or open-grown trees, generally have lower mean plant mass and carbon. Disturbance, especially by fire (in many savannas) or clearing (in most <u>field/woods</u> and <u>forest/field complexes</u>), typifies many of these transitional complexes.

MAINLY CROPPED, RESIDENTIAL, COMMERCIAL, PARK and associated marginal lands are ecosystems that have been modified even more intensively by humans. Other mostly nonwooded landscapes include various GRASS AND SHRUB COMPLEXES that have major importance as grazing lands. TUNDRA AND DESERT complexes have progressively less live plant mass as extremes of low temperature and aridity are approached; yet significant carbon may be stored there as peat or as soil calcium carbonate (calcrete or caliche) in the cold and dry regions, respectively. Limited areas of "special complexes" are MAJOR WETLANDS and OTHER COASTAL, AQUATIC, AND MISCELLANEOUS systems. These may include either wooded or nonwooded cover, or mixtures in juxtaposition.

Estimates of biomass in trees and total carbon in live plants per unit area are tabulated. Additional data and sources are also cited in the Appendices. The results help define the role of the terrestrial biosphere in the global carbon cycle. The low to medium estimates for recent global total biomass carbon (460 to 560 Pg* C) are well below an earlier estimate by others of 830 Pg C, which has been used commonly in calculating release of CO_2 and other gases to the atmosphere. Lowered estimates for global pools follow from refinements in estimates of (a) areas of wooded ecosystems (especially high tropical forests with closed canopies) and (b) representative present-day standing stocks of carbon per unit area.

Results also imply major historic reductions of global carbon for broad regions and most vegetation types. Lowered estimates of carbon due to forest harvest or clearing for crops in the last century imply lowered estimates of input of nonfossil CO_2 to the atmosphere. The map of Major World Ecosystem Complexes indicates where some of the recent and future changes of organic carbon are most likely: in tree formations and wetlands where wood or peat reserves are still high or in some of the interrupted woods where recent land-use transition rates have been high.

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*1 Pg = petagram = 10^{15} g = 1 gigaton = 10^{9} metric tons.

Forest regrowth offsets some releases of CO_2, so net sources to the atmosphere may be <1 Pg C/year in recent decades. There has been potential for several petagrams of carbon per year of additional releases of CO_2 in historical times and the potential remains today, especially when soils are included in the global analysis.

Direct ecosystem influences on albedo and other physical boundary conditions and on the releases of atmospheric CO_2, methane and other trace gases will combine with unrelated factors to condition the future changes of climate. Eventually geographic definition of these variables can also be inferred from the data on landscape types supplementing the map. Refinement and use of the map and its associated data bases continue in research, e.g., on flux estimates for fire, forest clearing, and other carbon exchanges in models of the global carbon cycle.

Keywords: Biosphere; terrestrial ecosystems; global carbon reservoirs; carbon cycle; vegetation formations; biogeography; climate regions; mapping; human impacts

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<u>Notation Convention</u>: We have used the following conventions in the report when referring to the groupings and ecosystem types shown on Plate 1.

1. All capital letters denote a major category, i.e., FOREST AND WOODLAND.
2. Upper-lower case letters and underline denote major subgroups, i.e., <u>Tropical Savanna and Woodland</u>.
3. Lower case letters and underline denote minor subgroups, i.e., <u>cool conifer</u>.

Italics are used for Latin plant names and for a few other foreign words that have not become standard English. Quotes are used for titles of books and maps and in some cases for emphasis.

Single-space format is used for calling attention to some definitions, including those of ecosystem groups, and associated characterizations or locations.

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CHAPTER 1

INTRODUCTION AND SCOPE

1.1 OBJECTIVES

To improve the global carbon inventory of human-modified vegetation (Olson 1970a; Baes et al. 1976, 1977; Olson et al. 1978), a seven-color map, Major World Ecosystem Complexes (Plate 1), was prepared to reflect the modern heterogeneous tapestry of major world landscapes. The legend of Plate 1 and Chapter 3 of this report explain details of pattern and texture of this tapestry -- the typical patchy character of what we call "complexes."* The purposes of this map (Plate 1) are: (1) to distinguish major regional complexes of vegetation that can be mapped on a global scale; (2) to establish a uniform data base relating major types of ecosystems to their areal coverage, estimated from summing map cells or obtained from independent sources; (3) to rank the complexes by estimated organic carbon in mass of live plants (phytomass), and (4) to use criteria for application of ecosystem research, resource surveys, and remotely sensed data so that trends of plant carbon over time can be inferred.

The specific objective of this report is to document the computer-based global map of vegetation patterns and associated carbon density, for more or less natural as well as managed or otherwise modified complexes of ecosystems. The results are a step toward a long-range goal of illustrating and quantifying human influences on the global carbon cycle. The data and information sources document the geographic basis underlying estimates of areas and carbon content of the earth's vegetation.

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*"Complexes" are defined as mosaics of vegetation or landscapes, commonly juxtaposed within mapping units or the 0.5° latitude by 0.5° longitude cells used in the map, Major World Ecosystem Complexes.

1.2 BACKGROUND

Available vegetation maps and resource inventories are of insufficient detail, accuracy, and currency to answer major questions about the biological "source or sink" of atmospheric CO_2. A number of carbon estimates were summarized and discussed in the SCOPE 13 and SCOPE 16 reports (Bolin et al. 1979; Bolin 1981), along with applications for modeling the global carbon cycle. Other inventories use different methods and classification systems for estimating terrestrial carbon and are therefore difficult to compare. Regional studies, concentrating on one area without appropriate attention to all others, may furnish useful but limited data on types and trends. Changes in one vegetation group are sometimes offset by changes in the opposite direction in other areas. Deforestation or other modifications to the landscape in one region may be balanced by reversion to forests in others. But the carbon cycle must be evaluated on a global scale. While more detailed but localized studies proceed, the map and data base documented in this report provide a unifying format for the continuing evaluation of changes in estimated carbon in plant mass, and eventually other components, of the whole terrestrial ecosystem.

We infer that the mass of carbon in live plants during prehistoric times (∿1080 Pg C according to Bazilevich et al. 1971) was large enough to put several hundred billion metric tons, or petagrams,* of elemental carbon into the atmosphere as CO_2 as forests were cleared or cut over (Olson 1974). Natural processes redistribute the released CO_2 via the atmosphere to the hydrosphere (mainly the ocean), lithosphere (sediments), or other parts of the biosphere's organic matter (Baes et al. 1977). Many steps of that redistribution need to be clarified for a global picture of changes in CO_2 and climate (SCEP 1970, Woodwell and Pecan 1973; Keeling 1973a; Baes et al. 1976).

If the mass of present world vegetation is still large, perhaps with most of the carbon it ever had (827 Pg C according to Whittaker and Likens 1973; Whittaker 1975), then past contributions of CO_2 to

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*1 Pg = petagram = 10^{15} g = 1 gigaton = 10^9 metric tons.

the atmosphere, ∿240-Pg release spread over thousands of years, would average out to a small fraction of 1 Pg C/year (Olson et al. 1974, 1978). However, this rate of contribution from vegetation could have accelerated to several petagrams of carbon per year recently (Baes et al. 1976, 1977; Woodwell and Houghton 1977; Bolin 1977; Olson et al. 1978; Clark 1982). Continuing loss of a fraction of this assumed reserve could still be large enough to sustain the flux from modern organic matter as a source of nonfossil CO_2 equal to or exceeding that from fossil fuels (5 Pg C/year) for some time (Woodwell et al. 1978).

However, if the vegetation pool is near 560 Pg C or less as reported here, a large fraction (∿0.5) of the original pool of carbon in plants has already been depleted and only part of the remainder is available to die, burn, or decay to CO_2. Temporarily, incomes and losses of CO_2 in air might balance one another quite closely. Heated controversies about this and other interpretations of the world's recent state of carbon cycling have led to a broadened interest in refining the previous estimates of carbon in world vegetation (Olson 1970a, 1981a; Ajtay et al. 1979; Bolin et al. 1979). Net rates of change of the atmospheric reservoir (income to CO_2 minus loss of CO_2 per year) also clearly need more attention (Bramryd 1979; Hampicke 1979a,b, 1980). A better understanding of the pool sizes is required for calculating transfer rates and interpreting their changes (e.g., when percentage losses are multiplied by the source to derive estimated total loss of organic C and gain of CO_2).

The carbon total in the vegetation pool, near 558 Pg C, derived below is surprisingly close to early estimates of Olson (1970a), Olson et al. (1970, 1978), and Tables 1.2 and 5.5 in Bolin et al. (1979). However, it is lower than the 827 Pg C suggested for about 1950 by Whittaker and Likens (1973). The latter high value is frequently used (e.g., Woodwell 1978; Hampicke 1979a, 1980; Prentice and Coiner 1980; Seiler and Crutzen 1980) in calculating extra CO_2 reaching the atmosphere due to clearing or burning of forests. Because of the controversy noted about such rates of transfer, and their implications for modeling possible future change of carbon dioxide concentration and climate, it is necessary to clarify this basic parameter of the biosphere and its geochemistry.

Depending on the history of exchange, modeling of the carbon cycle indicates that an amount equivalent to 35 to 50% of the carbon released by the burning of coal, petroleum, and natural gas could be accounted for by absorption into the oceans (Broecker et al. 1979, Elliott and Machta 1979). Simple models of the ocean favored absorption estimates in the lower part of the above range (SCEP 1970; Machta 1972a, 1973; Fairhall 1973; Siegenthaler and Oeschger 1978; Olson et al. 1978; Siegenthaler et al. 1978). However, the increased atmospheric CO_2, as approximated by records at Mauna Loa (Hawaii) and the South Pole, has averaged only slightly above 50% of the estimated releases from fossil fuels (Keeling 1973b; Rotty 1980, 1981a,b) since records were started during the International Geophysical Year (Machta 1972b, Keeling 1973c, Keeling et al. 1982). The difference between the CO_2 accounted for in the atmospheric record and that in the models for ocean uptake might indicate that the vegetation and its residues of litter and humus have recently been functioning as a sink for the unaccounted-for CO_2. Conceivably, plants could store even more significant amounts of excess CO_2 in the future, as higher CO_2 concentrations enhance photosynthetic fixation (Keeling 1973a, Strain and Armentano 1980).

The obviously rapid rates of cutting old forests in some regions, especially in the tropics or subtropics, led many investigators to suggest that these would have to be a major source of CO_2 (Olson 1974, Baes et al. 1976; Bolin 1977; Adams et al. 1977; Woodwell and Houghton 1977; Olson et al. 1978; Woodwell 1978; Woodwell et al. 1978; Bramryd 1979; Hampicke 1979a,b, 1980; Bach et al. 1980a,b). Additional CO_2 was released as human populations encroached on previously wooded landscapes for cropland and as the traditional cycle of slash-and-burn (swidden) agriculture had to be completed in a shorter time frame (Seiler and Crutzen 1980, Olson 1981b). Some of the CO_2 released by further burning can be attributed to forest and grass fires, which served to speed up the natural return of organic matter to CO_2 (Olson 1981b).

In 1976, a release rate of 1 to 3 Pg C/year from tropical, subtropical, and south temperate forest and woodland was suggested (Baes et al. 1976). Bolin's (1977) global estimate was also in this range. By taking a higher estimate of forest biomass (Whittaker and Likens 1973, Whittaker 1975), using conversion rates from forest to crop or pasture of approximately 1% per year over wider areas and including even higher assumed humus oxidation rates, Woodwell and various coauthors (Woodwell and Houghton 1977, Woodwell 1978, Woodwell et al. 1978) inferred that release of nonfossil carbon was near 8 Pg C/year. They estimated releases as high as 18 Pg C/year if all the uncertainties were taken on the high side.

Broecker et al. (1979) and others objected strongly, arguing that there was no way such very high estimates for nonfossil CO_2 sources could be reconciled with the best ocean data and models available. A better understanding of the oceans, including nearshore areas with richer nutrients and inputs from the rivers, could perhaps account for the absorption of the excess fossil carbon that oceanographers formerly attributed to extra storage in land vegetation. However, there appeared to be little leeway for storing much carbon from nonfossil as well as fossil sources (Olson 1981a).

At the Dahlem (Berlin) Conference, Woodwell and Houghton (1977) impressed other researchers with the dilemma of the missing carbon. Yet Zinke (1977) had noted that many forests and soils, which formerly had carbon content reduced by human disturbance, were already at a developmental stage during which net storage could be increasing locally. Revelle and Munk (1977), meanwhile, quantified the rapid clearing of forest for cropping by expanding human populations. They also showed how some high, possibly unrealistic, allocations of newly fixed carbon from vegetation to soils could conceivably be stored as humus if some very simplified model assumptions were valid. Other modeling attempted to reconcile the release of CO_2 in one part of the biosphere with storage elsewhere, based on reviews of land-use change and historic shifts in its parameters (Olson et al. 1978; Chan et al. 1979, 1980; Chan and Olson 1930).

1.3 SCOPE

The global ecology map (Plate 1) displays the spatial distribution of major world ecosystem complexes estimated for 1980. Except for more drastic changes incurred by humans, it also reflects the map of broad "Continental Ecosystem Patterns and Reconstructed Living Carbon Prior to the Iron Age" prepared earlier by Olson (1970c), after Bazilevich and Rodin (1967). Both maps were developed during more than 20 years of field investigation and consultations, and analyses of maps and other literature. The latter are cited mainly in Chapters 2 and 3 and the Appendices of this report. The map printing was an experiment, using computer-generated color separation plates derived from a file of land-cover types.

Counting the cells of each type in each 0.5° latitude band and adding their areas over latitude bands gave total area estimates for these ecosystem complexes. Some independent area estimates are brought together in Sect. 4.1 and confirm the thesis that some earlier estimates of forest area and forest contribution to global carbon were apparently overestimated. Current estimates of the range in density of carbon per unit area are discussed in Sect. 4.2 and the Appendices. Multiplying the low, medium, and high density estimates by ecosystem area gives corresponding estimates of the global total carbon by ecosystem complexes (Sect. 4.3).

Only the mass of green plants is considered here, since the amounts of animal biomass are small in comparison. The mass of fungi and bacteria is not necessarily negligible, but evaluating it is beyond the scope of this report. This mass of decomposers varies greatly with time and space. It is important for controlling flux or recycling rates rather than for its own inventory. The recycling rate of CO_2 by respiration is usually expressed relative to the substrates of standing, fallen, and incorporated soil residues. The range of uncertainty about total plant carbon and its component parts reveals where more attention could reduce the uncertainty. Implications of these data are discussed briefly.

Estimation of the inventory of carbon in major world ecosystems and of the exchanges with the atmosphere and other major reservoirs has thus been approached in two ways. In the first approach, development of broad global patterns uses potential vegetation maps, or associates vegetation types with climatic or other environmental factors independent of local disturbance. The distributions described by Bazilevich and Rodin (1967), Lieth (1975), Küchler (1978), and Bailey (1978) are examples of this approach. In the second approach, development of modern regional or stand-type estimates is based on analyses of current vegetation and land-use practices. This method utilizes updated resource maps of natural vegetation, forestry surveys, agricultural yields, and human and economic as well as geopolitical considerations. Both approaches have been applied in the development of our ecosystem map. The personal judgment of experts about ecosystem types, their locations and extent, and likely biomass or carbon in landscape complexes representative of different parts of the world is crucial in either approach.

Uncertainties for regions known poorly or inferred indirectly (by analogy) will remain for additional refinements. The digitized map offers a systematic way of locating future revisions of boundaries and ecosystem areas. As amounts of carbon per unit area or their transfer rates are analyzed in more locations, then the mean estimates that are currently applied as "default" values for each place a given type occurs can be suitably adjusted for variations among nations, among climatic or soil regions of a given ecosystem type, or for particular map cells. That stage is not nearly ready for analyses. If the climate itself changes significantly, whether due to CO_2 or to other possibly interacting causes (Manabe and Wetherald 1967, 1975, 1980; WMO 1979; Clark 1982), then the relation of the present patterns of vegetation and climate can be used in helping to project the impacts on change of vegetation and related resources.

CHAPTER 2

METHODS: GENERAL APPROACH AND TECHNIQUES

Developing estimates of area and carbon density per unit area of ecosystems requires quantitative summaries over many landscape types. A digitized data base underlying the map (Plate 1) assigns to each cell of 0.5° latitude x 0.5° longitude (∿55 x 55 km at the equator) a prevalent ecosystem type or complex of types. Numerical and statistical analyses can be performed using areal extent, climatic, and topographic data bases to further describe existing vegetation on a global scale. Each vegetation type, or various logical groupings of vegetation types, can be related to its present geographical distribution and climate or to possibly altered locations in scenarios that are sometimes assumed for modeling future climatic change. Estimates of lower and upper bounds and the expected values for carbon inventories can then be used in geochemical modeling.

John Hummel and Ruth Reck of the General Motors (GM) Research Laboratories (Warren, Michigan) developed a digitized land-use data base for application in a global surface albedo model (Hummel and Reck 1979). The "Oxford Economic Atlas Vegetation/Land-Use Map" on a modified Gall projection (Plate 6 of Jones 1972; re-used by Cohen 1973) was the principal source for the GM data base. Hummel and Reck assigned 49 categories of land use and water to cells of varying increments of latitude from 66.67°N to 60.28°S, with a constant grid unit of 0.91° for the longitude. Of the 49 categories, 24 were designated as land systems (Fig. 1) and 25 as water bodies. We obtained this data base and expanded the classification to 47 land categories. Figure 1 shows the relation of the Major World Ecosystem Complexes map classification system as it has evolved from the Oxford Atlas and GM systems.

We placed the data base on a geodetic cell format of 0.5° latitude x 0.5° longitude covering the globe to facilitate ease of producing computer-generated maps and performing analyses using auxiliary data bases. For example, support data on climatic factors (temperature,

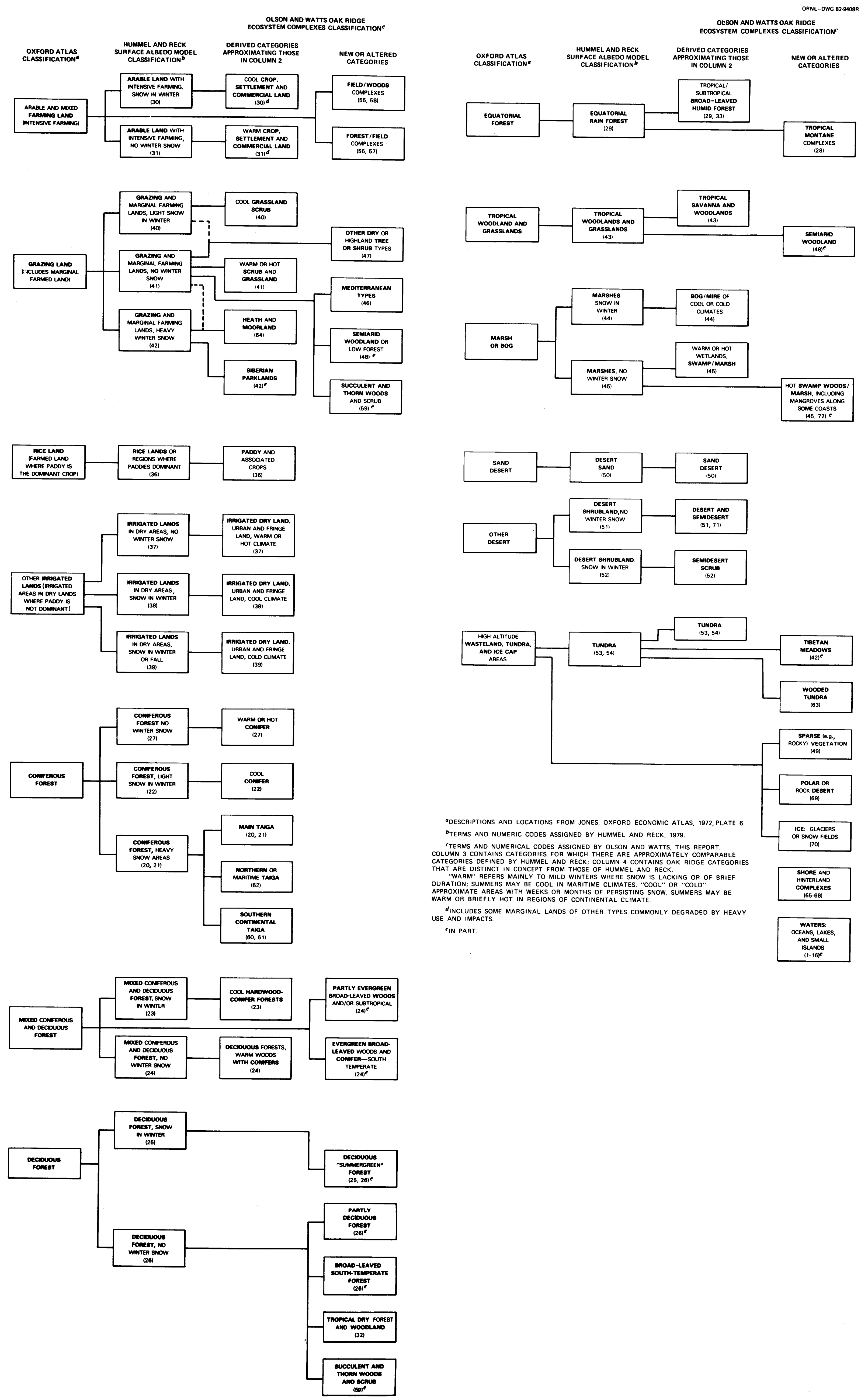

Fig. 1. Schematic diagram of the evolution of vegetation categories in the Oak Ridge National Laboratory map of Major World Ecosystem Complexes data base and relations to those of Oxford atlases and Reck and Hummel (1979).

precipitation, and biotemperature), elevation, biomass ranges and averages, areal extent of vegetation types, and estimates of the contribution of carbon to the atmosphere due to burning of vegetation have been developed and utilized. Summaries of the data base can thus be refined using groups of latitude-longitude coordinates or other regional and/or continental or hemispheric definitions.

2.1 LOCATING THE MAJOR NATURAL PLANT FORMATIONS

The present mapping was preceded by a number of historical efforts to map world vegetation. Rübel's (1930) "Pflanzengesellschaften der Erde" presented results gained from his own extensive travels and extracted from a century of prior biogeographic or geobotanical literature (e.g., Schimper 1898). This classification was illustrated by the world map of "Climatically Controlled Formation Classes of the Earth" by Brockmann-Jerosch (1930): see Chapter 3. Continuing Rübel's tradition, Ellenberg and Müller-Dombois (1967) defined the structural-physiognomic categories soon widely endorsed for mapping potential vegetation (Olson 1970b, Unesco 1973).

The biomass map and tabulations of Bazilevich et al. (1969) and Bazilevich and Rodin (1971) drew on the "Physical-Geographical Atlas of the World" (Gerasimov et al. 1964) and the geochemical synthesis of Rodin and Bazilevich (1967). The present map (Plate 1) draws upon published world ecosystem maps (Olson 1970c, 1971a), FAO forestry and agricultural surveys, and IBP syntheses on forest carbon and productivity. Excellent maps by Schmithüsen (1976) of world potential vegetation became accessible too late to define the main patterns of the map presented here, but they furnished an independent verification of many patterns.

2.2 ALLOWING FOR THE EXTENT AND KINDS OF HUMAN DISTURBANCES

We distinguish several ecosystem patterns that are related to human modifications (e.g., rice and other MAINLY CROPPED, RESIDENTIAL, COMMERCIAL, PARK; <u>Second-Growth Woods and Field Mosaics</u>) as well as to climate (Plate 1). To improve the global carbon inventory of human-modified vegetation, the map also reflects other locally heterogeneous mosaics of major world landscapes. Area estimates of crops by Hummel and Reck (1979) show that the economic atlas they used (Jones 1972) had a deliberate bias toward over-representing field crops when these exceeded forestry and grazing as income sources, even if woodlots exceeded fields in actual areal cover.

The wall maps of Maull (1966) on "Vegetationsgebiete der Erde" and the Olbricht-Haefke "Die Landschaftsgürtel der Erde" are other attempts to indicate additional aspects of agricultural as well as natural vegetation. The "Natural Vegetation" maps of Küchler (1978) and the Rand McNally "Environments" maps in Goode's School Atlas (Espenshade and Morrison 1978) can be used together to indicate which natural formations are most drastically changed, and where. Detailed worldwide mapping of forest patterns for individual countries is given by Wiebecke and Torunsky (1951-present). These "Weltforstatlas" sheets are valuable, but not always current or consistent. Traditional existing forest types from this and numerous local sources and observations were related to our broader global mapping units in many regions.

Maps from remote sensing were used, where available, in developing Plate 1 (FAO 1980) [e.g., in parts of Thailand, the United States, and Paraguay (Wacharakitti 1976; Williams and Miller 1979; Esser, in press)]. The legend was adjusted with some anticipation for wider use of a downward view of landscape patterns from space.

2.3 ESTIMATING LEVELS OF PLANT MASS AND CARBON IN ECOSYSTEM COMPLEXES

Any global mapping of geodetic cell units will result in regional mean values that are well below those found on selected stands with maximum biomass and carbon. Experience must be used in estimating the somewhat lower mean mass of live plants (phytomass) averaged over the heterogeneous landscape complexes. Appendix A illustrates methods of measuring stand means and local variations and deriving regionally weighted averages. Interruption by nonwooded landscapes accounts for many of the larger differences inferred for carbon density between mapping units and selected stands. Thinned and secondary vegetation, caused by either natural or human disturbance, further lowers the regional mean plant mass and its carbon. Ranges estimated for the legend in Plate 1 and in Chapter 4 required judgment and advice in allowing for such inherent irregularity of each ecosystem complex as a whole.

Methods of biomass estimation developed and tested in the 1950s and early 1960s in Europe, Japan, and the United States were applied in selected areas. The techniques of plant weighing and regression analysis relate plant mass to tree diameters and/or heights (Olson 1959, Shanks and Clebsch 1962). They were extended to productivity studies of Whittaker and Garfine (1962), Whittaker et al. (1963), Whittaker (1965), and Whittaker and Woodwell (1968, 1969, 1971). Work with J. D. Ovington of the British Nature Conservancy confirmed that various techniques gave essentially equivalent results regardless of the inevitable variability encountered among species (Ovington and Olson 1970). Sollins and Anderson (1971) tabulated substantial data relating tree mass to the more easily measured diameter at breast height (dbh) or to tree height (Appendix A). Analyses involved large numbers of leaves, branches, bole slabs, and (where feasible) stump and root samples that were cut, dried, and weighed promptly after harvest. Various other studies reviewed and tabulated by Art and Marks (1972) included cases where conversion from fresh to dry masses was based on a standard assumed moisture content for the species being sampled or for the season. Newbould (1967), Whittaker and Marks (1975), and the Appendices of this report give additional examples of deriving estimates of biomass and its carbon content.

Statistical techniques for estimating biomass and carbon in trees (with an example of biomass from Puerto Rico) and a description of tropical forests leading to a regional mean (e.g., Southeast Asia) are included in Appendix A. Brown and Lugo (1982) tabulated a large number of additional tropical or subtropical stand values and related these to life zones as defined by Holdridge (1947, 1967).

Several conferences on forest biomass were convened by the International Union of Forest Research Organizations (IUFRO 1972, 1973, 1976). At the 15th IUFRO Congress, Art and Marks presented a working table of biomass and net primary productivity for over 280 forest stands around the world (Art and Marks 1972).

Papers presented at the meetings of the Working Party on the Mensuration of the Forest Biomass in 1973 and 1976 (IUFRO 1973, 1976) extended the discussion of biomass estimation and sampling techniques. Studies ranged from biomass dynamics in a mixed deciduous forest watershed (Harris et al. 1973) to biomass sampling techniques and data in a tropical rain forest (Brünig 1973). Madgwick (1976) described techniques for estimating biomass and production, emphasizing the need for further study. Sharma (1976) used regression techniques similar to those described in Appendix A to estimate the biomass of two dominant tree species in the dry deciduous forest in India, while Smith (1976) discussed the use of timber inventory data to estimate forest biomass.

The International Biological Programme (IBP), established in 1964 by the International Council of Scientific Unions, conducted a series of studies of biological productivity on land, in fresh water, and in the oceans. The IBP goals were to better understand the biological basis of organic production as well as adaptability of humans to environmental changes. The IBP Synthesis Volumes bring together the results of the national and international activities involved in these studies. The international volumes of IBP are a source of much comparative biomass data for several ecosystem types including forest ecosystems (Reichle 1981), grasslands (Coupland 1979, Breymeyer and Van Dyne 1980), deserts (Goodall and Perry 1979, 1981), and tundra (Bliss et al. 1981). The national volumes of IBP cover additional detail on techniques as well as results.

Appendix B further documents these and many other sources. For tree formations, which dominate the world carbon total, Cannell (1982) briefly reviews the problems of combining the IBP, pre-IBP, and miscellaneous other data into a consistent set of summary tables which are now available in a unified format. The present study drew upon knowledge of many of the individual studies cited by him and the IBP books, and various chapters of Lieth and Whittaker (1975). Some of the reported values require corrections or other adjustments (e.g., for missing parts) before being generalized for the communities, complexes, or regions that they represent.

2.4 METHODS OF MANAGING DATA FILES

The data base, defining the Major World Ecosystem Complexes map (Plate 1), has a format similar to that used by Hummel and Reck (1979). It is a matrix of 360 rows and 720 columns, where the rows are the latitude bands and the columns are the longitude bands. Element (1,1) is centered on 89.75°N, 179.75°W. The matrix elements have an increment of 0.5°. Numeric codes were assigned to each vegetation type (assignment for each complex block shown on Fig. 1); there is no special significance attached to these code numbers and, as new categories have been added, the code has simply filled gaps or used the next number in sequence. This open-ended approach allows complete flexibility in adding new categories to the data base or subdividing previously defined categories without having to (1) predetermine the category groupings or (2) restructure an outline or reassign a numeric code each time a new category is added or existing categories are regrouped.

Each row of data consists of NP data pairs, where NP is the total number of pairs required to define the land or water cover for a given latitude band. The data pair is composed of the number of consecutive elements (left to right) for a given cover category and the numeric code assigned to that category as given in Fig. 1. This method of storing the data is compact and provides the capability for on-line interactive updating of each cell. This structure also allows subsetting the data base for user-defined application. Line printer maps can be produced directly from the file, while the computer-generated pen-and-ink (or other mechanical plotter) maps may require restructured temporary files to define the plotter symbol size and color assignments (if any) for each ecosystem complex type code. Thus, we were able to vary the color, symbol type, and size for special ecosystems (e.g., the broad-leaved and mixed forests) by latitude bands to better distinguish certain contrasts without yet assigning new cover codes.

A separate step is involved in converting from ecosystem complex type codes to carbon. There is considerable variation in the local carbon per unit area for a given type. A "medium" value for the type could be used at present (i.e., as a "default value") to apply in an interim data base for every land cell of a given cover type in the world. One interpretation of Plate 1 is for such a carbon map, with carbon content generally proportional to color density or size of the symbol. The approaches to local research sites and to regions, illustrated in Appendix A, are used in the present report as examples linking primary data to type means averaged over the whole world. Some refinements (e.g., in splitting boreal forest or taiga) are already included.

The next step, beyond the "default" data base of carbon for the whole world, is to separate additional type groups geographically (e.g., among regions of high and low as well as intermediate average carbon pool or flux rate). A third step, some years into the future, should draw upon enough locally surveyed locations and regions to justify substituting cell-by-cell results for the averaged values based on global or regional means.

CHAPTER 3

DEFINITION, CHARACTERISTICS, AND LOCATIONS OF MAJOR ECOSYSTEM COMPLEXES

Three distinct definitions of "percent cover" are useful and apply over three ranges of scale in the continuum of space and size:

(a) "Projective foliage cover (pfc)" refers to vertical projections to a horizontal plane (usually) from individual leaves or equivalent photosynthetic tissue. The upper canopy layer that defines the main structure (physiognomy) is normally used in giving a numerical rating; the number would be higher if woody understory or ground vegetation (field layer) were also included. A pfc rating would be less than 100% even under the canopy of an individual tree, and its average value would be lower when extended to a stand (i.e., by deducting for space between the trees). A mean would be still lower for a region, if some stands of the complex were essentially without trees. Specht (1970, 1981a,b) and colleagues in Australia use pfc to define gradations between "closed-forest" defined as having *ï*70% pfc. Table 1 shows their system. Gillison and Walker (1981) estimate that this foliage cover is equivalent to *N*90% of crown cover.

(b) "Crown cover" is a widely used term that may be imperfectly standardized. Conventional usage applies it to percentage of area covered by outlines or polygons projected vertically from tips of live branches. The pfc is lower than crown cover; light filters between branchlets, leaf blades, or needles in the idealized vertical projections-- even without considering the real-life fluctuations of extra light introduced by changing sun angle and blowing of branches. The geometry of overlapping crowns and leaves means that "leaf area index" (LAI), or ratio of one-sided leaf area to ground area, usually exceeds one in tall or dense forests that have high pools and production rates for organic carbon.

(c) "Percentage of types in a regional complex" applies to entire mapped areas (e.g., global cells or whole quadrangles) that normally contain complexes or mosaics of major and minor cover types. In Fig. 2, for example, the percentage of area with nearly treeless cover increases toward the top of the triangle. There are important complexes (called INTERRUPTED WOODS) in which treeless and also more wooded patches are both important in governing the structure and texture of the landscape, along with its carbon content, and perhaps trends of carbon and its release to CO_2.

Table 1. Approximate relations between structural vegetation terminology of Gillison and Walker (1981), Specht (1970, 1981a, 1981b), Carnahan (1976), Food and Agricultural Organization (FAO 1973, Persson 1974), and Major World Ecosystem Complexes Map

Life form of tallest stratum	Life form code[b]		Projective foliage cover (pfc) of tallest vegetation stratum for stand (or region for FAO)[a] 100-70%	70-50%	50-30%	30-20%	20-10%	10-5%	5-<0.1%
			Approximate equivalent crown cover (judged by Gillison and Walker 1981) >90%	90-65%	65-45%	45-35%	35-20%	20-10%	10-<0.2%
Trees[c] >30 m	vt	T		Tall closed-forest	Tall open-forest	(disturbed forest areas)			
20-30 m	vt								
Trees 12-20 m	t	M	Closed-forest	Open-forest	Open-forest	Woodland	Open-woodland		
10-20 m	m								
Trees 6-10 m	m								
3-6 m	ℓ	L	Low closed-forest	Low open-forest		Low woodland	Low open-woodland		
2-3 m	vℓ								
			"Closed" forest, sensu FAO Forest Survey: >20% crown cover						
					"Open" woodland (sensu FAO)				
						Woodland (Gillison and Walker 1981)			
							Savanna, etc. (Walker and Gillison 1982)		
			"Woodland" in the inclusive sense of Ovington (1962, 1965)						
Shrubs >2 m		S	Closed shrub	Open scrub	Open scrub	Tall shrubland	Tall open-shrubland		
Shrubs 0.25-2 m									
Heath-like		Z	Closed-heathland	Open-heathland	Open-heathland	Low shrubland	Low open-shrubland		
Chenopod (or other)		C	--	--	Low shrubland	Low shrubland	Low open-shrubland		
Shrubs <0.25		D	[Low scrub tundra]			Dwarf open-heathland (fell-field) [for tundra, desert]			
			Brush or scrubland (sensu FAO Forest Survey)						
Bunch ("hummock") grasses		H	--	--	--	"Hummock grassland"	Open hummock grassland		
Sedges		Y	Closed-sedgeland	Sedgeland		Open sedgeland	Very open sedgeland		
Other Graminoid		G	Closed-grassland	("Tussock") grassland		Open grassland	Very open grassland		
Ferns		F	Closed-fernland	Fernland					
Other herbs		X	Closed-herbland	Herbland (or forbland)		Open herbland	Very open herbland		

[a]When stands having tree overstory canopy percentage cover as low as 30% are even locally interrupted further by disturbance and abnormal topography, it seems likely that the regional cover of canopy projections may extend as low as the 20% crown cover guideline for FAO (1973) forest surveys. FAO and Persson (1974, Appendix) do not distinguish the gradations of "open-forest" and "woodland" between the extremes of "closed-forest" and "open-woodland." Operating definitions for the latter actually stress high percentage presence and continuity of grassy field layer cover instead of the actual tree cover percentages, or else the association of tree species that tend to be associated with such a field layer. If trees are judged capable of reclosing after recent disturbance, cover as low as 10 or 15% may be typed as "forest." Savannas, having even sparser trees over most of the area, may nevertheless be interspersed with stands that qualify as closed-woodland or (along streams or areas otherwise protected from fire) locally as open- or closed-forest. See also Unesco (1973) for slightly different emphasis, depending even more strongly on the potential vegetation inferred by reasoning and background knowledge instead of the actual vegetation (cf. Schmithüsen 1976).

[b]Major life form code in upper case after Specht (1981a,b). Tree heights given in lower case (vt, very tall, to vℓ, very low) are oriented to Gillison and Walker's (1981) spread for woodlands (or savannas in Walker and Gillison 1982)--not common usage in forests.

[c]"Trees" are defined by Specht (1970, 1981a,b), Carnahan (1976), and other Australian conventions as single-stemmed (monopodial) woody plants. In some regions, sprouting habits (e.g., *Tilia*), especially following disturbance (e.g., *Quercus* after fire, blow-down, or cutting), make multiple stems fairly common in forest and especially in woodland types. In Australia, Specht (1981a,b) associated closed-forest mainly with quite isolated relics of subtropical or temperate rain forest, which are regionally associated with wet sclerophyll *Eucalyptus* (e.g., *E. regnans*, *E. obliqua*) types considered "tall open-forest)."

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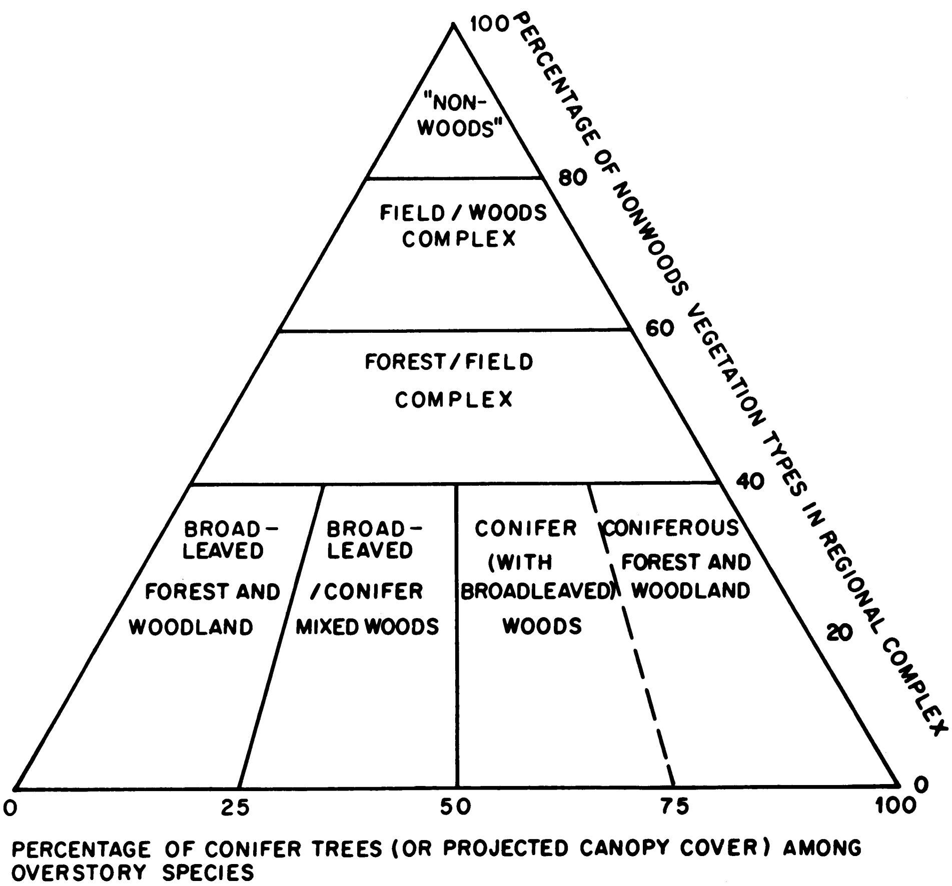


Fig. 2. Approximate relations of tree cover, regional percent of nontree formations, and major kinds of forest, interrupted woods, and nonwoods systems.

Landscape areas mapped on a world scale (with unit cells up to 55 x 55 km at the equator) contain a mixture of community or landscape types. The parts of each complex are impossible to map separately, except for small regions, on very large scales (e.g., 1:20,000 or larger air photographs, as used in soil conservation mapping in the USA) (Olson 1971a). Patchiness occurs as a function of differences in terrain, substrate, or elapsed time for development and stabilization of the soil and ecosystem features following disturbance (Jenny 1980, Burgess and Sharpe 1981). A common practice is simply to name the landscape areas or complexes by the single most extensive type. The prevailing type exceeds 50% of the mapping unit or unit cell of the grid if it is mixed with only one other kind of landscape inclusion. But where more than two kinds of vegetation or landscape (or water) are mixed together, the most common one may still cover less than half the total area in some cases. On Fig. 2, the percentage of nonwooded vegetation, alternating with forest and woodland, defines some of the transitional types described below as "second growth woods and field mosaics." Many of the types given here also meet conventional meanings of forest-type cover, as implied by percentages of individual tree canopy projections, used in the horizontal axis of Fig. 2. Other, more regional and climatically oriented distinctions are also used below. Those based on life forms (Fig. 3) are called "formation classes" like those of Brockmann-Jerosch (1930) or Unesco (1973). Walter (1979), Eyre (1963, 1971), Daubenmire (1978), and Whittaker (1975) provide good general introductions to the geography of the plant formations.

The legend blocks on Plate 1 are arranged in seven broad groups: FOREST AND WOODLAND; INTERRUPTED WOODS; GRASS AND SHRUB COMPLEXES; MAINLY CROPPED, RESIDENTIAL, COMMERCIAL, PARK; TUNDRA AND DESERT; MAJOR WETLANDS; and OTHER COASTAL, AQUATIC, AND MISCELLANEOUS. The map (Plate 1) uses various combinations of color, hue, symbol size, and pattern to subdivide these groups so that 44 mapping units, excluding ice and oceans, can be distinguished. Some details were edited manually for map printing. A few of the categories in the data base are combined for simplicity.

An overview or key to definitions and hierarchy of the vegetation complexes defined here is given in indentations on the left of Table 2. Wet or coastal ecosystem complexes are those with substantial influence of high water table, flooding, or shore processes. MAJOR WETLANDS have large fractions of their area with water above soil or sediment level for many weeks of many years. COASTAL ecosystems are close enough to ocean, lake, or large river shores to reflect their persistent local influence in the soil or atmospheric environment and parts of the vegetation mosaic. Typical land ecosystem types commonly occur also as fringes to either of these, or as hinterlands or inclusions in the mapped complex. Ports and resorts are typical human landscape types near coasts or along major rivers.

Table 2. Summary of areas, carbon, and production estimates by map legend elements for major world ecosystem complexes[a] (NOTE: Numbers after each main category in the first column are obtained by summing the indented lines (subcategories) under each main category. Likewise, subcategory totals are obtained by summing the sub-subcategories under each subcategory.)

Categories (legend elements)	Area (10^8 ha or 10^6 km^2)	Plant carbon Density (kg/m^2)	Plant carbon Total (Pg)	Net primary production (Pg/year)	Typical Unesco (1973) plant formations or formation groups
Major Regional Land Systems Groups	145		550.6[a]		
TREE FORMATIONS (WOODS)	58.17 (+2.6)[a]		476.7 (+6.6)		
Major FOREST AND WOODLAND	30.79		359.7	19.1	Mostly FOREST (I):
Mostly taiga and other conifer	10.66		121		
Main and Southern Taiga	7.16	8.7	62	3	IA10c-d, B3b-e; IIA2
Other Conifer	3.50	16.8	59	2.1	IA9-10, IIA2a-b
Mostly mid-latitude broad-leaved and mixed	5.03		50		
Temperate Broad-Leaved Forest	1.49	10	15	0.9	IA6-8, B3, IIB3
Mixed Woods: deciduous to evergreen broad-leaved, often with conifer	3.54	10	35	2.1	IB2, IIB2, plus preceding
Main Tropical/Subtropical Forest	15.1		189		
Broad-Leaved Humid Forest	10.38	15	155.7[a]	8.3	IA1-5
Dry Forest and Woodland	4.72	7	33	2.7	IIB1, Ai; IB1, A3
INTERRUPTED WOODS	27.38 (+2.6)[a]		117 (+6.6)	12.4(+1.4)	WOODLANDS (II) + shrubs (III), herbs (V), forest:
Tropical savanna or montane	7.32		25.6 (+0.6)		
Tropical Savanna and Woodland	6.72	3	20.2	3.3	VA1-4, IIB1
Tropical Montane Complexes					
Tall or dwarfed forest	0.6	9	5.4	0.4	IA1c-e (IA4, 9b)
Grass, scrub, paramo, rock	(0.6)	(1)	(0.6)	(0.4)	VC1-5; IIIA
Other dry woods mosaics	8.51		35.4		
Woods/Scrub/Grass Complexes	7.6		30.4		
Succulent and thorn woods	4.0	4	16	1.6	IIC; IC; VB; A2d-e
Mediterranean types	1.0	4	4	0.5	IA8; IIA1-2a; IIA1d; IVA2-3
Other dry or highland woods[b]	2.6	5	10.4	0.8	IIA-C; IIIA2b-B; VC1-7
Semiarid Woodland or Low Forest[c]	0.91	5	5	0.4	IIA1-2a; IC
Northern or Maritime Taiga, subalpine	4.35	5	22	1.3	IIA2b-c; IIIB3; IVD
Second Growth Woods and Field Mosaics	7.2		34 (+6)		
Forest/field (allocations)	5.2		26		Mixtures of above, plus woody and other crops and fallow areas
Tropical/subtropical humid forest	1.7	5	8.5	1	
Temperate/boreal forest	3.5	5	17.5	2.1	
Field/woods (allocations)	2.0				
Tropical woods	1.34	4	5.2	0.65	Sparser or lower woods remnants, with more fields or grazing lands
Temperate woods	0.7	4	2.8	0.35	
Fields, grass, scrub	(2.0)	(3)	(6)	(1)	
NONWOODS (trees planted, sparse, low, or absent)	84.2 (+2.6) 86.8		67.3 (+6.6) =73.9		
MAINLY CROPPED, RESIDENTIAL, COMMERCIAL, PARK, and associated marginal lands	15.9		21.5	12.1	Permanent (mostly woody) and other CROPS, ornamental plants, etc.
Irrigated land and surroundings	3.6		9.2		

Table 2. (continued)

Categories (legend elements)	Area (10^8 ha or 10^6 km^2)	Plant carbon Density (kg/m^2)	Plant carbon Total (Pg)	Net primary production (Pg/year)	Typical Unesco (1973) plant formations or formation groups
NONWOODS (continued)					
Paddyland	2.0	3	6	3	VA1-5, D, E (IA-B) + crops
Other Irrigated Dryland, etc.	1.6	2	3.2	2	VA-D (IB-C) + crops
Other Crop, Settlements, and Marginal Lands	12.3		12.3		VB-C (I-IV) + crops
Cool or cold farms, towns, etc.	3.0	1	3.0	1.5	
Warm or hot farms, towns, etc.	9.3	1	9.3	5.6	
GRASS AND SHRUB COMPLEXES	23.9		39.06	8.6	GRASSLAND (V), SHRUBS (III)
Main Grassland or Shrubland	21.4		26.76[a]		
Warm or hot shrub and grassland	17.3	1.3	22.6	7.0	VA2-5, B2-C6
Cool grassland/scrub	3.94	1	3.94	1.2	VB5, C6-7b
Heath and moorland	0.15	1.5	0.22	0.04	IVA; IIIA-B
Cold Grass or Stunted Woody Complex	2.55		4.2		
Tibetan, Siberian	0.85	1	0.8	0.1	VC6-8; IIA2
Wooded tundra	1.7	2	3.4	0.3	IIIA2a, B3b-d
TUNDRA AND DESERT	44.4		14.9	2.8	DWARF SHRUBS (IV), herbs (V), shrubs (III):
Tundra, arctic desert, and ice	26.2		9		
Tundra	11	0.8	9	1.4	IVB3, C7b-8, D; VC7b-8
Polar or Rock Desert	0.2	0	0	0	IVD2
Ice and Antarctic desert	15	0	0	0	Rock lichens
Nonpolar desert or semidesert	18.2		5.9		IIIC; IVC; VC3, D2b
Cool Semidesert Scrub	2.0	0.6	1.2	0.4	
Sand Desert	5.2	0.05	0.26	0.5	
Other Desert and Semidesert	11.0	0.4	4.4	0.5	
Special Wet, Coastal, or Water Complexes					
WETLAND and/or COASTAL	2.9		7.8	3.8	Shrubs (IV, III), herbs (V) trees (II, I)
MAJOR WETLANDS	2.5		6.8		
Bog/Mire of Cool or Cold Climates	0.9	2	2	0.4	IVE
Warm or Hot Wetlands	1.6	3	4.8	3.2	IB2a; III; VB5a(1), VE
Other COASTAL, AQUATIC, AND MISCELLANEOUS					
Shore and Hinterland Complexes	0.35	3	1	0.2	Various combinations
Subtotal for Land (± Ice)	148		558.4	60.2	
Aquatic Systems					
Major lakes	3.2	0.2	0.6		
Total: Land and Lakes	151		559		
Oceans	360		~3		
TOTAL: EARTH	511		562		

[a]Digits beyond significant figures are sometimes carried to minimize propagating rounding errors. Parentheses include some of the primarily nontree components of INTERRUPTED WOODS, but grassy parts of the Tropical Savanna and Woodland are not allocated separately. Grass and other herb communities are interspersed in some tree formations besides those where this is made explicit by listing of Unesco (1973) formation class V.

[b]Including malee, mulga in Australia; juniper and/or very open or low pine woods.

[c]Including brigalow and the more open semiarid woodlands in Australia; quebracho in Argentina and Paraguay; locally dense saxaul in Asiatic USSR and western China.

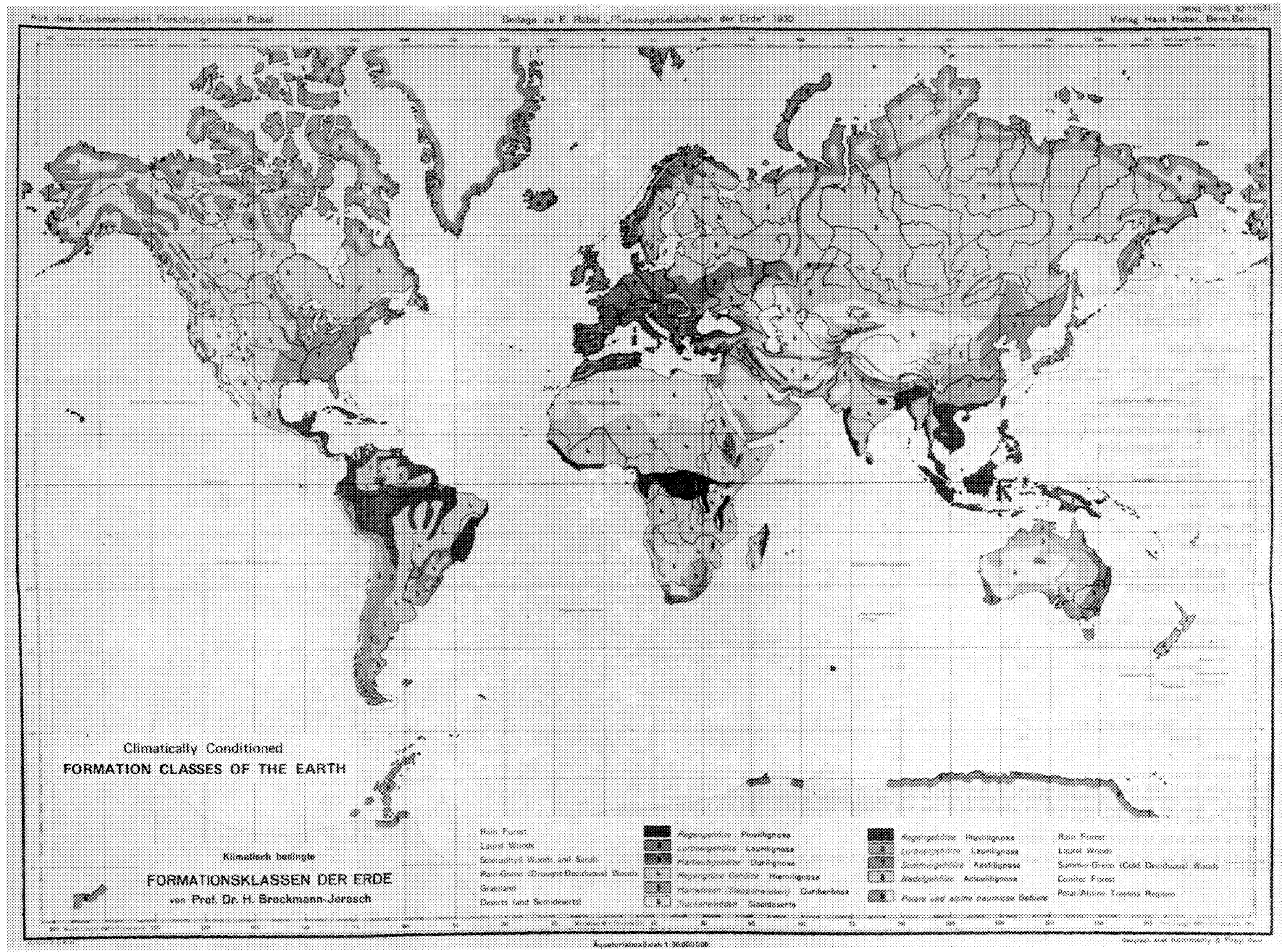
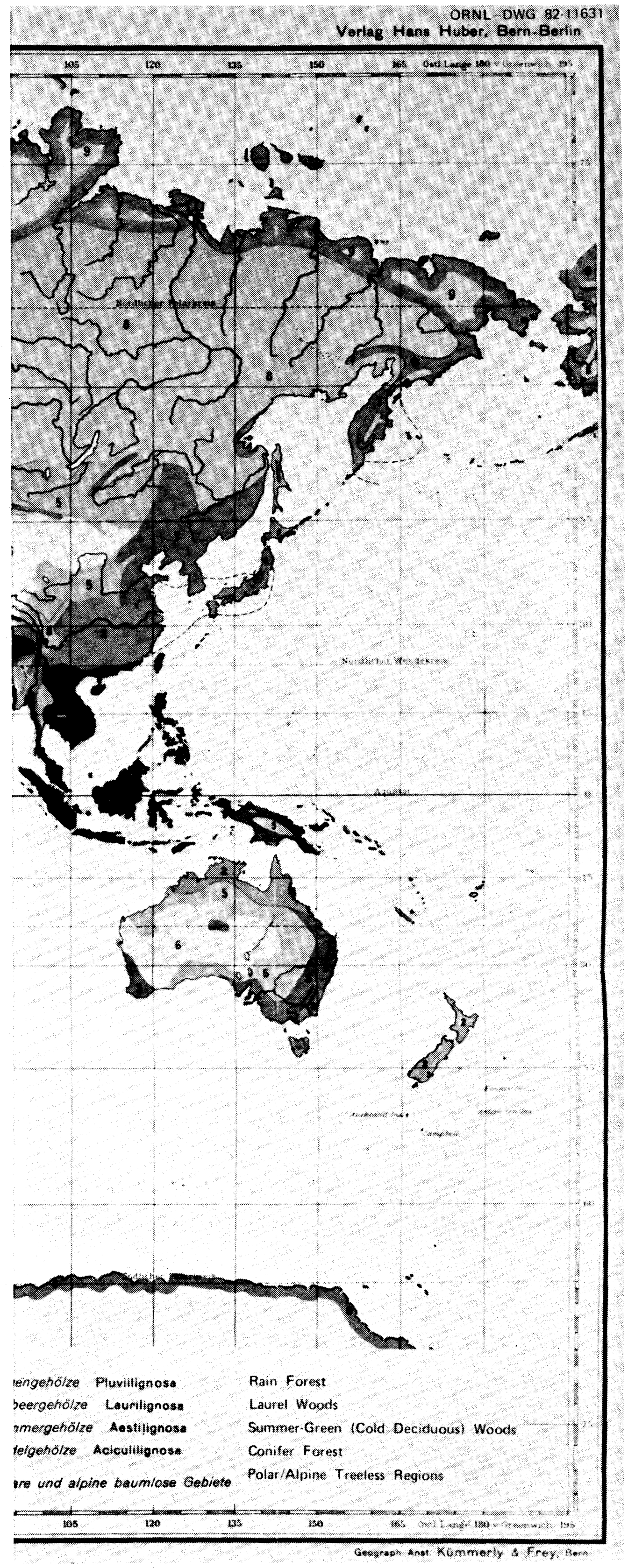


Fig. 3. Climatically conditioned formation classes of the earth.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3.1 MAJOR REGIONAL LAND SYSTEMS

Major regional land systems are those where flooding, if present at all, typically involves a few days (or hours) in a few years, or is extensive on a small percentage of the total area (most river courses and shore fringes). These land systems are elaborated first because they dominate patterns of the continents and the biosphere's global exchange with the atmosphere.

3.1.1 Tree Formations

These ecosystem complexes are ones with prominent trees [i.e., woody plants with one stem (monopodial) or occasionally several (sympodial)], at least 2 or 3 m high, and generally more than 5 m [8 or 10 m in the tropical forest (Unesco 1973)] for individuals of the upper canopy. Crown cover of the trees may be quite low (Table 1); tall or dense shrubs (multistemmed or sympodial, mostly below 2 or 3 m) can share parts of the upper canopy and much of the lower canopy (understory). FOREST AND WOODLAND as used here encompasses most of the diverging usage of these terms (Table 1). Open-forest (sensu Specht 1981b, 50-70% projective tree foliage cover; 70-90% crown cover) is commonly included in "forest" as mapped, but is sometimes included in "Woodland" by experts who emphasize the continuum of variation in the real landscape (Gillison and Walker 1981). Indeed "Woodland" in the narrower sense of Specht (1981a,b) and areas of natural bamboo and palm could qualify as "forest" in the inclusive sense of FAO (1973, p. 65) if the land being classified is "not used primarily for purposes other than forestry." The FAO also included areas temporarily unstocked and young natural or planted stands, which have not yet reached a crown density of 20%, and forest roads, streams, and other small open areas that constitute an integral part of the forest; excluded are isolated tree groups (typically ë0.5 ha or 5000 m^2), city parks, private gardens and pastures, and wind breaks and shelterbelts too narrow to be managed as forests.

"Other wooded areas" (FAO 1973, p. 66) include land with trees with crowns less than 20% area, or with shrubs and stunted trees even where covering more than 20% of the area, if not primarily used for agricultural or other nonforestry purposes, such as grazing of domestic animals. Areas with trees in lines (along roads or streams) are included here, allocating 0.8 ha per 1000 m of length, as well as those windbreaks and shelterbelts that were not included in forests. More extensive than all of these are "open woodlands" and woody "savannas" which intergrade and typically have grassy or other herbacous ground cover. Such cover now leads FAO (Fontaine 1981, FAO 1981) to prefer "mixed forest-grassland tree formations" instead of the terms "open woodlands" and "savannas," because those familiar words had been subject to such variable and confusing usage in different places and times.

First-hand observations on most continents and photographs clearly show a wide range of variation in biomass of plants and, hence, in their organic carbon. Sampling studies cited in this report show that where trees comprise more than a small fraction of the vegetative cover (Fig. 2), they contribute more phytomass, and hence more carbon, than is found in the nontree part of that stand or in most other kinds of ecosystems.

Where national data summaries exist within a framework different from the preferred worldwide synthesis, there is a natural tendency to use the categories as given instead of superimposing subjective guesswork to fit a new and perhaps more globally uniform set of categories.

3.1.1.1 FOREST AND WOODLAND

Conifer (softwood, gymnosperm, or needle-leaved) forest and Tropical/Subtropical Broad-Leaved Humid Forest of Plate 1 are examples of classical plant formation groups. Evergreen foliage is most common in both groups (Formation Subclass IA of Unesco 1973, Daubenmire 1978), but important exceptions are deciduous conifers (larch, *Larix*, bald-cypress, *Taxodium*); closely associated birch (*Betula*), *Populus*, and other summergreen or cold-deciduous broad-leaved trees or "hardwoods" (i.e., shedding leaves in winter); and drought-deciduous hardwoods that shed leaves in dry months of the more strikingly seasonal (e.g., monsoonal) parts of the hot, humid forest.

Conifer (excluding most taiga) is treated separately from the Boreal* zones. Ahti et al. (1968) and many others associate the term Boreal and taiga with conifer or mixed vegetations having northern species and only four summer months averaging above 10°C (Ritchie 1977). Some "hemiboreal" zones of those authors, and few areas of unusually massive Boreal conifer are included under Conifer. Note that there are many additional conifer stands occurring in regional complexes that are considered as "mixed" or occurring locally in broad-leaved (hardwood) regions by our definition. *Juniperus* and some other dry or highland tree or shrub types treated later include

*Upper case "B" here indicates proper noun (cf. Eyre 1963, Chapter IV; Olson 1971a) additional conifers, mostly open-forest to open-woodland, grading to or mixed with shrubs on poor soils. Other junipers and "cedars," "old field pine," and other secondary conifer stands, plantations, and post-fire conifers are as conspicuous in some forest/field complexes of regions naturally covered by broad-leaved forests as they are in conifer regions. Based more on the status of snow (and hence winter temperatures) than on summer or annual mean temperatures, cool and warm or hot variants of the conifer forest are distinguished on Plate 1.

Among Tropical/Subtropical Broad-Leaved Humid Forest, evergreen equatorial forest [most rain forest of Richards (1964), Unesco/UNEP/FAO (1978), or Eyre (1963, Chapters XIV-XV); *Regengehölze* or *Pluviilignosa* in Rübel's (1930) German and Latinized terminology of Fig. 3] is also distinguished from tropical seasonal forest on Plate 1. Walter (1979) describes how the number of dry months and the total annual rainfall interact in conditioning the distinctions between evergreen, semideciduous, and drought-deciduous tropical humid forest (Unesco 1973 Formation Groups IA1, 2 or 4; IB1, respectively). Champion and Seth (1968) describe and illustrate many of these for India where the monsoon climate gives extreme contrasts of very wet and very dry months at the same place. In Asia and elsewhere (e.g., gallery forests, commonly evergreen along streams or stream slopes of seasonally dry climates in Latin America and Africa), local soils or catchment storage of moisture carried over from wet to dry months may have more influences on persisting leaves than hundreds of miles of gradient in the regional climate (Eyre 1963, Chapters XVI-XIX).

Mostly Temperate Broad-Leaved Forest on Plate 1 includes predominantly hardwood complexes above the latitudes or altitudes where growth continues year-round on moist soils. Unesco (1973) formation group IB3, essentially deciduous (summergreen) areas (*Sommergehölze, Aestilignosa*), is typical of the northeastern United States, from central and northwestern Europe to Southern Siberia, Tadzhikistan, and northern Honshu, Korea, and China. Broad-leaved evergreen or partly deciduous forests [laurel forests or *Lorbeergehölze* or *Laurilignosa* of Rübel (1930), Brockmann-Jerosch (1930), and Schmithüsen (1976)] occur in southern Japan, Korea, and China; northern India; and some tropical/subtropical highland areas. Broad-leaved south-temperate forests occur in the southern hemisphere, such as wetter *Eucalyptus* of southeastern Australia and *Nothofagus* of New Zealand. Unesco groups IA6 and IA7 cover the gradients from wet to moist and tropical montane to warm temperate to subpolar (southern hemisphere) broad-leaved evergreens. Group IA8 (winter-rain evergreen broad-leaved sclerophyllous or hard-leaved forest) includes open- and tall-open ("wet sclerophyll") *Eucalyptus* forest of coastal eastern and southwestern Australia (Gill 1981, Ashton 1981).

"Mixed Woods" of conifer and broad-leaved evergreen or deciduous cover (Eyre 1963, Chapter VI) are commonly dealt with by simply associating with the end-member of the series which happens to prevail (lower corners of the triangle in Fig. 2). It is mostly on local or large-scale mapping that conifers (>75%) would be distinguished from 50 to 75% conifer in the USA and many other countries; pooling of both seems especially appropriate for global mapping. Commercially, historically, and for indicator values in ecology and geophysics (surface albedo effects), there are also reasons to distinguish mixed conifers as low as 25 to 50% from pure or nearly pure hardwood stands. A switch in legend terminology from forest to "woods" simply reflects a reminder that the history of many of these regions has reduced typical "forest" complexes to woodlands or open-woodlands (Table 2), through fire, other disturbance, and cumulative degrading of soil and site quality.

Mixed Woods of broad-leaved or hardwood trees and conifers are generally distinguished where both kinds of trees are mixed in the same stands. For global mapping, the units used here also include landscape mosaics that have mixed stands plus other stands of locally predominant conifers as described above alternating with broad-leaved stands. Former conifer stands, now cut over, may have conifer relics or regeneration no longer exceeding 50 or perhaps even 25% cover. The cool hardwood-conifer types are exemplified by birch-beech-maple (northern hardwoods) mixed with hemlock (*Tsuga*) and/or pine (*Pinus strobus, P. resinosa, P. banksiana* in the Great Lakes and New England-Acadian regions of North America). Mixed Woods with little or no snow include deciduous warm woods with conifers (such as the oak-pine forests of the southeastern United States), subtropical broad-leaved evergreen or at least partly evergreen broad-leaved and/or subtropical conifer, mostly montane forests with pine or *Podocarpus*, and south temperate or sub-antarctic [in southern Chile (Quintanilla 1980)] evergreen broad-leaved and/or conifer forests with such genera as *Northofagus, Podocarpus,* and *Auraucaria*.

The Main and Southern Taiga (Ritchie 1977) is climatically distinguished from other conifer forests by the long, severe winters (Rowe 1972, Walter 1979). In the main taiga, spruce (*Picea abies* and other species), fir (*Abies* spp.), and pine (*Pinus sylvestris* and others) are the principal evergreens, while larches (*Larix*) are deciduous conifers that become especially important in Siberia. Deciduous birch, various poplars (*Populus* spp.), and mountain ash (*Sorbus*) or alder (*Alnus*) are locally important broad-leaved species. What we identify as southern continental taiga has a relatively large proportion of the deciduous conifer and broad-leaved species in regions of continental climates that combine extremely cold winters with brief warm summers and frequent droughts. The Russian word "taiga" is used synonymously with Boreal forest and woodland, where capitalizing the word "Boreal" distinguishes this usage from the general meaning of boreal for anything "northern." Americans sometimes use taiga in a narrower sense limiting it to a "northern Boreal" subdivision described under INTERRUPTED WOODS.

Tropical Dry Forest and Woodland are widespread and often mixed in complexes south of the Tropical/Subtropical Broad-Leaved Humid Forests. Somewhat narrower fragments occur in the northern tropics and equatorial belts. They alternate and mix with more grassy savannas, so that points of separation become arbitrary or traditional (Walter 1979). In Africa (Huntley 1982), for example, the miombo (burned or otherwise degraded versions of maheulu) and mopane woodland occupy large areas of southern Zaire, Angola, and some neighboring countries (Malaisse et al. 1972). In Brazil, the cerradao tends to be more woody than cerrado (mostly savanna), which grades to more open tropical grasslands [campos, llanos (Eiten 1982)] or various thorn scrub and low woodland [East Brazilian caatinga, chaco (Bucher 1982)]. In southern and southeast Asia, the extreme contrast of the dry (spring/early summer) and wet (later summer) monsoon seasons selected more deciduous species, even among the moist seasonal forest types of Champion and Seth (1968). Here, almost all dry seasonal trees drop leaves at some time during the year. Many of the dry woodlands are leafless longer than humid seasonal forest. In Australia, most woodlands are lower and more open, by nature or as a result of prolonged human disturbance and naturally or artificially degraded soil conditions (Walker and Gillison 1982).

3.1.1.2 INTERRUPTED WOODS

Some tree formations may be as dense locally as the forests or woodlands just discussed, but they have various interruptions with no trees or with small ones over extended landscapes. These openings lower the plant mass and carbon when averages are taken over the whole complex of woody and nonwoody communities. (For an example, see Rutherford 1982 and Eiten 1982.) The characteristic feature defining Tropical Savanna and Woodland is a field layer of grassy vegetation with scattered trees and/or shrubs. A wide variety of production conditions is included under savanna, ranging from naturally dry grassy areas to degraded tropical seasonal forest. Formerly closed- or open-forest becomes increasingly degraded toward open woodland or grass by fire and/or cutting, often with shifting cultivation. Huntley and Walker (1982) provide regional descriptions and functional analyses of savanna ecosystems, and also of Semiarid Woodland or Low Forest and of other Woods/Scrub/Grass Complexes discussed further below.

Rainy Tropical Montane Complexes may have forests more locally dense than in nearby lowlands. However, interruptions by cliffs or avalanche openings and by subalpine and alpine complexes within the 0.5° x 0.5° mapped cells dilute the forest cover for each mountain region as a whole. Cloud forest may be stunted, yielding to scrub or grassland and perhaps alpine summits (Eyre 1963, 1971; "elfinwoods" of Whittaker 1975). A cell typically includes some lowland areas with additional open vegetation. Thus, mean carbon for an entire cell of montane complexes is expected to be lower than that for a closed continuous forest. However, the variance and standard error of carbon density must be wide and is in need of improved estimation, along with better averages for the main highland regions.

The narrower meaning of "taiga" noted in Section 3.1.1.1 covers a transition from Boreal forest and woodland with minor interruptions to northern fringes where most of the same trees occur, but tend to be more weatherbeaten, smaller, or localized to sites with more available nutrient, or less inhibition by waterlogging, or infrequent but sporadically devastating fires (Ritchie 1977, Rowe 1972). Such a partly scrubby transition zone, and similarly erratic "parkland" or tree groups near oceans (which lower the summer temperature and growing conditions) are mapped as Northern or Maritime Taiga (Bazilevich et al. 1968, 1971; Johnson and Vogel 1966). For mapping purposes, it was also combined with some subalpine woods and mountain taiga of similar stunted or sparse structure. In continental climates, trees and especially intervening scrub, tundra, or bog may be underlain by permafrost.

Various Second-Growth Woods and Field Mosaics are included with nontree patches in the forest/field complex and field/woods complex. In all of these gradations, plantations of trees or woody crops are common in some countries. The nonwooded phase includes row crops, pastureland, residential areas, and other nonwoody vegetation. The field/woods complex includes some formerly closed forest, mostly replaced by crops, grassland, or ornamental plantings. Other areas are naturally open savanna or woodland that has been altered by cultivation, grazing, or severe degradation of vegetation cover and soils. Russian wooded steppe meadows and American tall-grass prairie savannas typify areas where humus-rich grassland soils (Mollisols) are sometimes overgrown by woods that expanded after earlier restrictions related to fire and/or climatic change.

The Semiarid Woodland or Low Forest as mapped on Plate 1 refers mainly to some distinct landscapes of Australia (Gillison and Walker 1981, Johnson and Burrows 1981). Maps of Moore and Perry (1969), Carnahan (1976), and Specht (1981a,b) show rather sparse *Eucalyptus* woodland (*E. populnea* and others) inland from the more humid forests of the east coast. *Acacia aneura* or *A. excelsa* are most common in the understory, but may be codominant or dominant in some locations. Interspersed in the same semiarid belt and locally dominant on heavy cracking soils are low forests called brigalow (*Acacia harpophylla*: Moore et al. 1967). Here, trees have been mechanically uprooted from large areas to increase the area in open pasture instead of in poor woods or scrub pasture. Saxaul (*Haloxylon ammodendron*) is a quite different kind of low woods found naturally or sometimes planted on sandy soils of deserts of central Asia (Rodin 1979). It is mapped somewhat schematically in a few cells, but generally occurs in patches and stature too small to appear on such a world map. Most would occur in semidesert or other shrub cells and may be dense locally in sand desert. In northern Argentina and Paraguay, some of the more extensive quebracho areas are also mapped as Semiarid Woodland or Low Forest (Zon and Sparhawk 1923).

The Woods/Scrub/Grass Complexes constituting the remaining INTERRUPTED WOODS include three subdivisions. The mediterranean types include the classical broad-leaved evergreen scrub, open woodland, and some locally dense forests. Their hard-leaved (sclerophyll, *Hartlaubgehölze, Durilignosa*, Fig. 3) characteristic indicates good adaptation to the typical climate of abundant rain in a few winter months alternating with prolonged summer drought (diCastri and Mooney 1973, Walter 1979). High probabilities of fire in this climatic regime no doubt contribute to the large fraction of the landscape that has had a brief life span since the last burn and, therefore, has low average tree stature (Olson 1981b). However, the native trees and especially the planted conifers and *Eucalyptus* are common enough to increase the mean tree height, plant mass, and carbon over wide areas to well above the averages typical of scrub and grass vegetation alone. Through adaptations to soil storage of the winter rain, both evergreen and deciduous shrubs as well as the trees may be almost as productive as comparable plants in climates without the summer drought. Human disturbance, especially grazing and cropping, often with small-scale irrigation, further diminishes plant carbon in some areas, while tree planting, with fire protection, increases it in others.

A different distinctive tree/scrub mixture is the succulent and thorn woods and scrub of consistently hotter climates. In equatorial zones, such as eastern Brazil caatinga (Bucher 1982) and eastern Africa, the storage of water in thick tissues helps keep the plants alive between the one or two rainy seasons per year (Walter 1979). Drought, even in the seasons when rain is the normal weather condition, presumably helps further to explain the adaptations of the plants. Many have thorns. Most have low surface area for evaporation relative to the volumes of tissue wherein water storage occurs. Storage may be accentuated in succulent tissue and loss rates diminished by crassulacean acid metabolism (CAM) that permits carbon dioxide exchange at night when evaporation stresses are diminished.

Other dry or highland tree or shrub types as mapped include such sparse woodland types as pinyon-juniper (*Pinus edulis*, *P. monophylla*, and/or various *Juniperus*) in the western United States and other juniper communities in central and western Asia and Africa (Uzbekistan, Yemen, Abyssinia). Where remoteness of highlands effectively prevents harvest, large trees are sometimes found. However, the dry or cool climate, poor site conditions, fire, and human and goat disturbance in many places have reduced the mean size, cover, and estimated biomass as averaged over large areas.

Other kinds of vegetation in Australia are included in the same miscellaneous category. Mulga (*Acacia aneura*) is a predominantly shrubby vegetation but with spreading trees interspersed, especially in places within rooting distance of water reserves (Johnson and Burrows 1981). Mallee is a *Eucalyptus* shrub formation that sends up many shoots from large underground stems called lignotubers (Parsons 1981). These and some other shrub/low "tree" communities typical of Australia and some other semiarid regions appear to carry as much total biomass as small trees in other marginal environments. Further partly wooded or shrubby subdivisions could no doubt be made from what was originally very broadly defined (Fig. 1) as grazing lands by Hummel and Reck (1979) after Jones (1972).

3.1.2 Nonwoods

GRASS AND SHRUB COMPLEXES, TUNDRA AND DESERT, and a variety of MAINLY CROPPED, RESIDENTIAL, COMMERCIAL, PARK and associated marginal land complexes cover broad areas. Wide extent only partly compensates for the low density of carbon in live plants, in limiting global carbon storage. Yet growth and decay of organic matter in these systems contributes to much of the annual oscillation of the global atmospheric CO_2.

3.1.2.1 MAINLY CROPPED, RESIDENTIAL, COMMERCIAL, PARK and Associated Marginal Lands

Hummel and Reck (1979) mapped croplands over much wider areas than are in the arable land category of national land-use statistics. One reason for this is that the "Economic Atlas" (Jones 1972, followed also by Cohen 1973) tends to identify farming as the land use contributing the main income to a region, even where crops or pastures sometimes occupy a quite small fraction of the total area. To rectify this practical anomaly, the transitional categories of <u>forest/field complex</u> and <u>field/woods complex</u> were created (already discussed in INTERRUPTED WOODS, Sect. 3.1.1.2).

Agro-ecosystems are those dominated by cropping and associated human activities. Residental areas have homes (and associated gardens) dispersed widely among the cropped areas, and gradually replace the latter as settlements become suburban and urban. Commercial areas include extractive industries as well as cities and ports (mapped with coastal strips on Plate 1) and are shown as spots and transportation stripes on highway, railroad, and other atlases. Parks may be dispersed among these, as well as in more or less wild landscapes. Less concentrated mixtures of all the foregoing occur in the less intensely exploited farm ranch lands that are identified mostly with grazing (see GRASS AND SHRUB COMPLEXES in 3.1.2.2) or with the other landscape complexes. Even the latter are commonly managed or modified unwittingly by humans. Totally "unmanaged ecosystems" (Strain and Armentano 1980) cover a fairly small fraction of the land, mostly in quite inhospitable environments, but most of the world is "less managed" than cropland or tree plantations.

Paddyland is mapped separately on Plate 1 for regions dominated by rice cropping. Additional storage of humus carbon in anaerobic soil and sediment may occur in ponded fields. In the same regions, there are many other tropical and subtropical crops on sites less suitable for lowland or even hillside rice. The regional average plant mass and carbon are increased by permanent (mostly woody) crops and also by the typical configuration of trees around settlements and along those rivers and ridges that are less favorable for cropping.

Other Irrigated Dryland Row Crops tend to be in climates that are dry or at least have a pronounced dry season. There is incentive to extend cropping with irrigation as a supplement in areas not mapped as such. However, even in the cold, cool, and warm-hot variants of irrigated land, there is usually a significant area of surrounding dry landscape in mapping cells.

Other Crops, Settlements, and Marginal Lands occupy much more area than any of the irrigated lands. Only the relatively cool or cold farms, towns, etc., typically having three to five months growing season, are distinguished from the warm or hot farms, towns, etc., which have longer seasons (sometimes double cropping) and higher average plant mass and carbon. Section 4.1 gives more specific national data on the extent of arable lands and provides a method for testing the area estimates that were made independently on Plate 1 from general land/environmental-use maps (e.g., Espenshade and Morrison 1978) and from hundreds of other observations and sources. The Food and Agriculture Organization (1979 and later) yearbooks provide tabular detail on crops growing in different regions and on locations of irrigation.

The existence of tree cover in hedgerows and along some transportation corridors probably raises the mean plant mass and carbon for all of the foregoing artificial ecosystems, compared with levels typical of annual crop fields and lawns by themselves. Parks, other than wilderness or natural reserves (Eilart 1976), vary from intensely used tracts that have less carbon than crops to landscaped or wild areas having considerably more local tree biomass and carbon than crops (even orchards) and most commercial areas.

Marginal lands are associated with the main categories of agro-ecosystems and settlements. Surrounding croplands, there may be old fields or temporary fallow areas not yet planted for forest or grazing land use. Suburban fringes commonly include areas already removed from these forest or grazing land uses but not yet fully occupied by residential or commercial cover.

3.1.2.2 GRASS AND SHRUB COMPLEXES

Grassland or Shrubland is defined by prevalence of herb vs small woody life form (Eyre 1963, Chapters IX, X; Coupland 1979). They are more intermixed than many atlases indicate. Particularly in warm to hot climates, tall or low shrubs pose brush problems on many grazing lands when palatable grasses are reduced by overgrazing. Prairie, pampa, and some steppe grasses have gained ascendency over shrubs and trees on many other temperate areas. The roles of fire, other history, climate, and site in making dominance by grasses effective are still controversial issues (Kucera 1981, Mueller-Dombois 1981, Olson 1981b, Wright and Bailey 1982).

Warm or hot shrub and grassland is a broad category on Plate 1, for purposes of carbon inventory or cycling. The response of the plants and their grazing resources to changing carbon dioxide concentrations and to possible climatic change involves a common set of physiological problems. Some of these center on relationships between warm season grasses and other plants with metabolic pathways involving dicarboxylic acid (C_4) and a wider assortment of other plants with Calvin cycle (C_3) metabolism (Baker et al. 1982). Some maritime grasslands with mild winters and summers are included, but most share an absence of snow or its relatively brief duration compared with the following complexes.

Cool grassland/scrub is frequently snowy, and most is even more devoid of tree or shrub growth than the preceding complexes. The woody encroachment seen along some fringes or island seed sources suggests that many sites would have supported a mixture of woody and herbaceous growth in the cooler climates up to timberline. However, fires, mowing, or widespread grazing and poor seed sources commonly combined to limit the woody parts of this community. In any case, the dominant grasses and other herbs (forbs) mostly die down during cold or dry seasons, whether burned or not. Belowground parts (roots and "crowns" of stem structure), nevertheless, have continuity of plant mass from year to year (Coupland 1979).

Heath and moorland typically have some grass-like (graminoid) plants, but are defined by their shrubs, especially dwarf shrubs. Typical shrubs include heather and other members of the family *Ericaceae*, which define restricted European sense of the word "heath" [*Ericilignosa* of Rübel (1930) and *Heide* of many German authors]. Heath is also applied, as in Australia, to similarly appearing hard-leaved (i.e., sclerophyll) plants that are not closely related botanically, but which share a similar adaptation to acid infertile soils -- many are sandy, peaty, or both (Specht 1981c). Dwarf shrubs of the Mediterranean-type climate have already been discussed above. A third still broader sense for heath includes a variety of other low or sparse woody vegetation that is not tilled for field crops but that may be pastured or frequently burned to improve nutrient recycling and fresh shoot growth. Any of these concepts may apply over significant parts of the areas mapped as heath and moorland on Plate 1. However, grid cells are large enough that other kinds of ecosystems generally will be included, too. Moorland includes upland heaths, associated bogs with heather (*Erica*) or European heath (*Calluna vulgaris*), and a variety of other wet (cottongrass *Eriophorum*) or poor grass-like vegetation (Heal and Perkins 1978). In coastal Europe, prolonged human disturbance since Viking times or much earlier replaced former tree formations with various mixtures of all of the above. In the cold, foggy climate of the Aleutians, trees have long been absent naturally, and heath-grass (*Empetrum-Elymus*) meadows are differentiated, along with tussock tundra, with *Eriophorum*, on the higher mountains. Here, winter cold as well as summer heat are moderated by the oceanic climate with prolonged fog.

The grasslands, shrublands, and heaths just described are the main formations referred to as grazing land with other farming by the "Oxford Economic Atlas" (Jones 1972). Figure 1 identifies several of the INTERRUPTED WOODS complexes as additional grazing lands. National data on permanent pastures as defined by the FAO, with or without trees, are given in FAO (1979). Such land also includes some grazing lands of extremely Cold Grass or Stunted Woody Complexes.

Among Asian grazing lands with very short growing seasons are the Tibetan meadows on lower summits, slopes, or valleys of or near the Tibet highland. Many are shown on the new Chinese vegetation map and illustrated by photographs in the book describing it (Committee for the Vegetation of China 1980). The traditional raising of yaks and some nomadic tending of other livestock on these Tibetan meadows and timberline scrub have been important to Tibetan and Mongolian and other herdsmen since medieval and ancient times.

An aerial view of east-central Siberia shows not only Northern or Maritime Taiga, interrupted by tundra on many mountains and bogs in valleys and on plains, but also some parklands and even steppes in relatively dry valleys. Precipitation there and in dry tundra may be as low as 15 cm/year, with extremes of winter temperature reaching -79°C (Volkovintser 1974). Siberian parklands (on Plate 1) or steppe with stunted larches or no trees (dry tundra) identify some of these areas. Reindeer ranches are an extension of more conventional range management around Yakutzk, as in some open parts of the taiga, and the following wooded tundra and timerline areas.

Fringing the northern or upper altitudinal margin of Northern or Maritime Taiga is the so-called wooded tundra and timberline. Outlier conifer trees, if any, tend to be conspicuous by dwarfing or other distortion by wind, ice, and cold. In Europe, birch makes deciduous outliers more prevalent than evergreen. In Lapland and its Soviet counterparts, reindeer grazing has been important in wooded tundra as well as in parts of the Northern or Maritime Taiga. In some highlands, other stunted trees are also mapped as wooded tundra and timberline. Some islands and coastal outposts of southern Chile represent a very limited antarctic counterpart, dominated by contorted *Nothofagus* or southern beech.

3.1.2.3 TUNDRA AND DESERT

Large areas of the earth are too cold and/or dry to support much live plant mass or carbon. Bliss (1981) defines and describes the North American and Canadian low and high arctic Tundra, while Andreev and Aleksandrova (1981) do likewise for the Russian counterparts. Terminology varies between countries, but all refer to low vegetation with short growing seasons. Polar or Rock Desert is defined and mapped on Plate 1 to include the narrow extreme of high Arctic where low precipitation and extremely low temperature combine to give extremely low available moisture and spotty plant cover. Parts of Antarctica that are not covered by ice add substantially to the area of arctic Polar or Rock Desert, but this continent is not included in Plate 1.

Between the arctic and antarctic, some geodetic cells shown as Tundra approximate locations of highlands with alpine tundra. Some mountain meadow (cool grassland above the local timberline but not necessarily qualifying as Tundra) is also included. In addition, both of these are represented on some highlands that could be mapped as cool grassland/scrub, Tropical Montane Complexes, or other kinds of woods. The special vegetation of coarse herbs and marginal woody growth called paramo (Barclay 1977a, Whittaker 1975, Walter 1979) occupies relatively small areas of the equatorial Andes and a few other tropical mountains. These areas have little or none of the seasonal contrast that is so typical of Tundra, but fluctuations above and below freezing occur most months of the year. In subtropical latitudes, the Andes typically have puna vegetation of grass and cushion plants that have become adapted to a climate with both seasonal and diurnal fluctuations (Barclay 1977b). Puna areas may never become very warm, but are mostly mapped with other grassland/scrub having little snow except at the high altitudinal fringe of the nival zone.

Semidesert Scrub is shown on Plate 1 only for a few very notable cool dry regions. In Patagonia and North Central Asia, semishrubs (woody tops dying back partially) and shrubs as well as herbs (e.g., cushion plants) provide typical sparse cover (Petrov 1973, Rodin 1979). In the United States' northern Great Basin and parts of the arid Columbia Plateaus, which are not mapped as desert on page 22 of McGinnies (1981), taller species like *Artemisia tridentata*, the big sagebrush, dominate. Winters can be cold enough to retain snow, but the low quantity of total precipitation may leave much of this area relatively bare of snow cover in many winters.

Sand Desert includes wide areas of continuous blowing dunes: the eastern and western sand (or "erg") and similar dunes of the Saharan and Libyan desert in Africa, the Ar Rub' Al Khali (Empty Quarter) of Arabia, the Namib of southwest Africa, and several areas large enough to map in northwestern China (Petrov 1973). In addition, there are wide areas in Australia, the Kalahari, and some other deserts where blowing sand is common but sparse grass or shrubby vegetation coexists. Very low average foliage or crown cover, plant mass, and carbon are typical of all these areas. Oases and exceptional small patches of carefully reclaimed desert can support plant mass as high as that of grass shrubland or even sparse or dry savanna or woodland (Rodin 1979).

Other Desert and Semidesert regions are mostly warm to hot. Good descriptions on a continental basis are now available from several authors in McGinnies' (1981) section of the Goodall and Perry (1981) synthesis for the IBP. The extremely arid and arid deserts are rather consistently recognized and named in a vast additional literature on arid lands. It is the semiarid lands for which there is much variation in identity and interpretation. Inevitably, these grade into GRASS AND SHRUB COMPLEXES where the statistics of precipitation favor less sporadic or nomadic grazing uses.

3.2 WETLANDS, COASTS, AND WATERS

Only a few of the MAJOR WETLANDS and a sampling of areas with OTHER COASTAL, AQUATIC, AND MISCELLANEOUS complexes can be represented, even schematically, on a global map like that of Plate 1. Their special relations to the storage of dead as well as living carbon and their sensitivity to influences of climatic and sea level changes were among the reasons for including them. These estimates are subject to refinement as more attention is given to such special areas.

Besides the larger landscape complexes that are mapped separately, many smaller ones occur. Additional poorly drained ends of the moisture sequences of soils (sometimes called catenas, or "chains") in each of the major regional land systems could be identified with intermittently wet transitional ecosystems or even added to WETLANDS themselves. Similarly the sandy, saline, or rocky coastal habitats which terminate various tree or nonwoods formations along prominent shorelines are transitional to COASTAL COMPLEXES that reflect some peculiarities in carbon cycling or response to climatic change. AQUATIC systems interspersed in these landscapes include the streams, reservoirs, and other lakes which are counted along with the lands proper in total areas of each nation; all too seldom are these studied in a manner integrated with their catchment basins (Degens 1982).

3.2.1 MAJOR WETLANDS

The Bog/Mire of Cool or Cold Climates complexes are landscapes storing carbon in peat and are most extensive in cool to cold climates. Bogs are especially significant for the accumulation of acidic peat moss deposits undergoing very slow decay, partly to methane under anaerobic conditions. The main areas mapped are south of Hudson Bay and east of the Ural Mountains. Low Bog/Mire is not mapped separately where occurring extensively with heath and moorland or

Tundra. Dwarf bog shrubs, along with varying mixtures of stunted trees like *Larix* and *Picea mariana*, grade into main taiga and some of the less strictly Boreal forests. Mires also include fens, where the intake of mineral nutrients from groundwater or from surrounding uplands enhances their productivity but may also increase the turnover rates of organic decay.

Warm or Hot Wetlands locally include some additional mires that are mapped with the swamp/marsh and mangrove/tropical swamp woods complexes. Swamp/marsh complexes are more or less open mosaics of thickets, marsh, or still more sparsely vegetated wetlands, but some parts could be included as forests or open woodlands. In parts of the tropics and subtropics, mangrove/tropical swamp woods include some relatively tall forest, more or less reduced by cutting and other damage. More shrubby thickets occur in fringe areas that are climatically marginal for tree development or too young to mature since the last hurricane or wood cutting. Shoreline denoted in solid red on Plate 1 indicates the coastal presence and at least local dominance of mangroves. Extended broken red lines indicate the presence but lesser prevalence of mangrove. Barth (in press) maps the numbers of mangrove species and many isolated occurrences hitherto overlooked.

3.2.2 OTHER COASTAL, AQUATIC, AND MISCELLANEOUS Complexes

Shore and Hinterland Complexes peculiar to the coastal climates and habitats of each region are locally important along coastal lines of Plate 1 marking most coasts of continents and islands. Some coastal area symbols are placed in water deliberately to represent islands (e.g., barrier islands along sandy coasts), but flaws in printing registration occasionally place these or other symbols in areas of water. Tropical coasts (and associated noncoastal vegetation), temperate shore vegetation, high latitudes, and arctic waters where shore ice action is important are noted in Plate 1 and defined in the legend.

Ocean, Lake, and Small Islands complexes cover large areas, but may have low mass of living carbon. The largest of the world lakes are outlined; white geodetic cells (other than for glaciers) indicate locations of a few more lakes which prevail in 0.5° x 0.5° cells. Ocean ecosystems are not further discussed in this report. Very small islands may be mapped with or without additional legend symbols on or near the island. Clearly, a larger scale would be required for treating details along abrupt spatial gradients in either water or land. The mapping to date calls attention to such special complexes, in addition to the more extensive continental complexes.

"Miscellaneous" complexes offer an open place for identifying special combinations or variations of the preceding, or complexes of landscapes that were omitted through oversight or because of their generally small size.

CHAPTER 4

INFERENCE OF CARBON IN MAJOR ECOSYSTEMS

To estimate the total organic carbon in a region or vegetation type, the area, a_i, and density, d_i, of carbon per unit area for type i are needed. The product of areal extent and density gives v_i, the amount of carbon for each major world vegetation type. The resulting products, v_i, are then totaled over all map cells and vegetation types to give a global estimate, v, of global carbon in living plants.

$$\Sigma = \sum_{i=1}^{n} (a_i)(d_i) = v \quad . \tag{1}$$

Figure 4 presents the main results that can also be examined in detail in Table 2. The width of the boxes (horizontal axis) is proportional to areas covered by the ecosystem complexes. Height of the bars is our present best estimate of average carbon in the live plants of each complex, per unit area. Multiplying width by height in each segment of the box gives a product (i.e., box area) that is proportional to the contribution of the named ecosystem groups to the global total for plant carbon (Eq. 1).

Of the major land systems, Fig. 4A shows that the relatively uninterrupted closed FOREST AND WOODLAND and the more INTERRUPTED WOODS complexes each cover approximately 30 X 10^6 km^2. Higher carbon density of the former naturally gives it a larger share of carbon in the category we call "woods." Figure 4B gives the main categories of "nonwoods." In addition to these main land ecosystem complexes, the special (MAJOR WETLAND and COASTAL) complexes are also shown in the lower right corner of Fig. 4B as having limited area, and with a modest average carbon (i.e., intermediate between the high and low parts of their wooded and nonwooded portions).

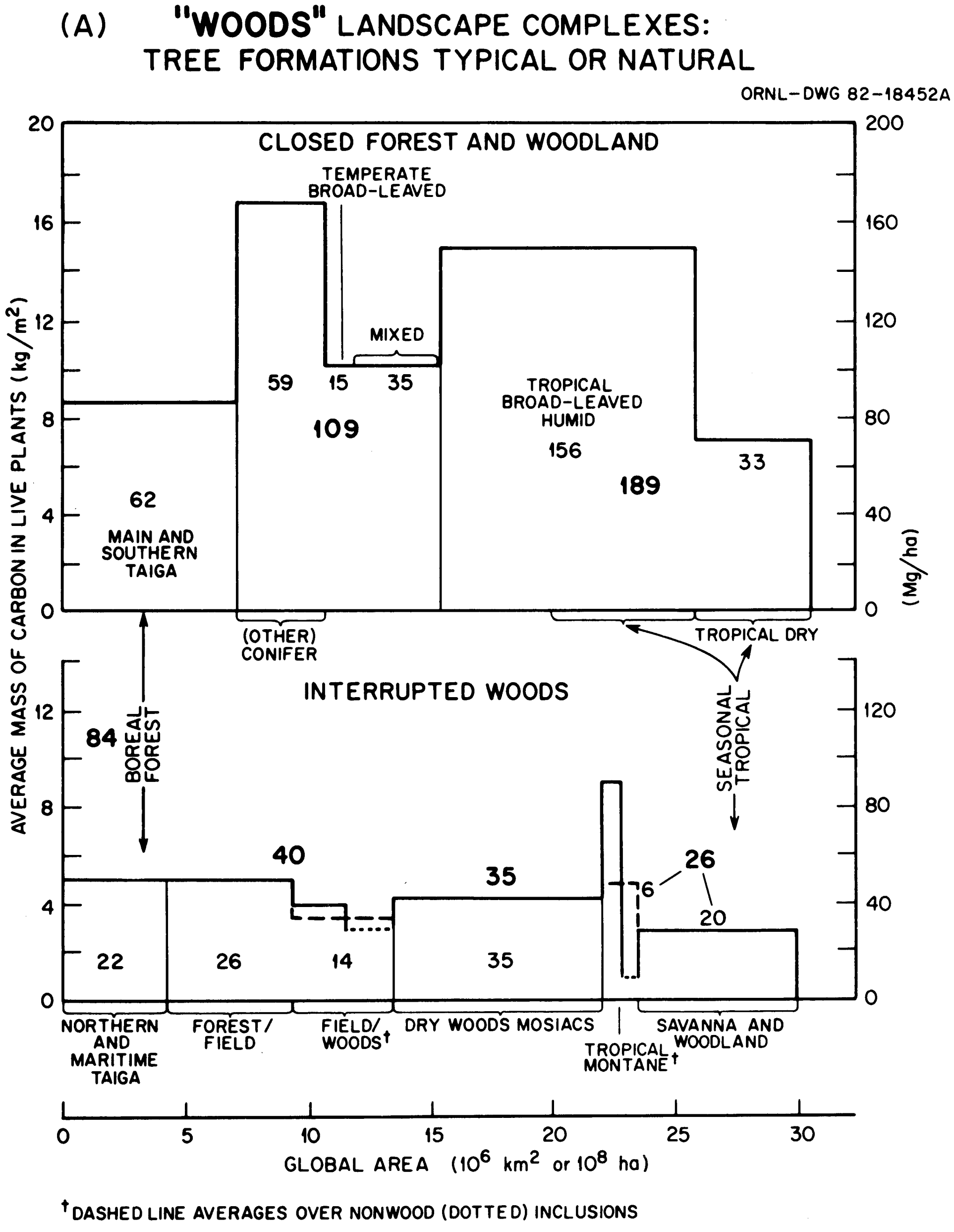

Fig. 4. Global picture of major ecosystems areas (horizontal), carbon per unit area (vertical), and carbon totals (box areas). (A) "Woods" landscape complexes, and (B) "Nonwoods" and "special" complexes.

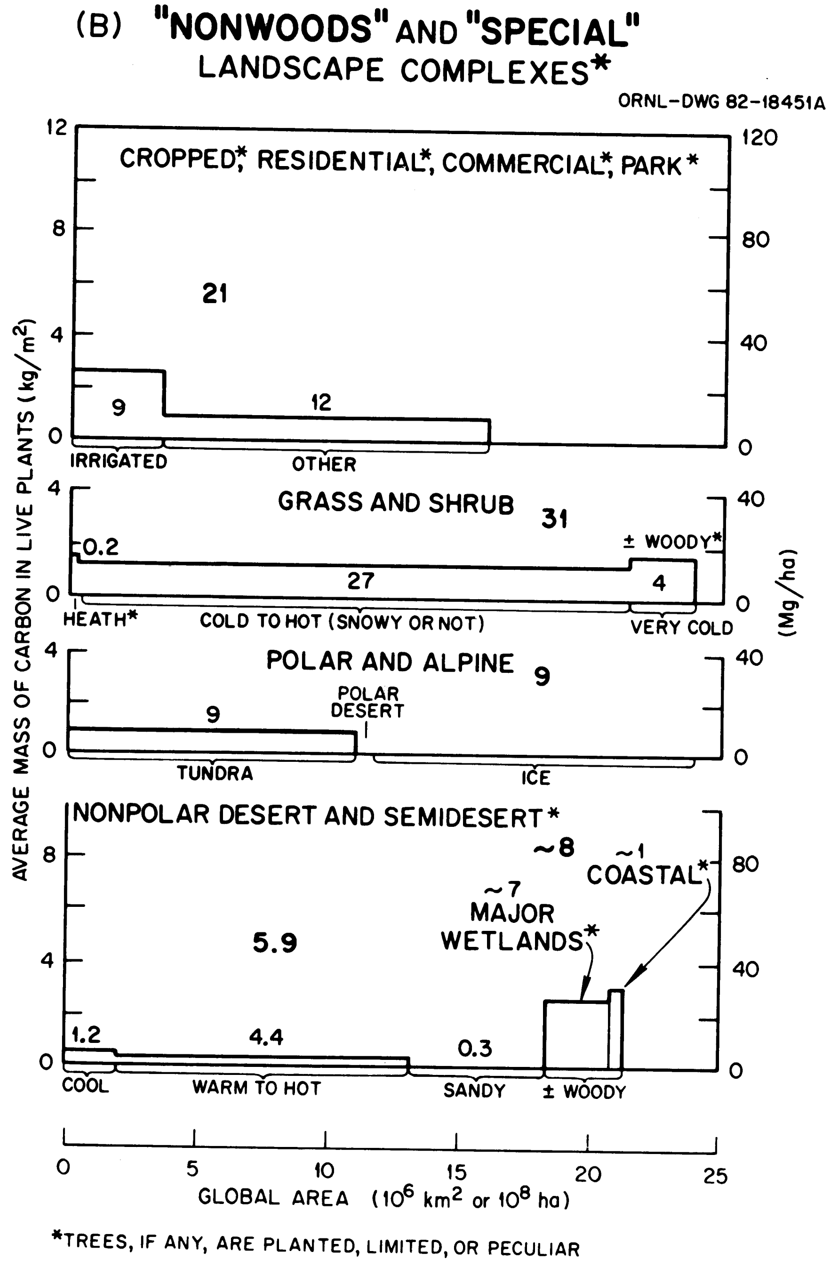

Fig. 4. Continued

4.1 AREAS OF ECOSYSTEMS AND LAND USE

This section discusses the estimated areal extent of the ecosystem complexes based on the map of Plate 1, the widths of the respective portions of Fig. 4. Among closed FOREST AND WOODLAND areas that are dense or tall (mostly both), the upper part of Fig. 4A shows approximately the same area of tropical broad-leaved forest (humid and dry together) as the denser parts of Boreal (taiga) forest, other conifer, plus mixed or broad-leaved temperate forest. However, tropical forest with long dry seasons, and seasonal humid forests with short or less severe dry seasons probably each occupy more area than the tropical wet forests (including rain forest).

Among the INTERRUPTED WOODS, relatively more area is occupied by grassy savanna and closely associated woodland patches (Fig. 4A; see also Huntley and Walker 1982) than by either the tropical dry, humid but seasonally dry, or constantly wet, closed forest. Areas and further subdivisions of other INTERRUPTED WOODS, nonwoods, and "special" ecosystems are discussed below. It is helpful at this point to note briefly some older sources of estimates of major ecosystem areas, and two kinds of United Nations statistics that offer independent current estimates of forest and nonforest land cover and land use. These sources confirm that the first reason for some previous overestimates of global plant mass (and hence its carbon) is simply because areas of closed forest were overestimated substantially. The independent source of area estimates based on Soviet atlases treat only the inferred natural extent of vegetation types. When the different bases underlying these and a few other very recent estimates are understood, we find an approach to consensus on areas as close as could be expected from the very uneven sources of biogeographic data.

Zon and Sparhawk (1923) had mapped world forests in a very preliminary way. They excluded the savannas as being too sparsely stocked to be attractive, and hence accurately inventoried, for forest products, even though the wood of the savanna's isolated trees is used widely for local construction and fuels (Persson 1974, 1977a,b). Areas of traditional broad nonforest categories were based on climate or life form: desert, tundra, or grassland. Areas of these and of the classic tree formations were analyzed by Shantz (1954). His wide experience from travels helped make corrections for the areas of each broad formation that were actually occupied by inclusions of the other formations.

Two distinct kinds of information from the United Nations Food and Agricultural Organization (FAO) are summarized briefly from surveys that were independent of the mapping in Plate 1. First, Table 3 is a very condensed summary of national and regional figures that are given from individual countries or by statisticians having no specialized expertise in forestry or the use of relatively wild lands. Total areas differ from land areas, essentially by the amounts of lake, reservoir, and estuary encompassed within national boundaries (excluding Antarctica). Estimates of "arable land" and "permanent crops" (mostly woody, such as rubber, orchards, vines, shrubs; also bananas, etc.) are documented in far more detail than we can review here in relation to various kinds of grains and other commodities (FAO 1979). Areas actually planted and harvested are smaller than the total lands that could be, because of poor weather in some years and other reasons for leaving some arable land idle or fallow. On the other hand, there are planted areas of shifting cultivation (swidden agriculture) that are known and recorded incompletely, if at all, in some countries, especially in the tropics. The columns showing recent statistical change to 1977 (the reference year in models of Moore et al. 1981) indicate faster increase in permanent crops (averaging 10%/year since 1967) than in other or total cropland (4%/year).

The total of 14.6×10^6 km^2 is somewhat smaller than the 15.9×10^6 km^2 summed up from Plate 1 for MAINLY CROPPED, RESIDENTIAL, COMMERCIAL, PARK, but the latter includes the areas in the named categories besides crops. Ryabchikov (1975) estimated only 12×10^6 km^2 as farm land and an additional 7×10^6 km^2 to include other crops grown in gardens, for decoration, and as more or less wild vegetation around fields and along roadsides (and presumably other transportation corridors). His sum of 17×10^6 km^2 is remarkably close to the 15.9×10^6 km^2 based on Plate 1. Both of these totals presumably

Table 3. Summary of land-use trends on a continental and global basis using the FAO land-use estimates (units = 10^3 hectares)

COUNTRY	TYPE	1961 to 1965	1967	1972	1977	1967 minus 1965	1972 minus 1967	1977 minus 1972	1977 minus 1967	1967 to 1977 change (%)
Africa	Total area	3031168	3031168	3031168	3031168					
	Land area	2964696	2964696	2964696	2964612					
	Arable & permanent crops	188103	197965	203766	208724	9862	5801	4958	10759	6
	Arable land	175829	184279	189649	193669	8450	5370	4020	9390	5
	Permanent crops	12271	13686	14117	15055	1415	431	938	1369	10
	Permanent pasture	807369	802840	801751	797935	-4529	-1089	-3816	-4905	-1
	Forest & woodland	664398	651532	640357	637003	-12866	-11175	-3354	-14529	-2
	Other land	1304826	1312359	1318822	1320950	7533	6463	2128	8591	1
N C America	Total area	2241492	2241492	2241492	2241492					
	Land area	2135549	2135549	2135549	2135536					
	Arable & permanent crops	255838	253200	267711	266643	-2638	14511	-1068	13443	5
	Arable land	250375	247639	261812	260383	-2736	14173	-1429	12744	5
	Permanent crops	5464	5561	5899	6260	97	338	361	699	13
	Permanent pasture	370262	369624	356870	354023	-638	-12754	-2847	-15601	-4
	Forest & woodland	728889	723940	720804	718189	-4949	-3136	-2615	-5751	-1
	Other land	780560	788785	790164	796681	8225	1379	6517	7896	1
So. America	Total area	1781851	1781851	1781851	1781851					
	Land area	1753548	1753548	1753548	1753562					
	Arable & permanent crops	82367	89814	98558	107675	7447	8744	9117	17861	20
	Arable land	62607	69393	77074	85160	6786	7681	8086	15767	23
	Permanent crops	19759	20421	21484	22515	662	1063	1031	2094	10
	Permanent pasture	407332	419867	434286	442964	12535	14419	6678	23097	2
	Forest & woodland	948299	939853	929803	920807	-8446	-10050	-8996	-19046	-2
	Other land	315550	304014	290901	282116	-11536	-13113	-8785	-21898	-7
Asia	Total area	2757442	2757442	2757442	2757442					
	Land area	2677049	2677049	2677049	2676993					
	Arable & permanent crops	436133	441129	447581	457901	4996	6452	10320	16772	4
	Arable land	416703	420977	425544	434322	4274	4567	8778	13345	3
	Permanent crops	19431	20152	22037	23579	721	1885	1542	3427	17
	Permanent pasture	548263	551412	551693	537495	3149	281	-14198	-13917	-3
	Forest & woodland	540986	553880	562028	571174	12894	8148	9146	17294	3
	Other land	1151668	1130628	1115747	1110423	-21040	-14881	-5324	-20205	-2
Europe	Total area	486949	486952	487012	487031					
	Land area	472858	472848	472839	472796					
	Arable & permanent crops	152189	148851	143749	142199	-3338	-5102	-1550	-6652	-4
	Arable land	137989	134326	129059	127368	-3663	-5267	-1691	-6958	-5
	Permanent crops	14201	14525	14690	14831	324	165	141	336	2
	Permanent pasture	89653	90335	88914	87118	682	-1421	-1796	-3217	-4
	Forest & woodland	143077	147038	151658	154656	3961	4620	2998	7618	5
	Other land	87939	86624	88518	88823	-1315	1894	305	2199	3
Oceania	Total area	850956	850956	850956	850956					
	Land area	842906	842906	842906	842906					
	Arable & permanent crops	35238	42990	44889	46471	7752	1899	1582	3481	8
	Arable land	34373	42082	43937	45515	7709	1855	1578	3433	8
	Permanent crops	865	908	952	956	43	44	4	48	5
	Permanent pasture	459250	461419	470013	464851	2169	8594	-5162	3432	1
	Forest & woodland	186582	186385	186127	155173	-197	-258	-30954	-31212	-17
	Other land	161836	152112	141877	176411	-9724	-10235	34534	24299	16
USSR	Total area	2240220	2240220	2240220	2240220					
	Land area	2227200	2227200	2227200	22227200					
	Arable & permanent crops	229496	229250	232431	232404	-246	3181	-27	3154	1
	Arable land	225080	224600	227500	227500	-480	2900	0	2900	1
	Permanent crops	4416	4650 F	4931	4904	234	281	-27	254	5
	Permanent pasture	371600	373300	375300	373600	1700	2000	-1700	300	0.1
	Forest & woodland	920000	920000 *	920000 *	920000 *	0	0	0	0	0
	Other land	706104	704650	699469	701196	-1454	-5181	1727	-3481	-0.5
World	Total area	13390078	13390081	13390141	13390160					
	Land area	13073806	13073796	13073787	13073605					
	Arable & permanent crops	1379364	1403199	1438685	1462017	23835	35486	23332	58818	4
	Arable land	1302955	1323296	1354575	1373917	20341	31279	19342	50621	4
	Permanent crops	76407	79903	84110	88100	3496	4207	3990	8197	10
	Permanent pasture	3053729	3068797	3078827	3057986	15068	10030	-20841	-10811	-0.4
	Forest & woodland	4132231	4122628	4110777	4077002	-9603	-11851	-33775	-45626	-1
	Other land	4508483	4479172	4445498	4476600	-29311	-33674	31102	-2572	-0.1

NOTE:
F = Estimated by FAO staff.
* = Estimated by national government.

include much of the urban and suburban land which the FAO would submerge as a relatively minor part of the 44.8 x 10^6 km^2 of "other land."

Most of this "other land" in Table 3 would be TUNDRA AND DESERT but considerably more is left to include some of the less accessible GRASS AND SHRUB COMPLEXES and some unproductive tree formations. The 30.6 x 10^6 km^2 of "permanent pasture" presumably includes the balance of GRASS AND SHRUB COMPLEXES area (with minor stunted woody fringes) and a very substantial part of our INTERRUPTED WOODS. The 40.8 x 10^6 km^2 of forest and woodland of Table 3 is only extensive enough to include the closed FOREST AND WOODLAND of Fig. 4, plus about one-third of the INTERRUPTED WOODS cover; the wooded areas having major market use for grazing, instead of for wood products, would be excluded by definition (FAO 1973).

The second FAO information source, with far more detailed information on tropical and other tree formations (Table 4), is the Forest Resources Division (Lanly, pers. comm.). While working there, Reidar Persson encouraged FAO to develop more critical regional appraisals, instead of depending on World Forest Survey questionnaires. More consistent data on forest areas and merchantable woody material (Persson 1974, 1977a,b; FAO 1973, 1976a,b) were received from correspondents and organized by experienced staff field officers. The sum of the forest and woodland category given in the FAO Production Yearbooks (e.g., FAO 1979) does not use such refinements promptly; the Yearbooks' main emphasis is on crops and grazing lands.

Table 4 shows the geographic distribution of tree formations, indicated by specialized surveys and evaluations. Persson's (1977b) best estimate and judgment of accuracy are given in columns 3 and 4 for closed forest (see Table 1 for broad FAO definition). For forests, Forestry Department estimates (in braces) (Fontaine 1981) are higher than Persson's, probably because more areas already disturbed by earlier logging and old shifting cultivation are included. Singh's recent "open woodland" estimates in col. 5 (updated by personal communication 1982) are lower than Persson's, mainly because he makes separate provision for tropical/subtropical fallow areas of both tree formations and scrub.

Table 4. Areas of closed forest, open woodland, and arable land plus permanent crops; also tropical fallows and scrub

Continent	Land area $(10)^6$ km^2 [a]								
	Total area[b]	Closed forest[a] Estimates	Closed forest[a] Accuracy	Open woodland[c] grass	Tree formations = forest + woodland		Fallows[d] of tree formations	Scrub and its fallow[d] areas	Arable land + permanent crops
1	2	3	4	5	6	7	8	9	10
TROPICAL & SUBTROPICAL COUNTRIES									
Mid-Africa[d]	21.48	1.682	1.37-1.76	7.1[d]	8.16[a]				
		[2.037][e]				[6.62][e]			
		{2.17}		{4.86}[e]		{7.03}	{1.66}[e]	{4.43}[e]	
America (S, Central)	16.91	5.67	4.6-6.65	2.5	8.17				1.03
		[6.593]				[8.23]			
		{6.79}		{2.17}		{8.96}	{1.70}	{1.46}	
Asia (S,SE)	8.99	1.75	1.45-2.32	1	2.75				2.70
		[2.62]				[2.97]			
Oceania	3.55[f]	0.5[f]	0.4-0.6	0.5[f]	1.0[f]				0.11
		[0.411+]							
Asia and Oceania[e,f]		{3.06}		{0.31}		{3.36}	{0.73}	{0.36}	
	50.93	9.6	8-11	11.1	20.08				
FAO: 1975→ 1980[e]		[11.66[g] →11.32]		[6.41]		[18.07]			5.49
Fontaine 1981 {for 1980}		{12.01}		{7.34}		{19.34}	{4.09}	{6.25}	
[Brown and Lugo (1980) after Persson (1974)]	48.44	10.44		7.93		18.38			
Unesco 1978	46.09	11.0		8.2		19.2			
SOUTH OF "TROPICS"									
South Africa[d]	3.08	0.016	0.015-0.017	0.65	0.666				0.19
South America	3.39	0.12	0.08-0.16	0.4	0.52				0.43
Oceania	4.69[f]	0.26[f]	0.2-0.3	0.62[f]	0.88				0.35[f]
	11.43	0.396	0.3-0.47	1.65	2.07				0.97
NORTH OF "TROPICS"									
Africa	5.75	0.016	0.013-0.027	0.06	0.066				0.2516
Asia (W,E, Central)	18.60	1.52	1.27-1.84	0.34	1.86				2.97
Europe	4.87	1.37	1.29-1.4	0.2	1.57				1.42
USSR	22.4	7	6.2-7.7	2	9				2.324
N. America	19.34	4.6	4.4-5.5	2	6.6				2.61
	70.96	14.51	14-16	4.60	19.10				8.16
Non-"tropical" subtotal	82.39	15.9	14.3-16.4	6.19	21.17				9.13
Totals	133.35	26.29		17	41.25				14.62
Accuracy			21.5-27.5	12-24					
Additional "scrub and brushland"				10-20			{10.34} "tropical"		

[a]Nonfarm estimates without brackets are mainly after Persson, especially Table A of his 1977b review. He evaluates the many sources of uncertainty leading to the range of accuracy estimated in column 4. Possible high biases of "official" national forest estimates may also be reflected in bracket summaries even though later FAO staff attempted independent judgments (see d).

[b]From Persson 1977b; finer breakdown and farmland from Yearbooks of United Nations Food and Agricultural Organization (e.g., FAO 1979). "Total area" includes not only land but also inland water bodies, estuaries, and wetlands that are sometimes flooded for long periods.

[c]The FAO supposedly uses "open woodland" as the designation for areas with a 5 to 20% crown cover. Yet, even such sparse cover may in fact be labelled "closed" forest if the community type normally has denser canopy (i.e., if it has been opened by fire, cutting, or other disturbance but might recover). Because of such disturbance, extensive forest areas that formerly were closed (according to either a loose or strict definition) have since become "open." Also, the label "open woodland" has been used in refining designations formerly called "forest" for administrative reasons.

[d]Before the 1980s it was difficult (e.g., Persson 1974) or impossible to estimate fallow land (formerly cropped but partly regrowing trees or shrubs) separately. Doing so identified components of the landscape that may have formerly exaggerated "woodland" estimates, especially for Mid-Africa, i.e., Sub-Saharan Africa excluding South Africa, Swaziland, Lesotho, Botswana, Namibia, and also Zimbabwe. Zimbabwe was included in (all tropical) East Africa by FAO (1981) map. They defined Botswana and Namibia as "Tropical South Africa" and excluded the first three from their tropical tables and Fontaine's (1981) summary.

[e]Square brackets have 1979 estimate of Lanly and Clement for 1975, and also 1980, following the arrow on the FAO line. Braces have K. D. Singh's 1982 estimates (pers. comm.), mostly represented in his contribution to Fontaine (1981). (Asia and developing Oceania are combined in that reference, without including tropical Australia.)

[f]3×10^6 km^2, including 0.11×10^6 km^2 agricultural area, 0.19×10^6 km^2 of closed forest, and 0.43×10^6 km^2 of open woodland for Australia, were allocated tentatively to tropical (including subtropical) Oceania. The 3 plus 0.55×10^6 km^2 of "Developing" Oceania islands gives the total area in col. 2. The 0.31×10^6 km^2 of forest in "Developing" Oceania plus an allocation of 0.19×10^6 km^2 from Australia's part of "Developed Oceania" forest gives the round number of 0.5×10^6 km^2 for the closed forest. The open woodland estimate for col. 5 includes only 0.07×10^6 km^2 for "Developing Oceania," and the allocation of 0.43×10^6 km^2 from Australia, summing to a rounded total of another 0.5×10^6 km^2.

[g]$(11.20 + 0.46) \times 10^6$ km^2 including 1975 "natural types" but possibly more or less disturbed stands (mostly hardwoods); excluding 0.05×10^6 km^2 of "industrial plantations" in 1975 and 0.0655×10^6 km^2 projected (in late 1978) to 1980.

Areas from dot counts on maps of the "Physical-Geographic Atlas of the World" (Gerasimov et al. 1964) and data from early studies were compiled by Bazilevich et al. (1968, 1971). However, these authors did not deduct farmed or fallow areas, nor adjust area or phytomass estimates for ecosystem types that show gross human or fire modifications of natural patterns and carbon density.

We previously reviewed the areal coverage which Bazilevich et al. (1968, 1971) estimated for the preagricultural landscape/soil categories and then attempted to allocate to them the proportions of clearing that had presumably occurred before and after 1860 (Table 2.1 of Olson et al. 1978). The estimates cited there, others from SCOPE 13 (Tables 1.2, 5.3, and 5.5 in Bolin et al. 1979), and additional study led to the following review of other authors' areal estimates and new ones based on the present data base.

One example of geographical allocation is the latitudinal distribution of our mapped complexes of Second-Growth Woods and Field Mosaics. Of the 5.2 x 10^6 km^2 currently mapped in the forest/field complex category, 1.7 x 10^6 km^2 occur between 30°N and 30°S latitudes. This category is meant to include additional degraded, regrowing, or planted areas of the tropical and subtropical, mostly humid forest types on Table 2. Table 2 also identifies where and how allocations of area and carbon are made between the wooded and nonwooded parts of certain ecosystem complexes. Proportionately more of the warm to hot field/woods complex, 2.6 x 10^6 of the total 4 x 10^6 km^2, is in these tropical or subtropical latitudes. The geographical distribution of the areal extent of the field/woods complex suggests that approximately 50% of this category could also be mapped as fields, grass or shrub. Most areas of these complexes also include some cultivated crops. Our first approximation for areas of both complexes assumes that these cropped areas are balanced by patches of FOREST AND WOODLAND, INTERRUPTED WOODS, or GRASS AND SHRUB COMPLEXES in the MAINLY CROPPED, RESIDENTIAL, COMMERCIAL, PARK landscapes. Unless otherwise noted or questioned, we tentatively assume that additional area offsets may occur among other nonprevalent types due to occurrences in other complexes. Presumably, further improvements in areal estimates can be made, based on region-by-region data. However, such improvements may require several years of additional work, preferably including independently verifiable and repeatable data from satellite imagery and related ground truth data.

Table 5 supplements Table 2 and Fig. 4 in the following ways. Re-allocations of area with affiliated vegetation of certain INTERRUPTED WOODS were just noted for the two broad groups of Second-Growth Woods and Field Mosaics. Proportions of bare and nonwooded to forest area in Tropical Montane Complexes are not known, but seem likely (from general geographic knowledge) to be in the range of 40 to 60% average over most regions. Provisionally the partition is taken simply as 50% until better allocations can be made. The choice has relatively slight effect on the carbon numbers unless much larger areas become identified as "montane." Other ways of regrouping are made just for convenience of associating various tropical, all Boreal, and mostly temperate tree formations to parallel more closely some other investigators' tables (cf. Whittaker and Likens 1973, 1975; Tables 2.1 and 5.5 in Bolin et al. 1979).

Finally a major purpose for including columns for low and high as well as medium estimates of carbon is to summarize aspects of variablility and uncertainty that were omitted for simplicity in Table 2 and Fig. 4. Carbon densities and totals will be discussed in Sects. 4.2 and 4.3 after more specific details about the ecosystem areas derived from the map (Plate 1) and some of the ancillary sources just reviewed are discussed.

4.1.1 Tropical and Subtropical Woods Areas

The 1.7 x 10^6 km^2 from the forest/field complex plus 10.4 x 10^6 km^2 actually mapped as Tropical/Subtropical Broad-Leaved Humid Forest totals 12.1 x 10^6 km^2, remarkably close to the 12 x 10^6 km^2 noted by Fontaine (1981) from the latest FAO regional forest summaries (braces in Table 4, column 3). Of the 1.2 x 10^6 km^2 mapped as Tropical Montane Complex in the 30°N to 30°S latitude band, the 0.6 x 10^6 km^2 was considered as subalpine, upper montane,

Table 5. Regrouped estimates of ecosystem areas and ranges of carbon in plants

Major world ecosystem complexes	Area (10^6 km^2 or 10^8 ha)[a]		Major subtotals	Phytomass C estimates[b]: Estimated densities[c] per unit area (kg/m^2) LOW	MEDIUM	HIGH	Global totals (Pg = 10^{15} g = 10^9 ton = Gton) LOW	MEDIUM	HIGH
TREE FORMATIONS ("WOODS")[d]: FOREST AND WOODLAND and INTERRUPTED WOODS									
Tropical Montane Forests	(0.5 x 1.2) =	0.6 forest[e]		6	9	15	3.6	5.4	9
Other Tropical/Subtropical Forest (lowland humid)									
Mangroves (of forest structure)[f]	0.2			3	7	10	0.6	1.4	2
Other wet site, other wet nonseasonal evergreen equatorial forest	2.8			15	20	25	42	56	70
Lowland "tropical wet" and rain forests[g]	3.0						42.6	57.4	72
Tropical seasonal forest									
Evergreen or deciduous "moist" forest, closed or regenerating well	6.0[g]			10	14	17	60	84	102
Planted, degraded, poor site, or marginal "forest"	1.4[h]			4	10	12	6	14	17
"Tropical moist" with lower carbon	7.4						66	98	119
Mapped "lowland" wet-moist closed Tropical/Subtropical Broad-Leaved Humid Forest		10.4					108.6	155.4	191
Additional forest/field area allocated[i] to tropical humid forest		1.7		4	5	8	6.8	8.5	13.6
Combined wet-moist tropical/subtropical closed forest (including seasonal humid)			12.7[e]				119[j] (130	169 to	214[j] 200)[k]
Mostly Temperate Broad-Leaved Forest	1.5			8	10	14	13	15	21
Mixed Woods: alternating evergreen and broad-leaved	3.5			6	10	14	21	35	49
Subtotal, mostly midlatitude		5.0					34	50	70
Remnants of above, interspersed with fields, etc. (forest/field)		3.5[i]		4	5	8	14	17.5	28
Broad-leaved forest, some with plantations and other conifers mixed or alternating: subtotal		8.5					48	68	102
Predominantly Conifer forest (mostly nonboreal)		3.5[i]		12	16.8	20	42	59	70
Mostly nonboreal conifer, temperate broad-leaved, and mixed forest			12.0				90	128	172
Tropical and temperate forest, mostly closed and humid: cumulative subtotal			24.7				209[j] (250	296 to	386 350)

Table 5. (continued)

Major world ecosystem complexes	Area (10^6 km^2 or 10^8 ha)[a]		Major subtotals	Phytomass C estimates[b]: Estimated densities[c] per unit area (kg/m^2) LOW	MEDIUM	HIGH	Global totals (Pg = 10^{15} g = 10^9 ton = Gton) LOW	MEDIUM	HIGH
TREE FORMATIONS: (continued)									
Boreal forest and woodland ("taiga")[l]									
Southern continental taiga forest with openings	1.6			6	11	14	10	18	22
Main taiga, closed or open woods	5.56			4	8	11	22	44	62
Main and Southern Taiga		7.16							
Northern or Maritime Taiga, stunted subalpine woods		4.4		2	5	8	13	22	35
Boreal forest and woodland: subtotal "cold woods"[d]			11.6				45[j]	84	119[j]
							(66	to	98)[k]
Tropical/Subtropical Woodland/Savanna/Tall Scrub[m]									
Tropical Dry Forest and Woodland, mostly drought-deciduous	4.7			5	7	9	24	33	42
Tropical Savanna and Woodland, moist or dry seasonal	6.7			2	3	5	13	20	33
Xerophytic succulent thorn woods and scrub or grass	4.0			2	4	6	8	16	24
Tropical dry: subtotal		15.4					45	69	99
Wooded parts in tropical field/woods	(0.5 x 2.6)[n]	1.3		2	4	6	2.6	5.2	7.8
Main partly wooded tropical areas outside major humid forests			16.7				48[j]	74	107[j]
							(60	to	90)[k]
Other Dry Woodlands, Forest, and Tall or Dense Scrub									
Mediterranean-type woods, with savanna, chaparral, etc.	1.0			2	4	8	2	4	8
Other semi-arid woodland or low forest	0.9			2	5	10	2	5	9
Other dry or highland tree or shrub types, fairly open	2.6			2	4	8	5	10	21
Seasonally dry or highland woods		4.5					9	19	38
Mostly temperate field/woods	(0.5 x 1.4)[n]	0.7		2	4	5	1.4	2.8	3.5
Partly wooded complexes, mostly of mid-latitudes			5.2				10[j]	22	41[j]
							(11	to	31)[k]
Combined cold to (seasonally) dry woods, averaging			33.5				103[j]	181	267[j]
							(142	to	220)[k]
Subtotal FOREST AND WOODLAND, and INTERRUPTED WOODS (including some savannas and fallows)			58.2				312[j]	477	653[j]
							(400	to	550)[o]

Table 5. (continued)

Major world ecosystem complexes	Area (10^6 km^2 or 10^8 ha)[a]		Major subtotals	Phytomass C estimates[b]: Estimated densities[c] per unit area (kg/m^2) LOW	MEDIUM	HIGH	Global totals (Pg = 10^{15} g = 10^9 ton = Gton) LOW	MEDIUM	HIGH
WETLANDS AND COASTAL (Woods and/or nonwoods)									
MAJOR WETLANDS (additional exist in other types)									
Swamps, and/or shrub or herb marshes	1.6			1.5	3	6	2.4	4.8	9.6
Bogs/mires of cool or cold climates (graminoid or woody)	0.9			1	2	6	1	2	5.4
Subtotal		2.5					3.4	6.8	15
COASTAL AND MISCELLANEOUS		0.35		1	3	5	0.3	1	1.4
Subtotal WETLANDS and COASTAL			2.85				4[j]	7.8	16[j]
							(5	to	15)[k]
NONWOODS (trees, if any, small, scattered, or plants)									
MAINLY CROPPED, RESIDENTIAL, COMMERCIAL, PARK									
Irrigated farms and settlements									
Paddyland plus associated settlements and trees	2.0			2	3	4	4	6	8
Other irrigated dryland row crop and pasture	1.6			1.5	2	3	2	3	4.8
Major irrigated areas: subtotal		3.6					6	9	12.8
Other Crops, Settlements, and Marginal Lands									
Cool or cold farms, towns, etc.	3.0			0.8	1	2	2.4	3	6
Warm or hot farms, towns, etc.	9.3			0.8	1	2	7.4	9.3	18.6
Subtotal		12.3					9.8	12.3	24
Combined Crop, Settlements, and Fringe Land			15.9				16	21.3	37[j]
							(17	to	30)[k]
GRASS AND SHRUB COMPLEXES									
Grass-scrub interspersed in field/woods: (1.3 + 0.7)	2.0 grass/scrub			2	3	4	4	6	8
Grass-scrub in Tropical Montane Complexes	0.6			0.6	1	2	0.4	0.6	1.2
Heath and moorland, maritime scrub with meadows	0.15			1	1.5	2	0.15	0.2	0.3
Very cold Tibet and Siberian meadows and parklands	0.85			0.5	1	4	0.4	0.8	3.4
Subtotal		3.6					5.05	7.6	12.9
Cool grassland		3.94		0.5	1	2	2	4	8
Warm or hot grassland, or maritime or montane grass with little or no snow	8.65			0.5	1	2	4.3	8.6	17.3
Similar, with relatively more shrub, trees	8.65			1	1.6	3	8.6	14	26
Subtotal, nonsnowy shrub and grassland		17.3					12.9	22.6	43
Combined GRASS AND SHRUB COMPLEXES (besides scrub in wooded tundra, tundra, and desert)			24.8				17.9	32.1	64[j]
							(20	to	50)[k]

Table 5. (continued)

Major world ecosystem complexes	Area (10^6 km^2 or 10^8 ha)[a]		Major subtotals	Phytomass C estimates[b]: Estimated densities[c] per unit area (kg/m^2) LOW	MEDIUM	HIGH	Global totals (Pg = 10^{15} g = 10^9 ton = Gton) LOW	MEDIUM	HIGH
TUNDRA AND DESERT									
Wooded tundra and timberline fringe		1.7		1	2	5	2	3.4	8.5
Tundra and Related Complexes									
Arctic Polar Desert (besides ice)	0.2			0.002	0.01	0.02	0.0	0.0	0.0
Other High Arctic Tundra	1.6			0.1	0.5	1	0.2	0.8	1.6
Low Arctic Tundra	3.8			0.6	1	1.2	2.3	3.8	4.6
Arctic: subtotal		5.6							
Other Tundra, alpine desert, meadow and paramo		5.7		0.5	0.8	1.5	2.8	4.6	8.5
Combined tundra, alpine, and woody fringe			13.0				7.3[j]	12.6	23.2[j]
							(10	to	15)[k]
Desert and Semidesert									
Sand Desert: scrub/herbs or barren	5.2			0.02	0.05	0.2	0.1	0.26	1.0
Cool Semidesert Scrub	2.0			0.3	0.6	1.0	0.6	1.2	2.0
Other Desert and Semidesert, mostly warm to hot	11.0			0.2	0.4	1.0	2.2	4.4	11.01
Semidesert, Desert, and Bare (nonpolar)			18.2				2.9	5.9	14
Combined TUNDRA AND DESERT			31.3				10.2[j]	18.5	37[j]
							(15	to	25)[k]
Arid, Cold, Other Grassland, and Scrub (combined "Nonwoods" besides major wetland, coastal, and crops, etc.)		56					28.1[j]	52.7	101[j]
							(45	to	90)
Total for "NONWOODS" excluding major wetland and other coastal		72					44[j]	74	138[j]
							(60	to	120)[o]
Total for "Land" (Total of numbers below double lines)			133				360[j]	557.8	807[j]
							(460	to	660)[o]
WATER AND ICE:									
Lakes, Streams, and Reservoirs[p]		3.2		0.1	0.2	0.3	0.3	0.5	0.9
ICE and Antarctic POLAR DESERT		~15					0	0	0
Total area for "Continents" (Land, freshwater, and ice)			150.6				460	558.3	661
Total area for Oceans			360				1	3	45
TOTAL FOR "WORLD"			510.6				(461	561.3	665)

[a]Areas from sum for 0.5° x 0.5° cells (adjusted for latitude), except for tundra. Arctic tundra divisions are after Tables 2 and 3 of Miller (1981).

[b]Above- and belowground estimates for year-round average. Carbon assumed mostly 0.43 to 0.47 of oven-dry mass.

[c]Judgments are essential where biomass or carbon of poorly sampled types can be estimated relative to types sampled more widely. Disturbance commonly makes the landscape support less biomass or carbon than for well-developed or "mature" types. Extra digits may be carried to minimize rounding errors, but do not imply accuracy of more than one or two significant figures. Uncertainties are indicated by low and high estimates (see footnotes j, k, and o).

[d]"Woods" here include forest, woodlands, associated savannas, and scrub where it commonly becomes tall (>2 m) or dense.

[e]Includes half the 1.2 x 10^6 km^2 provisionally mapped montane that is estimated to be woods. Carbon for this part is higher than the average for the whole montane complex, but much lower than for montane forest stands of maximum biomass.

[f]Areas mapped and tabulated as "swamps" probably include an additional ~ 0.1 x 10^6 km^2 of mangrove, mostly lower or sparser than areas included in (and closely interspersed with) other tropical forest, along many of its ocean shorelines. Mangrove total of 0.3 x 10^6 km^2 from Ajtay et al. (1979) matches this plus the 0.2 x 10^6 km^2 counted in "forest."

[g]Areas estimated by difference: subtracting 0.6 x 10^6 km^2 for montane forest from Persson's (1977b) best estimate of tropical closed forest (9.6 x 10^6 km^2), and tentatively allocating 1/3 to the "wet" tropics and 2/3 to "moist tropical lowland closed forest. The latter is mostly seasonal--evergreen, semideciduous, or drought-deciduous (e.g., monsoonal) humid forest. Slightly lower proportions of "moist" were estimated by Olson et al. (1978) and Brown and Lugo (1982), but most subtropical and some tropical wet forests are also "seasonal," and these remain to be mapped.

[h]Degraded, poor site, or other marginal forest is inferred by subtracting the 9 x 10^6 km^2 in footnote g from 10.4 x 10^6, mapped as "tropical lowland" closed forest. Similar figures are reached by Persson (1974) and Brown and Lugo (1982) with slightly different scope.

[i]"Forest/field" and "field/woods" complexes were defined mostly in areas where agriculture is the dominant economic land use, but where forest remnants and/or plantations or woody crops are important enough to raise the live carbon well above the averages expected for croplands and grass or scrub area. For simplicity, all forest/field is allocated to forest area, but assumed to have a low range of carbon because of interruptions, thinnings, young stages of regrowth or plantings, and cumulative disturbances by fire, grazing, or erosion.

[j]Ranges summed simply by adding all the low and high estimates probably suggest excessively wide uncertainty on totals, if some positive and negative errors tend to cancel one another.

[k]In view of footnote j, uncertainty for totals is estimated in parentheses below the range indicated by footnote j.

[l]Areas including some dense conifer forests typically have regional averages lowered by the substantial areas of open growth and regrowing forest following cutting, fire, or old-field successions. Some but not all of these recently disturbed forests are included in Mixed Woods and forest/field.

[m]Typically outside the equatorial belt of wet and seasonal moist forests, but may include nutrient-poor, drier-site, and rainshadow areas. These include frequently burned regions; some have higher carbon stands as exceptions to the general cover, especially as gallery woods along streams.

[n]Until regional data suggest refinements, field/woods areas are allocated half to woodland (with locally denser forest remnants) and half to scrub and grassland. Cropping and grazing are important in most of these complexes, but the areas so managed are provisionally assumed to be balanced approximately by forest, woodland, scrub, and grassland in other places that are mapped as cultivated.

[o]These ranges attempt further to allow for the likely compensation of errors (see footnote j), on the high and low side, for different areas and carbon densities per unit area.

[p]Only the largest bodies of inland water are mapped separately with the resolution of 0.5° x 0.5° grid cells.

and some of the lower montane forest or woodland (Grubb 1977), but the remainder would include even smaller areas of such diverse types as alpine, paramo, or high puna formations (Barclay 1977a,b), artificially cleared areas, and cliff or avalanche areas - all having much lower than average cover, biomass, and carbon (see short bar in Fig. 4A).

Even the 11 x 10^6 km^2 (the wooded 0.6 x 10^6 km^2 of Tropical Montane Complexes, plus 10.4 x 10^6 km^2 of Tropical/Subtropical Broad-Leaved Humid Forest) that are not mapped separately as forest/field complex probably include additional degraded forest areas in many countries (Persson 1974, 1977a,b; Wacharakitti 1976; Sommer 1976; Synott 1977; Lanly and Clement 1979; FAO 1981; Myers 1980a,b; Brown and Lugo 1980, 1981, 1982; Olson 1982). Persson's (1977b) estimate of accuracy spanned a range of 8 x 10^6 to 11 x 10^6 km^2 for closed forest. His best estimate, Table 4 (column 3), was 9.6 x 10^6 km^2. Subtracting the 0.6 x 10^6 km^2 of the montane forest suggests $\sim$9 x 10^6 km^2 of relatively dense nonmontane or marginal lower montane humid forest. Subtracting that in turn from 10.4 x 10^6 km^2 of area mapped as Tropical/Subtropical Broad-Leaved Humid Forest suggests that the latter includes approximately an additional 1.4 x 10^6 km^2 that have been fairly recently or seriously disturbed, or are marginal in site quality or already degraded, and hence lowered in carbon.

Some of the more degraded forest area could correspond with the 3 x 10^6 to 5 x 10^6 km^2, as estimated by Wong (1978), Fontaine (1981) and Seiler and Crutzen (1980) to be involved in the cycle of slash-and-burn agriculture, alternating with fallow periods of regrowth of trees. However, there are 1.7 x 10^6 km^2 of fallows in open woodland formations (Singh, pers. comm.). In seasonally humid savannas, as well as seasonal humid forests, burning is even more effective than in rain or wet forests (Olson 1981b) and commonly propagates coarse grasses that make further cultivation difficult (Mueller-Dombois 1981, Fontaine 1981).

Brown and Lugo (1980, Table 6) independently estimated 10.4 x 10^6 km^2 of closed tropical and subtropical forest when they allocated by country the portions of Persson's 1974 World Forest

Inventory. In 1982, they took 10.7 x 10^6 km^2 of closed forest as an approximation to the area of moist, wet, and rain-forest categories of Holdridge (1947), without claiming to test the equivalence. They also accepted "open woodland" as an approximation to the dry, very dry, and some thorn forest categories of Holdridge (1967). J. P. Lanly, K. D. Singh, and other FAO staff do not consider these approximations consistent with the detailed data underlying either Persson's or later summaries (Hall and Brown, pers. comm., December 1982). Tropical Dry Forest and Woodland (upper right of Fig. 4a) may range over the gamut of projected foliage cover (pfc) and crown cover given in Table 1. That includes very little closed-forest in the sense of Specht (1981a), much "woodland" in the sense of Gillison and Walker (1981, including open-forest in Specht's sense), and some open-woodland.

INTERRUPTED WOODS are increasingly exploited for fuel wood, although they do not contain much industrial timber. In the tropics they include ∿4 x 10^6 km^2 of succulent and thorn woods and scrub and small parts of other dry or highland tree or shrub types among the Woods/Scrub/Grass Complexes. These and the grassy Tropical Savanna and Woodland (6.7 x 10^6 km^2) plus Tropical Dry Forest and Woodland (4.7 x 10^6 km^2) occur in climates with long dry seasons (Fig. 4A). All of these types are reported to be expanding where closed, humid tropical seasonal forest is being destroyed or degraded along the latter's margins. In part, the conversion is due to accelerated use of fire by farmers and hunters (Olson 1981a,b).

The drier types, with naturally or artificially low biomass, cover more area than the 12 x 10^6 km^2 of Tropical/Subtropical Broad-Leaved Humid Forest and related types in Table 5, including degraded and marginal areas. The former account for large parts of the areas which Whittaker and Likens (1973) called tropical rain and tropical seasonal forest (24.5 x 10^6 km^2). They assigned to these types the very high average biomass values of 45 and 35 kg/m^2 dry matter (approximately 20 and 16 kg/m^2 of carbon), respectively. The main result was an unrealistically high estimate of the tropical tree formation carbon.

4.1.2 Other Ecosystem Areas

Table 5 provides additional comparisons of the areas of dry and humid tropical tree formations with the other mapping units of Plate 1. Other FOREST AND WOODLAND include 12 x 10^6 km^2 of mostly Temperate Broad-Leaved, Conifer, and Mixed Woods of hardwood and conifer, not counting the taiga zones. Temperate Broad-Leaved Forest types occur almost exclusively outside the tropics, but Mixed Woods are meant to include significant subtropical and even small tropical areas, especially in highlands. Boreal forests include slightly over 7 x 10^6 km^2 in Main and Southern Taiga which are predominantly FOREST AND WOODLAND with brief growing seasons. Northern or Maritime Taiga (4.4 x 10^6 km^2) includes the transition belt where trees become shorter and more interrupted northward, upward in altitude, or toward cold oceans where maritime climates diminish the effective growing temperature during the brief summer. The Semiarid Woodland or Low Forest groups identified earlier are in southern temperate/subtropical climates (0.9 x 10^6 km^2), while the succulent and thorn woods and scrub prevail in more tropical and equatorial areas. The other dry or highland tree or shrub types (2.6 x 10^6 km^2) are mostly nontropical.

Categories of "nonwoods" other than wetland or coastal each cover much wider areas. MAINLY CROPPED, RESIDENTIAL, COMMERCIAL, PARK comprises almost 16 x 10^6 km^2. GRASS AND SHRUB COMPLEXES not allocated to other groups such as savanna or desert comprise almost 25 x 10^6 km^2. This includes approximately 0.85 x 10^6 km^2 (type 42 on Fig. 1) divided between the extremely cold areas of Tibetan meadows and Siberian parklands or steppe areas where trees are also stunted or missing altogether. This does not include the 1.7 x 10^6 km^2 of dwarfed trees and scrub called wooded tundra and timberline. Wooded tundra and timberline (Plate 1) grades toward tall-shrub tundra (a negligible part of the tundra area) from Northern or Maritime Taiga. Arctic and other tundras (including mountain meadows and rocks nearly bare or lichen covered), along with the wooded tundra comprise 13 x 10^6 km^2 of arctic-alpine land. The Tundra, Polar or Rock Desert, and Ice estimates in Table 5 are based on Miller (1981) in part and on cell counts of our ecosystem map (Plate 1) below arctic tundra latitudes. Along with over 18 x 10^6 km^2 of nonpolar desert and semidesert, over 31 x 10^6 km^2 are very low in both the pools and exchange rates for plant carbon.

Areas of Bog/Mire of Cool or Cold Climates large enough to map are mostly in very northern areas, while Warm or Hot Wetlands along coasts, floodplains, and poorly drained interfluves vary irregularly with latitude. The Shore and Hinterland Complexes mapped to date (in addition to black shorelines) occur in proportion to the land distribution by latitude. Tentatively, such land areas given are estimated as 35% of the total area of cells mapped as Shore and Hinterland Complexes, since one or two quadrants of such cells typically overlap land. The prevalent ecosystem type is commonly used to identify the coastline cells if more than 50% of the area is land. The mapped cells of MAJOR WETLAND and OTHER COASTAL, AQUATIC, AND MISCELLANEOUS land complexes add up to less than 3 x 10^6 km^2. The collective addition of many small patches of such landscapes that are spread over the rest of the map would probably not double this total.

4.2 CARBON DENSITIES IN PLANT MASS (PHYTOMASS)

Ovington (1962, 1965) reviewed many estimates of local forest biomass density and production rates. By the early 1960s, plans had developed to use models relating inventories and production rates for a variety of ecosystems that included litter and humus materials (Olson 1963, 1964) as well as phytomass. The Oak idge biomass work concentrated on species that reach large s ze (Sollins and Anderson 1971, Sollins et al. 1973). Shanks and Clebsch's (1962) and Whittaker's (1966, Whittaker et al. 1963) harvesting estimates and litter decay estimates (Shanks and Olson 1961) in the nearby Great Smoky Mountains National Park deliberately sought old-growth forests, mostly of large tree dimension. This permitted using the working hypothesis of steady state in model balance calculations. Subsequent IBP studies mostly favored virgin or well-developed stands (Newbould 1967, Duvigneaud 1971, Reichle et al. 1975, Reichle 1981). A bias toward high global biomass pool inventories emerged only when these specially selected stands were uncritically averaged as if they were widely representative of average conditions.

Field stations of the Komarov Botanical Institute of the USSR Academy of Sciences (Rodin et al. 1968, 1972), many scientists following Remezov's tradition at Moscow State University, and other Soviet workers documented data for stands of many ages. But apparently they too selected many research sites which epitomized "high quality" instead of average ecosystem development (Rodin and Bazilevich 1968). For example, Rodin and Praudin's extraordinarily massive Brazilian coastal mountain rain forest (pp. 209-211 in Rodin and Bazilevich 1967) did not represent vast tropical areas subject to hurricane or other disturbance such as the El Verde Puerto Rican "lower montane" rain forest. Data from El Verde are analyzed by Ovington and Olson (1970) and tabulated in Appendix A of this report.

Very high local carbon levels have been documented for certain tropical and temperate rain forests (Rodin 1953, Brünig 1967, Fujimori et al. 1976, Waring and Franklin 1979). Poor soil conditions lowered tropical pools elsewhere [e.g., Rio Negro forest (Stark and Spratt 1977; Stark and Jordan 1978; Jordan and Escalante 1980; Jordan 1982)]. For Southeast Asia, Chan (1982) and Appendix A of this report illustrate typical ranges of variation and regional averages. For additional sources of information leading to global pools, see Appendix B.

Seeking stands approaching the natural upper limits for growth allowed by local climate and site is sometimes justified by the knowledge that some intermediate levels of plant mass and carbon for the realistic average landscape of young and old stands can be interpolated indirectly if needed. Depending on whether young or old stands are prevalent from the region's history of fire and cutting, this regional average must be more or less drastically below the upper bound estimated from virgin and mature stands. Rarely, if ever, is the selection of cover types, sites, and age classes by researchers expected or designed to make a systematic or random sampling to represent an unbiased estimate of regional average biomass or carbon. Routine resource inventories (like the forest surveys noted in the Appendix A) do seek such averages, but generally only for some merchantable subset of the total biomass (e.g., for sound, straight tree boles, exceeding 10, 30, or 50 cm in diameter at 130 or 137 cm above the ground level, on the uphill side of the tree; or above buttress level in some tropical forests). How to convert extensive surveys of this type to valid relations with complete biomass sampling is addressed further in Appendix A, but this remains a large problem for continuing studies of the biospheric carbon (Johnson and Sharpe 1982).

The best estimates for the regional averages, combining all the allowances the senior author could make in 1981, are given in the single column of carbon density shown for simplicity in Table 2. Parentheses there call attention to the lower averages attributed to the nonwoody areas of Tropical Montane Complexes to field/woods complexes (see also Table 5 and dotted lines in Fig. 4A).

Table 5 restates these numbers, but relocates the woody and nonwoody areas of these mixed complexes in proximity to related ecosystems so that sums of area and total carbon can more easily be compared with equivalent estimates by other authors. Table 5 also adds columns for low and high as well as medium estimates of average carbon density (and corresponding global totals). These are based on experience and judgment, combining all known or suspected components of sampling variance and bias that might make the medium estimates above the expected value (unknown true mean) in some cases and below it in others.

Based mainly on Appendix A and its sources, Table 5 also gives some further breakdowns of the tropical forest to illustrate how the admittedly high carbon density of lowland rain forest and some other wet-climate and wet-site closed forest might be offset by lower mass of most mangrove forests. (Some of these were covered separately in swamp woods.) Seasonal moist forest (evergreen to drought-deciduous) and other lower-mass forest types also affect the broad average of 14.9 kg C/m^2 that was rounded to 15 for Tropical/Subtropical Broad-Leaved Humid Forest in Table 2. The allocation of an extra 1.7 x 10^6 km^2 of forest/field area as predominantly younger Second-Growth Woods and Field Mosaics of this type increases the area matching "rain forest" in the very loose sense used by Whittaker and Likens (1973). That is still only 12.7 x 10^6 km^2 instead of their 17 x 10^6 km^2. For any plausible carbon density that might be assumed for this Second-Growth Woods, and for its additional dilution by fields currently in the mapped areas of INTERRUPTED WOODS, the corresponding combined carbon density is lowered to a mean near 13.3 kg C/m^2.

If all the low estimates on carbon density were added, the mean for all the wild and disturbed variants of the preceding paragraph might be as low as 9.4 kg C/m^2. Only by taking all on the high side might the mean be increased to 16.8 kg C/m^2 -- in the lower part of the 16 to 20 kg C/m^2 which Whittaker and Likens (1973) assigned to a tropical forest area almost twice as large as we find for humid tropical forest. It is implausible that all our errors would be either all on the high or all on the low side (footnote j in Table 5). A more credible range of uncertainty for mean carbon density would be 10.2 to 15.7 kg C/m^2, corresponding with the subjectively rounded global total range of 130 to 200 kg C (footnote k in Table 5).

The next regrouping of importance in Table 5 brings together the several kinds of taiga or Boreal forest. The arealy weighted mean of 8 and 11 kg C/m^2 for Main and Southern (Continental) Taiga, respectively, gives the 8.66 kg C/m^2 average, rounded to 8.7 in Table 2. Table 5 also brings up the Northern and Maritime Taiga and its estimated mean of 5 kg C/m^2, for convenience in grouping in the Boreal (taiga) total of 84 Pg C. The combined average density is 7.2 kg C/m^2. All low and high estimates would give 3.9 to 10.6 kg C/m^2 (footnote j); more credible uncertainty around the preceding mean would be 5.7 to 8.4 kg C m^2 (footnote k).

These figures all exclude the wooded tundra and timberline (often translated "forest tundra" and pooled with Boreal or taiga forest. Including it would increase the total C to 87.4 Pg C, but lower the average density to 6.6 kg C/m^2 over the combined area of 13.3 x 10^6 km^2). That complex is grouped with Cold Grass or Stunted Woody Complexes on Table 2 (i.e., with other potential grazing lands of GRASS AND SHRUB COMPLEXES). In Table 5, the same transitional zone is alternatively juxtaposed with the neighboring Tundra. Its higher carbon density does not quite offset the low carbon of high arctic and alpine complexes having much bare rock. The combined mean is very close to the round number of 1 kg C/m^2 taken for the average of various low arctic tundra communities.

Like Polar and Rock Desert, most Sand Desert is almost bare, and merely dilutes the overall desert mean to 0.3 kg C/m^2. Combining Tundra (along with wooded tundra and timberline but not Ice) and Desert (along with Semidesert) gives 0.6 kg C/m^2 weighted average. Again, summing low and high estimates indicates conceivable mean densities from 0.3 to 1.2 kg C/m^2. If some over- and underestimates of carbon cancel, the global totals of 15 to 25 Pg C imply uncertainty of their density average more like 0.5 to 0.8 kg C/m^2.

Between the massive forest and bare rock or sand, from hottest to coldest and wettest to driest habitats, best estimates for ecosystems with less extreme averages and uncertainties about carbon can similarly be read from Tables 2 and 5. The countries from which stand values of carbon density are available are given in Appendix B (Table B-1 for Tree Formations; Table B-2 for other ecosystems). The broad ranges of carbon given for major legend groups on Plate 1 are believed to span all the type means in each group and most of the mapping cell stand averages that contribute significantly to those means.

4.3 GLOBAL CARBON ESTIMATES

The total petagrams (billion metric tons, or gigatons) of carbon on Table 2, and ranges for these global total estimates given in the Low, Medium, and High columns of Table 5, were estimated by multiplying square meters of area by kilograms of carbon per square meter (Eq. 1). Huge though these totals are, present estimates are significantly below other recent high estimates reviewed briefly in Sect. 4.3.1. Credible ranges for the true but still imperfectly known totals are summarized in Sect. 4.3.2, considering the uncertainties just discussed. Finally, in Sect. 4.3.3 we review some early historic estimates based on an idealized assumption of the world carbon balance being in a steady state (Eqs. 2 and 3 below). That section and its equations also remind us that production and storage have not actually equalled the carbon loss (turnover) during the many millenia when primeval plant carbon was being drawn down to modern levels estimated in the present report. An analysis of net rates of change, probably still contributing almost 1 Pg C/year of excess CO_2 to the atmosphere, is treated by Olson (1982).

4.3.1 Recent High Global Carbon Estimates

When Bazilevich and colleagues extended available data to world maps (Bazilevich et al. 1968, 1969, 1971; Rodin and Bazilevich 1968), allowance for reduced forest area and reduced biomass per unit area due to human disturbance was not yet incorporated. Bazilevich (1974 and pers. comm.) and Rodin confirmed the understanding (Olson 1974) that their averages (mostly compiled by Rodin and Bazilevich 1967) refer to selected, mostly well-developed or potential vegetation, not typical managed or degraded vegetation/soil types. Hence, the phytomass total for all continents (2400 Pg dry matter of Bazilevich et al. 1971, approximating 1080 Pg C) has to be very much higher than an upper bound for modern conditions, where harvest, accelerated disturbance, and incomplete recovery are typical.

Whittaker and Likens (1973, 1975) criticized Bazilevich et al. (1971) for using extreme values as if they were means for wide areas. Yet, Whittaker's tabulations and averages clearly did not omit or de-emphasize the disproportionately large share of virgin stands which he and Becking selected in the Great Smoky Mountains (cf. comparisons of Olson 1971b), or the oldest oak forest that could be found on Oak Ridge sites [right column of Cannell (1982), p. 282], compared with more typical second-growth forests of Tennessee and North Carolina restated on pp. 282-283 of Cannell (1982). Multiplying high averages resulting from such old-growth forests by overly large areas designated as closed forest affects their own global estimates on the high side. Whittaker and Likens (1973) estimate of 1837 Pg of global plant dry matter, assuming 45% C, gave 827 Pg C for the continents. The latter value is often quoted (Bolin et al. 1979; Hampicke 1979a,b, 1980) and factored into high flux estimates for CO_2 to air (Woodwell and Houghton 1977, Woodwell 1978, Woodwell et al. 1978, Prentice and Coiner 1980), despite Whittaker and Likens' stated misgivings about how representative their estimate could be. The 1976 synthesis estimate (Baes et al. 1976) of 680 Pg C (about 600 Pg C for woody tops and roots and 80 Pg C for other live vegetation) also seems now like a high, but less extreme, upper bound (Olson et al. 1978).

4.3.2 Credible Ranges of Plant Carbon for Major Landscape Complexes

The less-degraded closed nonmontane Tropical/Subtropical Broad-Leaved Humid Forests (Richards 1964, Jordan 1982, Brown and Lugo 1982) and their degraded remnants (109 to 191 Pg C) still dominate the totals, and the uncertainties, for the tropical forest (119 to 214 Pg C) and for world woods (400 to 550 Pg C). Tropical Dry Forest and Woodland (24 to 42 Pg C), without or with much opening to shrub, and grassy Tropical Savanna and Woodland (13 to 33 Pg C) contribute intermediate amounts to the tropical woods total. However, these groups do deserve closer attention (Huntley and Walker 1982) because of rapid net lowering of live organic carbon by fire, as well as significant charcoal storage as a potential sink (Seiler and Crutzen 1980, Olson 1981b). Both fluxes could be important for changes in the global income/loss budgets of carbon and carbon dioxide. Succulent and thorn woods and scrub [e.g., caatinga in northeastern Brazil as discussed by Bucher (1982) and mapped by Hueck and Seibert (1972), rather than oligotrophic wet forest caatinga on poor, sandy Upper Amazon Spodosols (Stark and Spratt 1977, Stark and Jordan 1978, Brunig et al. 1979, Jordan and Herrera 1981)] may have still less carbon mass (8 to 24 Pg C) to affect global totals. An additional 11 to 31 Pg C in other dry, low, open, or scrubby woods are mostly temperate or marginal subtropical.

The Temperate Broad-Leaved Forest, Conifer, Mixed Woods, Main and Southern Taiga, and Northern or Maritime Taiga include 48 to 102 Pg C (broad-leaved and mixed types), 94 to 119 Pg C (Taiga), and 42 to 70 Pg C (other Conifer) in the FOREST AND WOODLAND pool of carbon.

Carbon density in live plants in nonwoods ecosystems is low. The main uncertainties concern how much to add for the scattered trees or wooded inclusions not counted in woods per se. GRASS AND SHRUB COMPLEXES (20 to 50 Pg C) do not contribute nearly as much as woods to global totals nor do Tundra (10 to 15 Pg C) or various Desert and Semidesert (3 to 14 Pg C). MAINLY CROPPED, RESIDENTIAL, COMMERCIAL, PARK agro-urban and fringe areas contribute only slightly larger totals and uncertainties (17 to 30 Pg C) than Tundra and Desert taken together, but less than our estimate of GRASS AND SHRUB COMPLEXES. MAJOR WETLANDS add at least 5 to 15 Pg of live carbon, but these ecosystems are more important for storage of carbon in soils and sediments.

In taking the final step from such ranges to an estimated value of carbon per unit area and a global total in Table 2, there is still considerable leeway from judgment and experience to use the sampled averages differently. Adding all the low and high estimates in Table 2 for nonwoods would give 44 to 153 Pg C, but the compensation of some errors on low and high sides would narrow the credible range from 60 to 120 Pg C. The true total is obviously large compared with wetland and coastal (8 Pg C), but small compared with the current estimate of 476 Pg C for the main "Tree Formations." Only by taking the high estimate for every unit in Table 2 could we approach the value routinely cited and used by Whittaker and Likens for carbon in global plant mass. A more credible current estimate is 558 ± 100 Pg C for land vegetation. However, as closer refinements are made, future estimates seem more likely to move downward than upward.

4.3.3 Discussion of Earlier Estimates of Organic Carbon and its Annual Production Rates

Lieth's (1978) review of production rate estimates notes Liebig's (1862) extrapolation that 64 Pg C/year would be taken up if the global land area fixed carbon at the estimated rate of 0.5 kg C m^{-2} $year^{-1}$, based on uncorrected harvest data from a typical European meadow. Schröder's (1919) classic was also based primarily on production rates but included an indirect inference about global plant mass. He conjectured a global forest biomass estimate of 550 Pg of carbon, using a common geochemical hypothesis of steady state. This assumed that his annual carbon income estimate for all world forests (11 Pg/year) equals annual loss. The loss is the product of the unknown pool size multiplied by a mean annual turnover fraction (i.e., 1/residence time, averaged over the varying actual times between photosynthetic input and loss by cutting or death of tree or branch, leaf, etc.). The steady-state equations were equivalent to those used in ecosystem modeling of litter (Jenny et al. 1949, Olson 1963), humus (Jenny et al. 1949), or multicompartment systems (Olson 1964, Sollins et al. 1973, Innis 1978, Bazilevich and Titlyanova 1980, Breymeyer and Van Dyne 1980):

$$\text{(income)} = \text{(loss)} \tag{2a}$$

$$\text{(forest production)} = \text{(1/residence time)} \times \text{(pool size)}, \tag{2b}$$

$$11 = \text{(fractional turnover)} \times \text{(pool size)}. \tag{2c}$$

If the turnover time were 50 years, then elementary algebra provides the pool estimate:

$$\text{(pool size)} = \text{(production)} \times \text{(residence time)} = 11 \times 50 \tag{3a}$$

$$= \text{(production)/(turnover) fraction} = 11/0.02 \tag{3b}$$

$$= 550.$$

These estimates are remarkably close to those of the present report. Yet they hinged strongly on their authors' intuitions about the meadow value or mean tree mass age chosen for one-step extrapolation to the world.

Other early estimates of biomass or its carbon were generally much lower. Hutchinson (1954) seemed ready to follow Rubey (1951) and others in accepting an estimate near 700 Pg for carbon in humus. However, he rejected Rubey's estimate of 29 Pg for living mass, stating that "A value of the order of 10^{17} g would be reasonable...." Craig (1957) also rejected the very low estimates, but considered 0.06 g/cm^2 of the whole earth (511×10^{16} cm^2 land plus water area), or 307 Pg, as accurate enough for his models of isotope distribution among major global carbon pools. In his diagrams, live organic carbon was taken as 50% of the atmospheric content, then estimated to be 644 Pg.

Müller's (1960) synthesis on carbon cycling combined extensive records of biomass as a function of stand age (Møller 1947, Møller et al. 1954) with other data. Numerous species and sites were compared by Ovington (1962, 1965, and earlier works cited there). Müller's own field and laboratory research on photosynthesis and respiration in Denmark and the Ivory Coast were updated by Müller and Nielsen (1965). Müller's (1960) judgment retained a global estimate of approximately 300 Pg of plant carbon (also followed by Lieth 1963).

Production rates fluctuate from year to year with changing weather. But if that could be averaged out, production is generally presumed to vary less than stored biomass and carbon do, following a temporary readjustment period when old ecosystems are replaced by young ones, or by different ones using undegraded sites. There are important losses in productivity: where soils are eroded, air is polluted, water is less available, or less of the potential growing period is used by substitute vegetation. But additions of nutrient and water on the localities that reward cultivation may offset some loss of organic production rate, on a given site, or elsewhere. Reviews of the problem and data on production and carbon cycling have been made in earlier reports (Olson 1964, 1974, 1975; Lieth and Whittaker 1975; Olson et al. 1978; Ajtay et al. 1979) and are beyond the scope of this report. Nevertheless, a few more words are needed along with summary values (from Table 2) in order to relate these values to the map of Plate 1.

Many of those references cited below include estimates of net primary production, the intake of organic matter from CO_2 and water by photosynthesis (and incidental mineral uptake) minus the plants' own loss or "tax" due to respiration. Comparatively few studies have enough independent measurements of respiration, especially for enough times in the cycle of seasons and growth, to allow for the latter respiratory losses and to infer the photosynthetic rate or gross primary production (Olson 1964, Cooper 1975). Many of the International Biological Programme studies made fuller allowance than earlier research did (Lieth and Whittaker 1975) for various losses that tend to occur concurrently with growth, thereby obscuring and generally underestimating the inference of total production from harvest of plants through time.

The resulting findings are numerous only for aboveground plant parts. Careful excavation is often made for root systems as well. Allowance for the sloughing of part of the production as roots grow and perhaps exuding of organic matter is approximate at best (Gilyarov et al. 1968, Singh and Singh 1981). Commonly the adjustment, or even the harvest, required to infer belowground production is so difficult that it is not even attempted or completed. Conversion factors from aboveground growth rates, like those for root mass, may be substituted. That makes it important to distinguish between cases where the study in question has included its own basis for inferring belowground mass or production, and many others where an approximation is made from related research, or from plausible but untested assumptions (Rodin et al. 1968).

If syntheses were limited to those few experimental situations where photosynthesis/respiration balances and detailed root studies had been attempted and were successful, very few geographic points would be available. Most would be restricted to mid-temperate latitudes, or else to a few expeditionary situations for short periods in very cold or hot, rainy, snowy or dry, or windy, exposed situations. For these reasons and others, conclusions about regional and global production of organic matter are sometimes derived through indirect inference from climatic measurements that are more routinely made and summarized (cf. Leith and Whittaker 1975).

Even the preliminary summary of Table 2 indicates that all major complexes besides Tundra and Desert contribute significantly to the biosphere's annual flux. The global total near 60 Pg C/year is very similar to that of Ajtay et al. (1979) and only slightly larger than old estimates of Deevey (1960) and Olson (1970a, also Olson et al. 1970). It is significantly above estimates of Lieth (1963, 1975) and Fung et al. (in press), and could possibly modify the interpretation of seasonal exchange which especially concerns these authors. For these reasons, and for a more basic understanding of biospheric cycling of elements, it is still important to evaluate and possibly improve these inferences of carbon flux.

CHAPTER 5

IMPLICATIONS AND CONCLUSIONS

5.1 GLOBAL DISTRIBUTIONS OF PLANT CARBON IN LANDSCAPES

The reasons for downward revision in estimates of carbon in mass of present vegetation are: (1) diminished areal extent of relatively continuous closed FOREST AND WOODLAND, and (2) lesser mass and carbon per unit area in live plants of these and INTERRUPTED WOODS. The inferred products of area and mass per unit area were summed to give approximately 477 Pg C in these groups of tree formations, among major regional land systems. After minor adjustments for some inclusions of nonwoody landscapes in the former (Tables 2 and 5, Fig. 4a), approximately 74 Pg C is currently attributed to plants in land systems without trees, or with relatively few trees or those of low status, or artificially planted: the mainly "nonwoods" landscapes. These figures exclude separate allowance of 8 Pg C for MAJOR WETLANDS and COASTAL COMPLEXES; allocation to these could be increased by redefinition but that would just cover more of the small inclusions that are currently accounted for along with the major land systems. Variations of such figures due to different grouping and rounding are small compared with inherent uncertainties near 20% in most of them.

A generous allowance for emergent as well as submerged freshwater plants brings the total to near 559 Pg C as a medium estimate for land and lakes. Seaweeds and plankton may add ∿3 Pg C in the oceans, but that is imperfectly known. The total of ∿562 Pg C for all live plants is a tentative medium estimate, within a wide range of other possibilities. A review of actual variability among literature values observed locally and ranges of uncertainty for inferring regional averages suggests that ±100 Pg C is a credible margin of error around this expected value.

On the high side, the estimates of over 800 Pg C for plants seem misleading unless massive tropical forest is far more extensive than we find in more detailed regional analysis (Appendix A). Further revisions on the low side, well below 560 Pg C, would be less surprising if recent use of forest inventories and new remote sensing were more fully utilized. The standing, fallen, or partly decayed residues of plant material are not included in these figures, nor are the somewhat larger estimates attributed to humus within soil profiles (Post et al. 1982a, 1982b).

5.2. IMPLICATIONS FOR HISTORIC CHANGE

The global carbon budget can readily become unbalanced by a small relative shift in either income or loss, for either atmospheric or biospheric carbon (Olson 1982). It is a remarkable feature of the earth's geochemical regulatory system that the balance of CO_2 and climate have averaged as close to zero as various geologic indicators of net change seem to indicate (Lovelock 1979).

Carbon in postglacial but preagricultural world vegetation might have approached 800 to 1100 Pg, near a global carrying capacity (Bazilevich et al. 1971, Olson 1974, Olson et al. 1974). But for recent centuries, such very high totals seem incompatible with estimates presented here. Previous estimates of 680 to 700 Pg C (Baes et al. 1976) now seem high for the present, perhaps being appropriate for 100 or more years ago (Olson et al. 1978).

Recent estimates of 560 to 590 Pg C for actual current vegetation may reflect an interim medium consensus (Olson et al. 1978, Bolin et al. 1979) that is also compatible with the Major World Ecosystem Complexes map (Plate 1). Further downward adjustment of estimates (below 500 Pg) is conceivable as forest disturbance, incomplete regrowth, and poor site conditions are more precisely evaluated.

The unequal changes of large income and loss rates could make the small net balance shift from source of atmospheric CO_2 to a temporary sink, and back to source. Because humus pools are even larger than phytomass, but slower to adjust, a closer review of their relations to release of live plant carbon is also clearly important. The inferred release of carbon from vegetation and soils could help to explain the increase from lower atmospheric CO_2 which Oeschger (pers. comm.) infers from ice cores containing inclusions of preindustrial and preagricultural atmospheric gases.

5.3 CONCLUSIONS

The rates of CO_2 release to the atmosphere and removal from it are controlled differently by factors affecting photosynthesis, respiration, and burning as well as by shifts in land use and climate. These relations and further improvements in knowledge of the plant pools undergoing change will affect our ability to integrate understanding of biology and geography into geophysical modeling of element cycles and climate.

1. The map of Major World Ecosystem Complexes (Plate 1) provides a current reference base for interpreting the role of vegetation in the global cycling of CO_2 and other gases. It combines improvement in available ecological data and techniques for computer generation of maps.

2. Landscape areas inferred from the map and other sources and weighted averages of carbon in various kinds of vegetation suggest significantly lower carbon in global vegetation ($\sim$560 ± 100 Pg C) than has been sometimes used in recent analyses of global geochemical cycles.

3. Tabulations still show tree formations holding most of the plant carbon. Yet decreases in area and mass of closed forest have already been so extensive that hundreds of petagrams (billion metric tons) of C were probably released over centuries or millenia prior to recent industrialization and human population growth.

4. The remaining plant pool is still large enough to contribute a few petagrams of C per year to atmospheric CO_2, if conversion as well as harvesting of massive tropical forest continues (a significant fraction of recent releases of 5 Pg C/year from burning of fossil fuels). The problem remains, however, to infer how much of that release is offset by renewed storage in untilled areas of the tropics. In temperate or Boreal zones, even more forests are regrowing after earlier harvesting and clearing and because of recent fire protection (Olson 1981b, 1982).

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APPENDICES

These Appendices explain in greater detail methods and data used for relating the map of Major World Ecosystem Complexes (Plate 1) to the vegetation's carbon. Most detail is provided for tropical forest examples in Appendix A, for which there has been the greatest uncertainty and large differences between present and some previous global estimates. Appendix B identifies the countries in which sample plot values of mass (or implied carbon) are available for these and other complexes. Publications cited above or in the Bibliography offer sources of still more information.

While concentrating on the map and its data sources, this report clarifies how some improvements can be made in future versions. The authors welcome data and advice to aid such improvements, as well as suggestions or techniques for summarizing real change over time. Readers can derive alternative values, e.g., using different average conversions from mass to carbon, inferences from aboveground samples to total mass (including roots), or expansions from local (and possibly atypical) stands to regional complexes. Using specific examples, we start with the estimation for a single site, and then consider a larger region (Southeast Asia and nearby islands), and finally the whole earth to illustrate the approach taken in deriving present estimates.

APPENDIX A

DETAILS ON ESTIMATING BIOMASS AND CARBON: TROPICAL EXAMPLES

Many early studies, especially on plantations of even-aged monocultures, sampled a single tree of intermediate size and multiplied mass of its parts by the number of trees to estimate stand mass and sometimes inventory of chemical elements. Since no one tree would be "representative" in every respect (Gholz and Fisher 1982, foliage vs bole mass), an early extension of this technique was to stratify the tree population (e.g., into 3 to 5 size categories), and calculate weighted averages for the stand from these. Appendix A.1 illustrates an extension for coping with multiple species of widely varying size, by statistical regression methods. Mathematical refinements of this approach may still be in order. Bias may arise from doing the regressions on logarithms, and then taking antilogs from the resulting regressions for the final summaries in original units of mass (Beauchamp and Olson 1973). Departures from linearity (e.g., between foliage and other biomass) may require other methods of mathematical analyses (Hozumi et al. 1968, 1969).

A.1 BIOMASS ESTIMATION FOR AN INDIVIDUAL SITE

The following example draws on Ovington and Olson's (1970) study on the biomass and chemical content of the Puerto Rican El Verde "lower montane" rain forest--more like lowland forest than the stunted elfin forest or "summit forest" of nearby peaks (Howard 1970). Many complementary studies are documented in Odum and Pigeon (1970).

A few biomass studies in tropical rain forests have involved clear-felling and weighing of all plant material (e.g., Nye and Greenland 1960). In the El Verde experimental plots, no destructive sampling was allowed. Therefore, several possibilities for allometric analysis of plant dimensions were examined. Relations between mass and stem length or diameter or some combination were expressed as regressions (Table A-1).

Table A-1. Regression data for predicting tree mass in El Verde Forest.[a] Source: Ovington ad Olson (1970)

Species group compartment	Intercept a	Coefficients	
		b_1	b_2
A - "Light" trees[b]			
Leaf	2.9254	0.0012	1.3277
Branch	2.7453	0.0004	2.2401
Bole	4.3821	0.0010	1.9379
Roots <0.5 cm	1.3583	-0.0003	0.8582
Branch + bole	4.5978	0.0009	2.0008
Roots >0.5 cm	3.0020		2.5538
B - "Heavy" trees[c]			
Leaf	3.0115	0.0004	1.8169
Branch	2.6456	0.0007	2.2707
Bole	4.5939	0.0005	2.2212
Roots <0.5 cm	0.8625	-0.0004	1.9700
Branch + bole	4.7647	0.0007	2.1158
Roots >0.5 cm	3.0089	0.0001	2.6212
C - Minor species[d]			
Leaf	4.0243		1.5726
Branch	4.1189		1.9357
Bole	5.3717		1.8010
Roots <0.5 cm	1.5415		0.9779
Branch + bole	5.6533		1.8433
Roots >0.5 cm	4.2850		1.9367
Palm[e]	3.8463	2.9123	

[a]Major tree and shrub species were treated using natural log of diameter, and height, untransformed because of slightly better pattern of linear dependence. This is equivalent to the form used in forestry volume tables of the Tabonuco forest. Weights predicted are in natural logarithms; antilogs or exponentials transform the data back to mass.

[b]Group A - *Cordia borinquensis, Cyrilla racemiflora, Cordia sulcata, Dacryodes excelsa, Ardisia glauciflora, Micropholis garciniaefolia, Meliosma herbertii, Ocotea leucoxylon, O. moschata, O. spathulala, Palicourea riparia, Tabebuia pallida.*

[c]Group B - *Andira inermis, Buchenavia capitata, Casearia arborea, C. guianensis, C. sylvestris, Comocladia glabra, Guatteria caribaea, Guarea trichilioides, G. ramiflora, Homalium racemosum, Inga laurina, I. vera, Linociera domingensis, Matayba domingensis, Magnolia splendens, Mangifera indica, Manilkara bidentata, Miconia prasina, M. tetrandra, Ormosia krugii, Sloanea berteriana.*

[d]Group C - *Alchornea latifolia, Alchorneopsis portoricensis, Byrsonima coriacea, Cecropia peltata, Clusia gundlachii, Croton poecilanthus, Calycogonium squamulosum, Dendropanax arboreus, Drypetes glauca, Didymopanax morototoni, Daphnopsis philippiana, Eugenia stahlii, Ficus laevigata, F. sintenisii, Guettarda laevis, Hirtella rugosa, Ixora ferrea, Ocotea portoricensis, Psychotria berteriana, Sapium laurocerasus, Tetragastris balsamifera, Trichilia pallida, Myrcia deflexa, M. splendens, M. leptoclada.* Mass of minor species was estimated using natural log of diameter alone as a predictor.

[e]Mass of palm *(Euterpe globosa)* was estimated using natural log of height alone as a predictor.

For the palm (Euterpe globosa) the natural logarithm of height x_i (centimeters to the highest leaf tip) was the most satisfactory predictor of tree dry mass, y_i, in the form:

$$\ell n\ y_i = a + b\ \ell n\ x_i \quad . \qquad \text{(A1)}$$

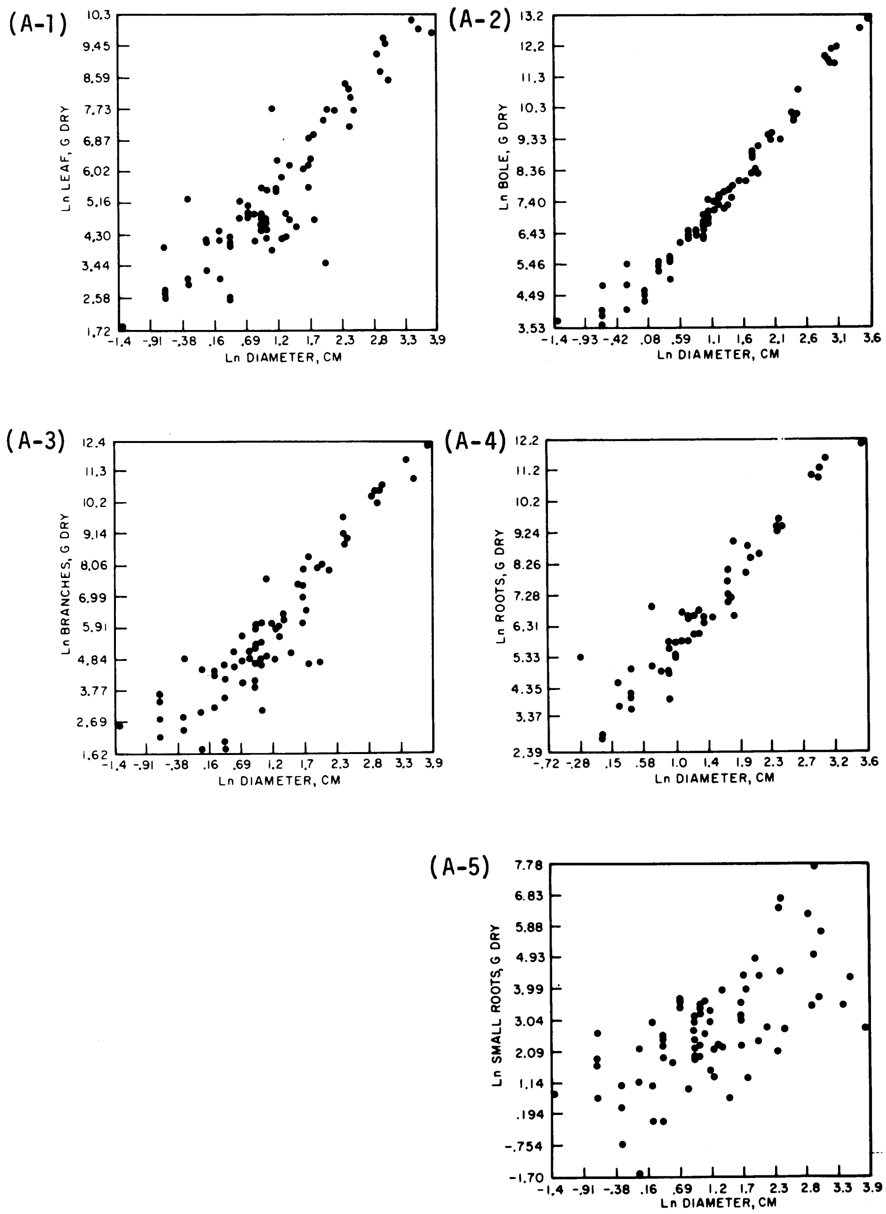
Natural logarithm of diameter (centimeters at 130-cm height above ground = x_2) was the single predictor used for a group (C) of minor species. For two groups of major species, unexplained variance could be reduced best by using regressions with both height (untransformed) as well as the log of diameter:

$$\ell n\ y_i = a + b_1\ x_1 + b_2\ \ell n\ x_2 \quad . \qquad \text{(A2)}$$

Most of the reduction of unexplained scatter that was gained by using both x_1 and $\ell n\ x_2$ as predictors of dry mass was given by diameter for the groups of species (other than palm, Euterpe) listed in groups A, B, and C in footnotes to Table A-1. Figs. A-1 to A-5 show this dependence of height on diameter for the plant parts (leaves, branches, bole, roots) greater than 0.5 cm, and retrievable roots less than 0.5 cm--typical examples of allometric relations connecting various measures of plant parts.

From these relations, the weights of plants then could be estimated for all 11 experimental forest blocks (Table A-2). The graphical relations between the dry weights of tree components and the diameters for all groups pooled are given in Figs. A-1 to A-5.

After several successive regroupings of like species, a satisfactory arrangement of three broad groups (Table A-1) was made. Even within these groupings, there was considerable scatter, but most of this seemed to be due to inherent variability in form and wood density of individuals. This was also found in a number of similar Japanese studies, commonly using another regression form of mass on the product of squared diameter multiplied by height (e.g., Ogawa 1965b, Hozumi et al. 1969).



Figs. A-1 - A-5. Logarithmic relations of El Verde lower montane forest tree diameters (at 1.3 m height) to: dry mass of leaves (A-1); branches (A-2); bole (A-3); roots coarser than 0.5 cm (stump and other) (A-4); roots finer than 0.5 cm (A-5). Three groups of species with 23 individuals of 9 genera in Group A, 25 individuals of 11 genera out of 13 in Group B, and 22 individuals in 8 genera out of 22 in Group C are combined in the scatter plots shown here (see Table 2 of Ovington and Olson (1970)].

Table A-2. Biomass of major living components of the El Verde Lower Montane Rain Forest.[a] (average g m^{-2} or Mg km^{-2} predicted from regression; multiply by 10 for kg ha^{-1}). Source: Ovington and Olson (1970)

Area and subdivision	Leaves	Branches	Bole	Roots (>0.5 cm)	Nonpalm total	*Euterpe globosa*
Radiation center, later irradiated						
0 to 10 m radius[b]	1018	6017	29364	12422	48821	126
10 to 30 m, northeast	1134	6145	26799	10448	44526	3
10 to 30 m, southeast	921	3644	15364	6190	26119	112
10 to 30 m, southwest	948	4428	18275	8155	31806	145
10 to 30 m, northwest	639	3062	11113	4158	18972	66
0 to 30 m total	922	4508	19162	7813	32405	87
South control center[c]						
0 to 10 m radius	259	893	3705	1678	6595	16
10 to 30 m, northeast	346	1243	5110	2255	8954	575
10 to 30 m, southeast	754	3129	12518	5789	22190	382
10 to 30 m, southwest	527	2509	10303	4880	18246	445
10 to 30 m, northwest	723	4989	20446	11217	39375	40
0 to 30 m average	551	2737	11162	5447	19897	322
North cut center						
0 to 20 m radius	1024	3924	16173	5807	26928	59
Weighted average[d]	788	3677	15345	6480	26292	

[a]Excludes tree ferns, epiphytes, individuals of less than 1 cm diameter at 1.3 m, and a few small unidentified trees.

[b]Includes one emergent *Cyrilla racemiflora*, 105 cm diameter, with estimated values of 441, 4017, 20220, and 8856, respectively.

[c]Estimates differ slightly from earlier calculations by including trees which were unidentified in the stand table data and which are here treated as relatively minor species (Group C of Table A-1).

[d]Contributions proportional to plot areas, 2862, 2862, and 1256 m^2 circles.

For leaves (Fig. A-1), variance is great for trees of all sizes. The extremes may reflect variations between suppressed trees in low canopy layers versus individuals that are dominant or favored by sunlight through emergence above the rest of the upper canopy. Branch mass is more predictable, in spite of contrasts between multilimbed or narrow-crowned individuals (Fig. A-2). Bole mass, the biggest part of the total plant mass in old forests, is very predictable, even for pooled data of all three species groups (Fig. A-3).

Figure A-4 refers only to roots >0.5 cm, including stumps; some outlying values could reflect old root stocks of sprouting trees or other growth habits that make massive underground parts. The large variations in small roots (Fig. A-5) are partly artifacts, owing to unavoidable losses before and during collection. These data on roots <5 cm diameter have not been used in Table A-2. Reasonable allowances for such losses can be made but have small influence on biomass estimates. They would be more important for calculations of turnover, because the death and replacement of small roots is a continuing or episodic process, consuming an important but poorly known fraction of the ecosystem's total carbon production (Singh and Singh 1981).

Dry matter must be calculated by summing individual tree weights derived by regression equations, as in Table A-2 for the 11 experimental subplots. Although the resulting values were within the range given by Ovington (1965) for mixed tropical rain forests, some values were far from maximum. For example, leaf mass was about 30% of the maximum value recorded in the literature. Simple generalization from literature values representing especially favorable conditions apparently has resulted in significant error. In many cases, authors convert from dry weight to carbon using a standard value (45% in Whittaker and Likens 1973; 50% in Brown and Lugo 1982), so that relatively slight differences in the assumed conversion factors are not confounded with the much greater variation noted between stands, types, and regions. Variations among analyses of actual percent carbon compiled for various tissues [Ajtay et al. 1979 (Table 5.4)] are great enough to make some further adjustment desirable, but not so urgent as a broader geographic sampling of the wide variation of dry matter per unit area.

A.2 MASS PER UNIT AREA FOR MAJOR REGIONAL TYPES: SOUTHEAST ASIA

Results of similar analyses for the major natural and secondary woody vegetation types of Southeast Asia are summarized in Table A-3. Some Australian mangrove examples are also included to illustrate the high value of roots compared with tops in some tidally flooded forests of this type. The contrast between these well-developed mangrove forest stands and the less massive ones from the Philippines, Thailand, and Vietnam leads to an overall mean of 6.9 kg C/m^2 (rounded to 7 for the provisional "medium" value in Table 5). A slightly higher value was given for tropical swamp forests other than mangrove in section B of Table A-3.. Measurement data on tops by Hozumi et al. (1969) could be converted to totals by using the uncertain estimate of 2 kg C/m^2 for belowground parts, based on the Japanese group's root data from other kinds of stands. Chan's (1982) analysis of Malaysian stem volume data explains his rather indirect estimates from merchantable wood volumes to equivalent carbon for aboveground stems and roots. The volumes clearly include cases well above and below the adjusted harvest results of Hozumi et al. (1969). Chan's tabulations, incidentally, remind us of the much higher values of humus carbon in the soil column of Table A-3 compared with plant carbon. The commercial stem volumes from Sarawak, Malaysia (FAO 1974), are for merchantable trees (e.g., >50 cm diameter), making it difficult to convert to total mass or carbon. It is, nevertheless, clear from the highest volume numbers for the Malaysia site and in Papua New Guinea that some of these wet-site forests rank high in the range expected for rain forests on better-drained sites. The high value of 20 kg C/m^2 under the MAJOR WETLANDS legend (Plate 1) would allow such occasional outliers to be identified there with <u>mangrove/tropical swamp woods</u> category. Table A-3 suggests a rather skewed distribution, with many more lower values estimated there. Still lower regional averages for wetlands seem likely because of interruptions by shrubby or herbaceous and aquatic parts observed in many swamp/marsh complexes.

In section C of Table A-3, the "high stocking" and very tall lowland wet forest, including rain forest, is well above the global mean we consider representative for <u>Tropical/Subtropical Broad-Leaved</u>

Table A-3. Stem volumes and carbon in aboveground stems by vegetation type (may include belowground stems, "roots," and some stump; noted in ( ) where estimated by ratio instead of by harvest)

Vegetation	Stem volume	Leaf carbon	Total live aboveground	Root	Root/top ratio	Fine litter	Large litter	Soil	Reference
	$(m^3 \cdot ha^{-1})$	$(kg \cdot m^{-2})$				$(kg \cdot m^{-2})$			
A. MANGROVE FOREST AND SCRUB									
Australia[a]			6.56	6.63					Briggs (1977)
Australia			5.06	7.21					Briggs (1977)
Australia			3.87	6.57					Attiwill and Clough (1980)
MEAN			5.16	6.80	1.32				
SUM OF TOP + ROOT			12						
Papua-New Guinea	450[b]								Paijmans and Rollet (1977)
Philippines	39								Walsh (1977)
Philippines	34								Banaag (1972)
Philippines	23								Banaag (1972)
Philippines			2.07	(2)	(1 assumed)				de la Cruz and Banaag (1967)
SUM			4						
Malaysia	39								Walsh (1977)
Malaysia	232								Walsh (1977)
Thailand			0.54	(0.43)	(0.8 assumed)				Zinke (1976)
Vietnam			1.53	(1.22)	(0.8 assumed)				Zinke (1976)
Vietnam			2.25	(1.80)	(0.8 assumed)				Zinke (1976)
MEAN			1.60	(1.11)					
SUM OF TOP + ROOT			2.7						
MEAN OF ALL 7 IN GROUP A			6.9						
B. SWAMP FOREST									
Indonesia	193[c]								Dilmy (1971)
Kampuchea, Melaleuca			7.73	(2)[d]					Hozumi et al. (1969)
Kampuchea, Melaleuca	(200–300)[e]								Tran (1974)
Peninsular Malaysia	20[c]		(2.0)[e]	(1.0)[e]				(24–36)[e]	Chan (1982)
Peninsular Malaysia	130[c]		(12.0)[e]		(3.0)[e]			(38-114)[e]	Chan (1982)
Sarawak, Malaysia	51[f]								FAO (1974)
Sarawak, Malaysia	87[f]								FAO (1974)
Sarawak, Malaysia	189[f]								FAO (1974)
Sarawak, Malaysia	224[f]								FAO (1974)
MEAN			7.24	(2.0)					
SUM OF TOP + EST. ROOT			9.2						
MEAN OF 10 IN GROUPS A & B			7.6						

Table A-3 (continued)

Vegetation	Stem volume (m³·ha⁻¹)	Leaf carbon (kg·m⁻²)	Total live aboveground (kg·m⁻²)	Root (kg·m⁻²)	Root/top ratio	Fine litter (kg·m⁻²)	Large litter (kg·m⁻²)	Soil (kg·m⁻²)	Reference
C. HIGH-STOCKING LOWLAND WET FOREST									
Indonesia	188[c]								Dilmy (1971)
Indonesia	198[c]								Dilmy (1971)
Indonesia	219[c]								Dilmy (1971)
Indonesia	239[c]								Dilmy (1971)
Indonesia	246[c]								Dilmy (1971)
Indonesia	320[c]								Dilmy (1971)
Indonesia	434[c]								Dilmy (1971)
Papua-New Guinea	380[b]								Paijmans (1970)
Papua-New Guinea	437[b]								Paijmans (1970)
Papua-New Guinea	477[b]								Paijmans (1970)
Papua-New Guinea	992[b]								Paijmans (1970)
Malesia		1.13	39.6	2.93	(0.074)[d]	0.75			Brunig (1967)
Peninsular Malaysia	580[g]								Wong (1967)
Peninsular Malaysia	735[g]								Wong (1967)
Peninsular Malaysia			18.0						Wycherley and Templeton (1969)
Peninsular Malaysia		0.34	18.95						Kira (1977)
Peninsular Malaysia		0.35	19.40						Kira (1977)
Peninsular Malaysia			21.38			0.22	2.45	6.87	Kira (1977)
Peninsular Malaysia			16.47	2.25	0.137	0.16			Whitmore (1978)
Peninsular Malaysia			18.37	5.99	0.326	0.63		5.18	DeAngelis et al.(1981)
Peninsular Malaysia	140[c]		(12.0)[e]	(5.0)[e]				(4–11)[e]	Chan (1982)
Peninsular Malaysia	310[c]		(21.0)[e]	(7.0)[e]					Chan (1982)
Sabah, Malaysia		0.51	22.19						Kira and Ogawa (1971)
MEAN (excluding old "Malesia")			21.8	5.0	(0.23)				
SUM OF TOP + ROOT			26.8						
D. LOW-STOCKING LOWLAND RAIN FOREST									
Peninsular Malaysia	110[c]		(8.0)[e]	(5.0)[e]				(3-11)[e]	Chan (1982)
Peninsular Malaysia	220[c]		(13.0)[e]	(5.0)[e]					Chan (1982)
Solomon Islands	236[h]								Whitmore (1975)
MEAN			(10.5)[e]						
SUM OF EST. TOP + ROOT			15.5						
UNWEIGHTED MEAN IN GROUPS C & D			21.0						

Table A-3 (continued)

Vegetation	Stem volume ($m^3 \cdot ha^{-1}$)	Leaf carbon ($kg \cdot m^{-2}$)	Total live aboveground ($kg \cdot m^{-2}$)	Root ($kg \cdot m^{-2}$)	Root/top ratio	Fine litter ($kg \cdot m^{-2}$)	Large litter ($kg \cdot m^{-2}$)	Soil ($kg \cdot m^{-2}$)	Reference
E. MONTANE RAIN FOREST									
Indonesia	760[b]		24.71[d]						Dilmy (1971)
Papua-New Guinea (actual high)		0.4	22.73	2.84[d]	0.12	0.39	0.55	59.9	Edwards and Grubb (1977)
Papua-New Guinea (av)			13.95[d]	1.8[d]	0.13				Edwards and Grubb (1977)
Papua-New Guinea (range)			(10.98-			(0.39-			
Papua-New Guinea (range)			41.62)			0.25)			
Papua-New Guinea			12.87[d]						Enright (1979)
Thailand						0.73		11.4[i]	Yoda and Kira (1969)
Thailand						0.89		12.8[i]	Yoda and Kira (1969)
MEAN OF UNCERTAIN VALUES[d]			17.2	2.3					
SUM OF TOP + EST. ROOT			19.5						
F. HEATH FOREST									
Peninsular Malaysia		0.31	12.96						Kira and Ogawa (1971)
Sarawak, Malaysia			11.07						Brunig (1976)
Sarawak, Malaysia			31.91						Brunig (1976)
Sarawak, Malaysia	195[b]								Brunig (1973)
Sarawak, Malaysia	1760[b]								Brunig (1973)
MEAN			18.6	(2.4)	(0.13)				
G. CONIFEROUS AND HILL EVERGREEN FORESTS									
Indonesia	429[b]								Dilmy (1971)
Peninsular Malaysia		0.31	12.96						Kira and Ogawa (1971)
Thailand		1.53	17.61					9.7	Sabhasri (1978)
MEAN			15.3						

Table A-3 (continued)

Vegetation	Stem volume (m³·ha⁻¹)	Leaf carbon	Total live aboveground		Root	Root/top ratio	Fine litter	Large litter	Soil	Reference
		(kg·m⁻²)					(kg·m⁻²)			
H. BROAD-LEAVED EVERGREEN FOREST										
Kampuchea		0.68	14.49		2.70	0.18				Hozumi et al. (1969)
Kampuchea			15.53		3.15	0.20				Hozumi et al. (1969)
Thailand		0.38	14.99		1.44	0.10	0.09		7.54	Ogawa et al. (1965)
Thailand		0.33	14.63							Kira and Ogawa (1971)
Thailand							0.13		5.71[i]	Yoda and Kira (1969)
Thailand							0.18		7.16[i]	Yoda and Kira (1969)
Thailand			17.10							Tran (1974)
MEAN ROOT RATIO						(0.16)				
Region	(150-200)[e]									Tran (1974)
MEAN			15.35		2.43					
SUM OF TOP + ROOT				17.8						
I. MIXED DECIDUOUS FOREST										
Thailand		0.22	6.48		0.72	0.11	0.15		3.74	Ogawa et al. (1965)
Thailand		0.21	12.06		1.13	0.09	0.13		8.89	Ogawa et al. (1965)
Kampuchea	120									Tran (1974)
MEAN			9.27		0.93	0.10				
SUM OF TOP + ROOT				10.2						
UNWEIGHTED MEAN IN GROUPS H & I				14.0						
J. SAVANNA AND DRY DIPTEROCARP FORESTS										
Thailand		0.12	3.11		0.45	0.15	0.17		2.42	Ogawa et al. (1965)
Kampuchea	80									Tran (1974)
MEAN			3.11		0.45					
SUM OF TOP + ROOT				3.6						
K. OLD SECONDARY FORESTS										
Peninsular Malaysia	50[c]		(4.0)[e]		(2.0)[e]					Chan (1982)
Peninsular Malaysia	160[c]		(10.0)[e]		(5.0)[e]					Chan (1982)
Philippines			8.87[j]							Kellman (1970)
MEAN			7.62		3.5					
SUM OF TOP + ROOT				11.12						

Table A-3 (continued)

Vegetation	Stem volume ($m^3 \cdot ha^{-1}$)	Leaf carbon ($kg \cdot m^{-2}$)	Total live aboveground ($kg \cdot m^{-2}$)	Root ($kg \cdot m^{-2}$)	Root/top ratio	Fine litter ($kg \cdot m^{-2}$)	Large litter ($kg \cdot m^{-2}$)	Soil ($kg \cdot m^{-2}$)	Reference
L. BAMBOO BRAKE									
Burma		0.30	6.61			0.46	0.75		Rodin and Bazilevich (1967)
Burma		0.32	1.85			0.40	1.90		Rodin and Bazilevich (1967)
Burma		0.48	7.58			0.63	0.95		Rodin and Bazilevich (1967)
MEAN			5.35						
M. SWIDDEN FALLOW									
Thailand (4 year)			1.13					7.8	Sabhasri (1978)
Thailand (4 year)			1.15						Sabhasri (1978)
Thailand (7 year)			1.20					8.1	Sabhasri (1978)
Thailand (7 year)			1.29						Sabhasri (1978)
Thailand (10 year)			1.29						Sabhasri (1978)
Thailand (10 year)			2.71						Sabhasri (1978)
Thailand (10 year)			2.87						Sabhasri (1978)
Thailand (10 year)			4.37						Sabhasri (1978)
MEAN			2.00						
N. SUBALPINE SCRUB									
Thailand								8.1[i]	Yoda and Kira (1969)

[a]Included for comparison purposes.
[b]Estimated as 0.5 × basal area × mean height.
[c]Volume of woody material with diameter ⩾ 30 cm.
[d]Uncertain value.
[e]Values in parentheses are estimates.
[f]Commercial timber with diameter ⩾ 50 cm.
[g]All woody material with diameter ⩾ 7 cm.
[h]All woody material with diameter ⩾ 10 cm.
[i]Soil carbon to 50 cm depth.
[j]Average of two sites, and assumed 50% moisture content.

Humid Forest, regardless of whether the Malesian (Borneo) outlier of Brünig (1967) is included or not. Brünig (pers. comm.) suggests one reason for high Borneo values is the higher genetic potential of dipterocarp and other species of the Southeast Asia region, compared with those of Latin America and Asia. But there are also substantial areas in this region of low-stocking rain forest (section D of Table A-3) due to artificial or natural disturbance (e.g., wind damage) and soil leaching on hilltop sites in the lowland (Chan 1982).

Other evergreen forest subtypes in which local gaps partly offset the locally high stand carbon and fairly high means are montane rain forest (section E), heath forest (section F), and hill evergreen broad-leaved forests with some conifers (section G). Broad-leaved evergreen (somewhat seasonal) forest of Kampuchea and southern Thailand (Kao Chong) averaged near 18 kg C/m^2. Two seasonal mixed drought-deciduous forests on lower and mid-slopes of Ping Kong, northernmost Thailand (section H), averaged 10•2 kg C/m^2 when roots were estimated from regressions from the preceding stand. Ogawa et al. (1965 a,b) used the term dry "dipterocarp savanna forest" for the stand (#3) on the ridgetop directly above the last two preceding stands; photographs and a crown map (Fig. 2 of Ogawa 1965a) indicate a condition straddling open-forest and woodland in the narrow sense of our Table 1, rather than "savanna" (there are almost no grasses, but many shrubs). The surprisingly low 3.6 kg C/m^2 (section J on Table A-3) is probably below average even for our Tropical Dry Forest and Woodland type, but is here grouped with that complex rather than with savanna in Appendix B (see below). Yet this example, bordering on Tropical Montane Complexes, and general aerial observations in other areas mapped as Tropical/Subtropical Broad-Leaved Humid Forest remind us again how local stands having low carbon help to offset the unusually high carbon values in section C of Table A-3.

Prior disturbance history further offsets the high carbon values, and must be considered in seeking regionally representative averages for carbon. Even sparse tribal populations and sporadic, partial commerical cutting leaves some fraction of the landscape in secondary forests (section K of Table A-3). Aboveground carbon of 7.6 kg C/m^2

suggests a total not exceeding 11 kg C/m^2, even if a generous root mass of an extra 50% were assumed (to allow for coppice sprouting, or for a generally higher ratio of roots to tops for smaller trees). Bamboo stands occur naturally, but also expand in disturbed areas, in varying proportions to the associated overstory stands (section L of Table A-3, after Rozanov and Rozanova 1964). Recently abandoned (swidden) plots, 4 to 10 years after shifting cultivation (section M on Table A-3), had only 1.13 to 4.37 kg C m^2 (in aboveground parts only, after Sabhasri 1968). All these examples would occur in, and would lower the mean carbon of, many areas mapped and included in area totals for tropical humid forest.

A.3 INFERENCE OF AREALLY WEIGHTED AVERAGES FOR CARBON

Chapter 4 explained how provisions for censused agriculture, for patchy clearing and regrowth, and for older or less severe disturbance, have been attempted in narrowing areas identified as closed, high, humid tropical forest. Results seem quite compatible with informed forestry surveys (Table 4). The U.S. National Academy of Sciences (NAS 1982, Appendix, Table 1) provides a very recent review of national or (usually) more localized forestry inventories from all tropical continents. It illustrates Persson's (1974, 1977b) arguments for the desirability of more information of that type, combined with a regional ecological perspective that is beyond the scope of such economic inventories. The example of Southeast Asia (and adjacent Melanesia islands, east of Indonesia) will be carried one step further here, by summarizing findings on areal extent of forests in a region of rapid change. For Peninsular Malaysia, Chan (1982) published a regional carbon analysis, combining such area data with the carbon mass data reviewed in Table A-3. The following additional areas are included in an extension of that work.

Persson (1974) estimated that Southeast Asian and Melanesian tropical forest covers approximately 2.77 x 10^6 km^2. Insular Southeast Asia (Indonesia, Malaysia, Papua New Guinea, and the Philippines) has 0.95 x 10^6 km^2 (Myers 1980a,b) of mostly evergreen tropical moist forest. Seasonal, partly deciduous <u>Tropical/Subtropical Broad-Leaved</u>

Humid Forest and also Tropical Dry Forest and Woodland occur in continental Southeast Asian districts having either a relatively low annual rainfall or a long dry season, but not necessarily both (Walter 1979).

For estimates of wooded area in individual countries, we depend heavily on the summaries of Persson (1974), FAO (1976), Unesco (1978), and Myers (1980). The Statistical Yearbook for Asia and the Pacific (UN 1975) provides areas of major crop species in these countries.

In continental Southeast Asia, only Thailand is known to survey its forest resources periodically. The two latest surveys (Boonyobhas and Klankamsorn 1976, Wacharakitti 1976) used satellite remote-sensing technology. Information on vegetated areas in other countries is scarce and probably obsolete. For Burma, Myers (1980) cites 0.365×10^6 km^2 of forested area. Reliable estimates of forested area in Laos, Kampuchea, and Vietnam are not immediately available. The few reviews that have been published (e.g., Persson 1974, Myers 1980) depend partly on data antedating the major military actions in this region.

The three major countries of insular Southeast Asia (Indonesia, Malaysia, and the Philippines) have organized national surveys of their forest resources. Some preliminary results from Malaysia are given in papers presented at the ASEAN seminar on tropical rain-forest management (Anon. 1978a,b,c) and at the seventh Malaysian Forestry Conference (Anon. 1979a,b,c). Meijer (1970) discusses regeneration of Malaysian forests after clearing has stopped.

In the Philippines, the 1971 land-use pattern and timber stocking estimates given by FAO (1976) have been updated to conditions at the end of 1976 (Anon. 1978d). Recent surveys based on LANDSAT imaging reveal that forest covers only about 38% of the national land area (Myers 1980, Grainger 1980).

About 12×10^6 km^2 of the land area in Indonesia are considered forest land (Anon. 1978e). However, the actual area supporting productive forest is poorly known (Myers 1980). According to Warsopranoto (1974) and Subagio (1974), approximately 0.36×10^6 km^2 have been invaded by grasses of the genus *Imperata*, and the rest of the area is covered mainly by secondary or poorly stocked forests.

Approximately 0.4 x 10^6 km^2 of Papua New Guinea are still covered with forest (Persson 1974, Myers 1980). Many vegetation types are present (Paijmans 1976), primarily due to the dominance of a central mountain range, rising in places to more than 4500 m (Löffler 1977). In lowlands, the major forest type is basically evergreen equatorial forest. Patches of tropical seasonal forest forest may occupy drier sites along the rain-shadow slopes. The lowland forest graduates to Tropical Montane Complexes with subalpine scrub (Paijmans 1976). The combined effect of low temperature and high rainfall allows the montane forest to store relatively large amounts of biomass and soil carbon (Edwards and Grubb 1977) per unit area. However, better estimates of the limited highland areas not already disturbed by tribal farming and fires are needed.

Some islands of Melanesia (Winslow 1977) are virtually covered with forest. Human occupancy has denuded much land in others, as in parts of Papua New Guinea (Watson and Cole 1977). However, seasonal typhoons also produce gaps in the forest canopy that would reduce the average phytomass of the forest (Whitmore 1974, 1975).

It should be clear from these examples why a coordinated matching of areal extents and carbon masses for the areas estimated is needed. For either a region like Southeast Asia or the entire world, it is possible to define the area of tropical "rain" forest very broadly [as Whittaker and Likens (1973, 1975) did in their global estimate of 17 x 10^6 km^2 area]. However, in that case, the carbon per unit area would be even lower than the values presented in Tables 2 and 5. The lower average would encompass seasonally dry types and the many kinds of variation and disturbance and incomplete recovery illustrated in Appendix A.2. We could instead define the existing ecosystem complexes, or life zones approximating their potential development, more narrowly (Olson et al. 1978, Brown and Lugo 1982). Then the special types represented by extremely high plant mass and carbon will at last become identified with much more limited areal extent. The mean carbon densities of 14 kg C/m^2 in humid forest and 15 kg C/m^2 for Tropical/Subtropical Broad-Leaved Humid Forest in this report compare with 14.99 kg C/m^2 for the unweighted average of 33 stands of rain, wet, and moist forest recently compiled by Brown and Lugo (1982, Table 3, lines 1, 2, 4 and 6), if the conventional value of 45% carbon is used instead of their 50% carbon.

This report, and Appendix B, are still concerned mainly with an overview covering the biosphere as a whole, because that is what is exchanging so much carbon with the atmosphere. The more detailed regional example in this Appendix illustrates some of the data used in associating carbon with the areas in Tables 2 and 5 (derived from Plate 1, and confirmed in Table 4). The possibility of treating other regions in more detail, so that categories, maps, and tables would do less averaging over the real variability that exists in natural and disturbed landscapes has been posed. If methods could be further refined to make separate carbon estimates for the thousands of map cells in each region, the challenge would then be turned around: to see whether the regrouping of these isolated points would re-emerge into patterns similar to those already reflected more broadly in the map of Plate 1.

APPENDIX B

SOURCES OF ADDITIONAL INFORMATION BEARING ON GLOBAL CARBON

In addition to sources previously cited for mapping the locations of ecosystems, the following tables list countries from which the most equivalent estimates of plant mass (or implied carbon) have been summarized. Stands of many ages are compared for some forest types, especially those which occur most commonly as plantations. Simplicity of measurement and research interests in early growth rates explain why averages for such plantations are more likely than not to over-represent young age classes and low biomass, compared with regional averages of certain planted or natural types, especially conifers. The contrasting research motives of finding the upper bound for carrying capacity, or at least nearly "mature" stands where loss rates are approaching production input rates, were noted in Chapter 4 as reasons why several early compilations over-represented the distribution of unusually massive stands--especially for "virgin" or "old growth" forest or "climax" community types.

The "local ranges" of variation, derived partly from inspection of tabulated data and partly from the bounds of definition of the various surface categories in the data base for types listed in Table 1, were already summarized in Table 3 in the data sampler of Clark (1982, pp. 436-483). Very wide ranges represent cases where the nature of terrain and the landscape complex suggest large departures from the mean. Such ranges could exist for extended complexes within whole map cells, counties, etc. For individual stands, still wider variations may exist, but these probably represent too small an area to modify type averages for the cover category or complexes. On the other hand, the uncertainties in this expected or mean carbon density, and of the global total for each category based on that mean, have a somewhat narrower range. Many of the high and low values (especially the extremes) tend to cancel each other. An attempt was made in Table 5, and is explained in several of its footnotes (j, k, o), to apply the best judgment from experience in suggested means and ranges of uncertainty arising either from random variability or from the biases that might have occurred in selecting and grouping data. Sampling in the studies cited below was actually done for a variety of special purposes and made no pretense at either random or systematic coverage of age classes, site qualities, etc. For this reason and others discussed earlier, simple averages of data for a type group in the following tables might or might not be close to the global or regional weighted average (i.e., giving proportional representation for the many unsampled areas fitting the definitions of each category or complex).

B.1 TREE FORMATIONS

The grouping of ecosystems in Table B-1 was made to diminish the inevitable repetition of citations; compilations and many original references often include stands from more than one subcategory. In many cases, we need further analysis of the climate itself (or locations for which stand climate could be inferred, relative to weather stations at other places) or at least knowledge of snow persistence, before separating the hot, warm, cool, or cold subtypes. Brown and Lugo (1982) have started that for tropical areas. The small number and sparse coverage for vast areas obviously point to some priorities where new field effort or discovery of overlooked prior work are possible.

Additional information sources can be anticipated from recent initiatives for using biomass for energy (e.g., Ferm 1982, Kuusela 1982). Reporting on these is deferred here because so many documents are in preliminary form. Most are limited to plantations too young, small, or atypical to be widely representative, even for second-growth woods (Korsmo 1982).

Table B-1. Major sources of summaries of tree and plant mass (and carbon or related information) for tree formations of the world (FOREST AND WOODLAND plus INTERRUPTED WOODS). Some references cover additional countries or types[a,b]

Main group of ecosystem complexes	References[c]	Location
Taiga (Boreal forest) and other Conifer		
Northern or Maritime Taiga	Johnson and Vogel 1976	USA-Alaska
	Marchenko and Karlov 1962	USSR
	Manakov 1961 plus the following 4 references	USSR
Main and Southern Taiga (Boreal)	RODIN AND BAZILEVICH 1967[a,b]	USSR
	Pozdnyakov 1975	Siberia
	Gortinsky et al. 1975	European USSR
	CANNELL 1962	Canada Finland USSR Sweden
Conifer plantations	CANNELL 1982	Australia Belgium Ireland Italy Japan Netherlands New Zealand United Kingdom USA USSR
	Gholz and Fisher 1982	USA
	OVINGTON 1956, 1957, 1962, 1965	United Kingdom[a,b]
Other Conifer forest (and open woodland)	Malinovsky 1975	USSR
	Gortinsky et al. 1975	European USSR
	Pozdhyakov 1975	Siberia
	CANNELL 1982	Canada France Germany Japan Nepal

Table B-1. Continued

Main group of ecosystem complexes	References[c]	Location
		Sweden
		Switzerland
		USA
		USSR
	ART AND MARKS 1971	USA[a,b]
	REICHLE 1981	USA[a,b]
Mid-latitude broad-leaved and mixed woods	OLSON 1971	USA
	DUVIGNEAUD 1971	Europe[a,b]
Temperate Broad-Leaved Forest	CANNELL 1982	Australia
		Belgium
		Bulgaria
		Canada
		Czechoslovakia
		Denmark
		Finland
		France
		Germany
		Hungary
		Italy
		Japan
		Nepal
		Netherlands
		New Zealand
		Poland
		Rumania
		Sweden
		United Kingdom
		USA
		USSR
	Ovington and Madgwick 1959[b]	United Kingdom
Mixed woods: deciduous to evergreen broad-leaved forest or woodland, often with conifer	CANNELL 1982	Czechoslovakia
		Japan
		Poland
		Rumania
		Sweden
		Switzerland
		United Kingdom
		USA
		USSR
	Whittaker and Woodwell 1969, 1970, 1971	USA

Table B-1. Continued

Main group of ecosystem complexes	References[c]	Location
Tropical/Subtropical forest and interrupted woods		
Broad-leaved humid forest	CHAN 1982	Malaysia[b]
	RODIN AND BAZILEVICH 1967	Brazil[b]
	Fittkau and Klinge 1973	Brazil
	CANNELL 1982	Brazil
		Columbia
		Ghana
		Ivory Coast
		Japan (Okinawa)
		Kampuchea
		Malaysia
		Panama
		Thailand
		Venezuela
		Zaire
	Jordan 1981a, 1982	Venezuela
	Freson et al. 1974	Zaire
	Brünig et al. 1979	Venezuela
	Huttel and Bernhard-Reversat 1975; Huttel 1975	Ivory Coast
	Drew et al. 1978	Thailand
	Sabhasri et al. 1968	Thailand
	BROWN AND LUGO 1982	Latin America[a,b]
Dry forest and woodland	Vyas et al. 1979	India
	CANNELL 1982	India
		Puerto Rico
		Zaire
		Thailand
	Ogawa et al. 1965a,b	Thailand
Savanna and woodland	Menault and Cesar 1979, 1982	Ivory Coast
	Cesar and Menault 1974	Ivory Coast
	Lamotte 1975, 1982	Ivory Coast
	Cresswell et al. 1982	South Africa
	Huntley and Morris 1982	South Africa
	Rutherford 1982	South Africa
		Zimbabwe
	San Jose & Medina 1975, 1976	Venezuela

Table B-1. Continued

Main group of ecosystem complexes	References[c]	Location
Tropical Montane	CANNELL 1982	Guatemala
		Jamaica
		Papua New Guinea
		Puerto Rico
		Venezuela
	GRUBB 1977	Papua New Guinea[a]
Other (dry or cool woods, mosaics, scrub, or grass)	Bucher 1982	Argentina
		Brazil
	CANNELL 1982	Australia
		France
		Nepal
	Gudochkin 1955	USSR
	Rodin 1979	USSR
	Rodin et al. 1972	USA
	Gray 1982	USA

[a]Reference also covers additional nations or types listed above the callout.

[b]Reference also covers additional nations or types listed below the callout.

[c]References in "capitals" indicate sources of additional references.

B.2 NONWOODS AND WETLAND/COASTAL FORMATIONS

The lower average carbon in formations with few trees, low trees, or none at all (Table B.2) means that the inventory contributions of their woody components are limited. Also, carbon in nonwoody parts is relatively small as well. Production for some formations is very high, but turnover of carbon is so rapid that the average pools remain low. Carbon fluctuates more or less regularly where seasons dictate and sometimes irregularly with the weather of successive years. The resulting variability in space and time makes it hard to infer appropriate averages over the whole year. Where results are given only for a year-end harvest, or for a time of maximum green tops, it would be desirable to know more about the normal (and abnormal) cycles of changing top and root mass.

For regions that are MAINLY CROPPED, RESIDENTIAL, COMMERCIAL, PARK, data exist for merchantable commodities, but total mass (especially of belowground parts) and its carbon require more attention. Weeds were included with maize in fields studied by Ovington and Lawrence (1967). Chephekar (1972) shows that weedy growth in marginal lands around Bombay may quickly accumulate as much plant mass and carbon as many crops do, except where fertilizers and irrigation are managed near optimal levels. Evans (1981) draws on extensive experience of experimentation in fields and phytotrons to estimate maximum production and crop mass, sometimes with multiple cropping each year. For rice, sugar cane, and a few specialty crops, the theoretical maxima may be approached in the field, but usually the averages over wide areas would be substantially lower than the theoretical maxima (Iwaki 1974, Wojcik 1979).

Biomass of grasslands is presented in numerous tables of the IBP Synthesis Volumes. The aboveground biomass of green shoots in grazed and ungrazed natural temperate grasslands of the United States and Canada is described by Sims and Coupland [1979 (Table 5.3)]. Numata [1979 (Table 11.3)] summarizes aboveground biomass values from Rychnovska (1972) and Balatova-Tulackova (1973) for meadow sites in Eastern Europe, Japan, and the USSR. Seasonal and monthly variations in aboveground biomass at several tropical grassland sites are compared

Table B-2. Major sources for data on plant mass (or its carbon) or related information for nonwoods and wetland/coastal formations

Main group of ecosystem complexes	References[a]	Location or aspect
MAINLY CROPPED, RESIDENTIAL, COMMERCIAL, PARK	FAO 1979	All countries and crops
	Hubbel 1965	Tropical countries
	Chepkekar 1972	India (Bombay): Urban weeds (monsoonal)
	Evans 1980	Maximum crop growth
	Bray, Lawrence and Pearson 1959	USA, crops and herbs[b]
	Ovington and Lawrence 1963	USA, maize with weeds
	WOJCIK 1979	Poland, rye and/or potatoes
	Iwaki 1974	Japan, various
	Willoughby 1979	Australia, improved pasture
	Hutchinson and King 1980	Israel, improved pasture
	LOOMIS and GERAKIS 1975	Many countries
GRASS AND SHRUB COMPLEXES		
Hot, warm or cool grassland	COUPLAND 1979	Australia
	BREYMEYER and VAN DYNE 1980	Canada
	COOPER 1975	Czechoslovakia
		Finland
		Germany (Fed. Rep.)
		Hungary
		India
		Ivory Coast
		Japan
		Netherlands
		Panama
		South Africa
		Uganda
		USA
		USSR
		Zaire
		United Kingdom
	Bazilavich 1975	USSR
	HEAL and PERKINS 1978	United Kingdom
Heath and moorland	HEAL and PERKINS 1978	United Kingdom[c]
	CANNELL 1982	
Wooded tundra	BLISS et al. 1981	Finland
		Norway
		USSR

Table B-2. Continued

Main group of ecosystem complexes	References[a]	Location or aspect
TUNDRA AND DESERT		
POLAR	BLISS et al. 1981	Australia (Macquarie Island) Austria Canada (Devon Island) Finland (Kevo) Greenland (Disko Island) Norway (Hardangervidda) Signey Island South Georgia Island USA/Alaska USA/Colorado USSR
Other Desert and Semidesert	RODIN 1979	USSR
	Other GOODALL AND PERRY 1979, 1981	Various
	Cannell 1982	USA-Fouquieria
	COOPER 1975	Various
WETLANDS AND COASTAL		
	Hussey and Long 1982	United Kingdom USA
	Rychnovska	Czechoslovakia Denmark Netherlands Sweden

[a]References in "capitals" indicate sources of additional references.

[b]References also covers additional nations or types listed below the callout.

[c]References also covers additional nations or types listed above the callout.

by Singh and Joshi [1979 (Tables 17.1 and 17.4)], while belowground biomass is considered by Singh and Joshi [1979 (Table 17.6)] and Coupland [1979b (Table 33.2)]. Other important tables in Coupland (1979a) describe the biomass of bacteria and fungi [Ulehlova 1979, (Table 13.3); Paul et al. 1979 (Tables 7.1 and 7.2)], consumer biomass [(Dyer 1979, Table 6.1)], and canopy biomass for grassland sites around the world [Coupland 1979b (Table 33.1)].

Biomass of desert ecosystems is small and considered only briefly here. Rodin [1979 (Table 7.3)] compares phytomass data for several vegetation communities at five desert and semidesert sites in the USSR. Values for the absolute amount of phytomass range from 5 to 34 Mg/ha. The highest of these figures (equivalent to 3.4 kg/m^2, and approximately half as much carbon) is a good example that could be taken near an upper extreme for desert landscapes, or as a low extreme for very dry, low Saxaul (*Haloxyon ammodendron*) "forests." For other Desert and Semidesert complexes, totally bare areas, especially on sand deserts, would lower the regional averages considerably.

In tundra, aboveground live plant mass is affected by latitude, altitude, available nutrients, and soil water. Influenced by increases in mean annual temperature and length of growing season, phytomass increases from the polar deserts of the High Arctic to the shrub tundra of the Low Arctic and alpine regions [Tikhomirov et al. 1981 (Table 7.1); Wielgolaski et al. 1981 (Table 6.5)]. Above- and belowground biomass for communities in arctic, alpine, and antarctic sites also shows a wide variation within each zone [Wielgolaski et al. 1981 (Table 6.5)]. Aboveground phytomass for polar deserts, tundra, and forest tundra in the USSR is compared by Tikhomirov et al. [1981 (Table 7.1)].

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