Global Vegetation and Land Use: New High-Resolution Data Bases for Climate Studies

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ABSTRACT

Global vegetation and land-use data bases (1° latitude by 1° longitude resolution), designed for use in studies of climate and climate change, were compiled in digital form drawing upon approximately 100 published sources complemented by a large collection of satellite imagery. The vegetation data were encoded using the UNESCO classification system; land-use data were encoded using a classification system developed by the author. The vegetation and land-use data were then integrated into a land-cover data base. Area! estimates for most ecosystems from the land-cover data base were found to be significantly different from area] estimates derived from two other global land-cover sources. Possible explanations for discrepancies among these data bases include differences in ecosystem definitions and source material used in compilation. From areal estimates of major ecosystems, derived from the new vegetation and land-cover data bases, it is estimated that the total ecosystem reduction caused by agricultural activities amounts to 17.6 X 10^6 km^2 globally, with the greatest reduction occurring in non-tropical forests. Extensive subsistence agriculture which remains largely unreported in crop inventories accounts for 2.6 x 10^6 km^2 of this figure, with the balance of 15 X 10^6 km^2 agreeing encouragingly well with FAO's (1980) reported global crop area of 14.5 X 10^6 km^2. As an example of the flexibility of the new data base, areal estimates and brief definitions of selected ecosystem subdivisions are presented for the world and mapped for North America.

1. Introduction

Terrestrial vegetation is an important factor in the radiation balance of the earth and in numerous biogeochemical cycles related to climate maintenance and climate change. Vegetation is subject to modification by natural cycles and trends, and by human activities. A reliable estimate of the past and present status and distribution of vegetation, in a form which is accessible, manageable, and applicable to a variety of research areas, is necessary.

Until recently, the large body of vegetation data, dispersed throughout such sources as vegetation maps, published literature and satellite imagery, has never been digitally compiled into a consistent format at a resolution appropriate for global research. The dispersed and inconsistent nature of vegetation information, along with its availability primarily in the form of printed maps, imposed limitations on its organization, modification and incorporation into quantitative studies such as carbon and climate modeling. Some of these problems are addressed in this study by the compilation of global, multi-source files of vegetation and land-use data, in digital form, at a resolution of 1° latitude by 1 ° longitude. The data will be available to users through the NCAR archive. The following is a description of the new data files, including sources and compilation strategy, along with a comparison with other land-cover data bases, and discussion of results and possible applications to the study of climate and climate change.

2. Previous vegetation and land-use compilations

Historically, study of the spatial distribution of plant communities has been approached in terms of vegetation mapping. Small-scale vegetation maps are compiled, using field observations and both large-scale and other small-scale maps as data. These sources are aggregated and subjectively weighted resulting in classification and boundary delimitation of the vegetational landscape. The final product is a subjective composite of information reflecting the biases and unrecorded choices of the compiler. The many sources of data and their various dates of acquisition make it difficult to determine the time frame represented by a specific map. In many cases, the map does not include documentation of the sources used in compilation, or of the relative weights given to various sources which may conflict. Where source information is provided, it is not uncommon to find that several maps have borrowed heavily from a single older source.

There is an inverse relationship between map scale and size of the area represented on a map. In addition, while .there are few specific rules, there is normally some practical relationship between map scale and the expected degree of generalization represented. Small-scale maps (e.g., 1:100 million or 1 cm: 1000 km) are commonly useful for depicting general patterns over large areas while large-scale maps (e.g., 1:50 000 or 1 cm: 0.5 km) may depict more detailed variations in smaller areas. As a result, classifications used to categorize vegetation vary in response to 1) the size and characteristics of the area being mapped, 2) scale of the final map, 3) availability of data and 4) purpose for which the map is produced. Vegetation distributions may be delimited by physiognomic characteristics (Raunkiaer, 1937; Richards *et al.,* 1940; Dansereau, 1951; Fosberg, 1961; Ellenberg and Mueller-Dombois, 1967; Kiichler, 1967), species (Braun-Blanquet, 1965), region-specific formations (Brttnig, 1970; de Rosayro, 1974), or climate (Koppen, 1931; Holdridge *et al.,* 1971). The diverse classification methods that have been used make it difficult to compare and synthesize the many sources needed to construct a globally consistent data base. In addition, presentation of data in the traditional format of printed maps has impeded compilation, use, and modification of the data on a global scale. First, since modifications can only be accomplished *in toto,* involving a new publication of the entire map, updating and modification are costly and less frequent than needed. Second, even if traditional vegetation maps could be frequently updated or modified, they still provide information in a qualitative form which is unsuitable for incorporation into quantitative studies such as climate or carbon modeling and incompatible with commonly used digital data sets.

In recent years, three projects were undertaken to produce digital files of global vegetation/land cover. Two were designed for surface albedo studies (Hummel and Reck, 1979; CLIMAP, 1981); one, a modified version of Hummel and Reck documented in Watts (1982), was developed at Oak Ridge National Laboratory (ORNL) for use in carbon modeling. Since these files are not maps, they have no scales; grid spacing or resolution (the smallest area for which data are recorded) replaces scale as a general indicator of spatial precision. Consideration of resolution and vegetation classification system gives an indication of the overall precision and utility of data bases of this kind. The classification schemes used in the first two of these works reflect their specific design for use in albedo studies. The vegetation categories are general descriptions of land-cover characteristics (tropical woodland/grassland, deciduous forest, arable land) but do not conform to those of recognized classification schemes such as Fosberg (1961), Ellenberg and Mueller-Dombois (1967) and UNESCO (1973). While these broad groupings are adequate for albedo studies, other areas of global-scale research (e.g., primary productivity, biomass and hydrology) of potential climatic significance require a more detailed vegetation classification than these data provide. In other words, albedo-significant categories of vegetation do not necessarily coincide with biomass-, hydrology- or productivity-significant categories. For this reason, ORNL modified the Hummel and Reck classification system with the aim of defining variations in carbon density within broad vegetation types.

The data file compiled by CLIMAP, with a resolution of 2° latitude by 2° longitude for the ice-free land surface of the globe, is based on a useful concept using a single multi-component description for each land cell, incorporating vegetation/land use (dominant and co-dominant), percent water, percent bare soil, elevation, and soil color. This idea is a major step in design toward adequately describing the terrestrial landscape by integrating multiple surface characteristics. The vegetation classification scheme includes nine major types, which are further subdivided depending upon extent and type of the co-dominant vegetation. Five comprehensive sources provided the basis for compilation of the land-cover data in this work. This compilation was designed for and used exclusively in surface albedo studies. Therefore, the use of a general vegetation classification in this data base does not pose a problem, since this classification scheme is adequate for distinguishing albedo-significant categories.

The creation of Hummel and Reek's data base involved encoding a single, generalized small-scale (1:88 million) vegetation/land-use map (Oxford Atlas, 1973) of the world into digital format (GM Research Memo, 1978) with resolution ranging from 0.4°-0.9° latitude and longitude. Hummel and Reck included 12 vegetation types subdivided into a total of 24 groups based on amount and duration of snow cover which are important for albedo studies.

The Hummel and Reck data file served as a basis for the work of the ORNL Carbon Group, presented in map form at a scale of 1:30 million (Olson and Watts, 1982). First the data were reorganized into a consistent 0.5° latitude by 0.5° longitude grid. The 12 general vegetation types were further annotated with climatic (e.g. tropical, subtropical, boreal) and elevational (lowland, montane) characteristics, resulting in a total of 43 types. Some of the subdivisions were analogous to Hummel and Reek's snow-related groups as in the case of coniferous forests. Substantial revisions were made in the treatment of cultivated lands. The arable, grazing and marginal farm categories of Hummel and Reck were distinguished into intensively and extensively cultivated lands, and forest/field and field/woods complexes. The guide for these modifications was the need to identify vegetation types on the basis of carbon density (biomass) for carbon modeling studies at ORNL.

3. Compilation of the new data base

The new global vegetation and land-use data bases compiled in this study differ in several important aspects from traditional vegetation-distribution maps and from the three recently compiled digital formats discussed above. The differences were shaped by a strategy to design a data base with legitimate application to a variety of climate-related research areas including surface albedo, biomass, primary productivity, surface roughness, and ground hydrology. Specifically this meant: 1) recording the data in digital form at a relatively fine resolution (1° latitude by 1° longitude) which allows flexibility in spatial aggregation to coarser resolutions; 2) employing a flexible physiognomic vegetation classification scheme (UNESCO, 1973) which allows access to the vegetation data at several hierarchically defined levels of detail and ordering of the data into a structure appropriate to several different research interests; and 3) recording sources and reliability estimates of each vegetation and land-use designation during compilation in an attempt to reduce uncertainties and isolate areas associated with greatest errors.

Vegetation and land-use data were acquired independently since they are useful as separate data bases and because they are not commonly integrated in published maps or in the literature. While sources varied widely in terms of quality, date of publication, scale, and classification, an attempt was made to record 1) the natural-vegetation landscape existing before modification by human activities, and 2) present land-use patterns. These two data files could then be integrated to produce a land-cover data base.

The newly compiled data bases (for all 1° latitude by 1° longitude land cells, excluding Antarctica) consist of 1) spatially-dominant natural vegetation annotated with data source, source reliability, and source date; and 2) spatially dominant land use annotated with data source, source reliability, and source date.

Before actual compilation began, several decisions were made regarding storage, resolution, classification and annotation in order to anticipate and maximize future applications.

a. Resolution

A 1° latitude by 1° longitude resolution was chosen as appropriate for detailed global or continental research. This decision was structured by considerations of a logistically useful resolution of the final data base ancl precision of the data available for compilation as reflected in scale and classification schemes of sources. For example, while generalized data can easily be encoded at a fine resolution, the resulting data base may not accurately reflect landscape variations at that resolution; a map of the data will not differ from the original generalized source. Every 1° by 1° cell of less than 50% land was considered water and not included in the file. Antarctica was excluded since vegetation is limited.

b. Vegetation

The UNESCO classification scheme (UNESCO, 1973) was chosen as the most useful available framework within which to synthesize the varied vegetation data which have been published. This widely recognized system, designed for global vegetation mapping and inventory, synthesizes components of several classification theories and incorporates extensive biome description. The system classifies vegetation on the basis of lifeform, density, and seasonality (evergreen, deciduous), with supplementary terms on altitude, climate and vegetation architecture. A portion of the forest section of the scheme is shown in Fig. 1. Vegetation types are designated by a series of numbers and letters indicating, in order of increasing detail; *formation class, formation subclass, formation group, formation,* and *subformation.* (For example, forest is designated as 1, evergreen forest is I.A, tropical evergreen forest is 1.A.1.) The system allows for recording and retrieving data at various levels of detail depending upon quality of available sources, spatial resolution of the data base and vegetation characteristics which are significant in various applications. As mentioned above, vegetation data were compiled to reflect the vegetation landscape for the present climate prior to modifications by agricultural activities. Legends from each of about 70 published vegetation sources (see *Annotation of Data* below) were "translated" into the UNESCO system, and data were encoded consistently according to UNESCO. While the

Formation Class		1. CLOSED FOREST	
Formation Subclass	A. EVERGREEN	B. DECIDUOUS	C. XEROMORPHIC
Formation Group	1. tropical ombrophilous	1. tropical/subtropical drought-deciduous	1. sclerophyllous
	2. tropical/subtropical seasonal	2. cold-deciduous with evergreens	2. thorn
	3. tropical/subtropical semi-deciduous	3. cold-deciduous without evergreens	3. succulent
	4. subtropical ombrophilous		
	5. mangrove		
	6. temperate/subpolar ombrophilous		
	7. temperate seasonal broadleaved. summer rain		
	8. winter rain sclerophyllous		
	9. tropical/subtropical needleleaved		
	10. temperate/subpolar needleleaved		

FIG. 1. **UNESCO forest classification, in abbreviated form, showing hierarchical divisions incorporated into the scheme.**

TABLE 1. Cultivation intensities and vegetation/land-use associations.

Cultivation intensity	5	5	4	4	4	4	4	3	2	1
Percent cultivated	100	100	75	75	75	75	75	50	20	0
Land use	Intensive subsistence with rice dominant	Large-scale commercial	Small-scale commercial	Dairy-ing	Planta-tions	Medi-terranean	Intensive subsistence with some cash crops	Extensive subsistence with marginal cash crops	Rudimentary subsistence	Nomadic herding grazing
Forest	X		X	X	X		X			
Woodland			X			X	X	X	X	
Shrubland						X	X	X	X	X
Grassland		X						X	X	
Desert										X
Tundra										X

1° by 1° resolution of the file allows flexibility in terms of aggregation to coarser spatial resolutions, the hierarchical framework allows generalization in terms of vegetation type. A simple calculation of global albedo may be satisfied by retrieving data at a general level of formation subclass (i.e., evergreen forest, deciduous forest, tundra, desert), while an estimate of zonal or hemispheric terrestrial biomass may require retrieving more detailed formation or formation-group data (cf. Fig. 1). Technically, at least 225 vegetation types can be designated with this system; 148 were used in this study.

c. Land use

Dominant land use was compiled at the same resolution as the vegetation data. It must be noted here that only the presence (and type), or absence of agricultural activity was recorded in the land-use data base; the exact location and areal extent of cultivation was impossible to recover within the scope and resolution of this work. For that reason a hierarchical land-use classification was developed by the author which emphasizes variations in the intensity and permanency of modifications to the natural vegetation, e.g., large-scale and small-scale commercial farming, extensive and intensive subsistence agriculture, grazing, dairying, plantations, and mediterranean agriculture. When available, crop combinations were also included in each designation. Land-use data were acquired from about 40 sources (see *Annotation of Data* below), including many national atlases and a consistent back-up reliance on the *World Atlas of Agriculture* (1969) with map dates from 1969 to 1976.

d. Land cover

The vegetation and land-use data were integrated to produce a global land-cover data base reflecting present anthropogenic and natural-vegetation characteristics. Empirically it is clear that different farming systems result in varying modifications to natural vegetation; quantification of such effects, according to agricultural systems, is a more difficult task. Each type in the land-use data base was qualitatively evaluated by the author in terms of the expected intensity and permanence of its effect on the natural vegetation. From this, estimates of the percent area cultivated/percent area natural were prescribed for each land-use type (Table 1). Urban areas are not spatially dominant in any cell at this resolution and are implicitly included in the modified/cultivated category. When determining global area occupied by natural ecosystems and by various agricultural activities, these percentages were used as scalars for the vegetation and land-use designations. For example, small-scale commercial farming, like that practiced in the eastern U.S., is assumed to produce a landscape that is 75% cultivated (natural vegetation replaced by managed vegetation) with the remaining 25% retaining the natural vegetation. The land-cover data base, then, is composed of the vegetation and land-use designations with their spatial importance defined by the cultivation intensities as shown in Table 1.

e. Annotation of data

Each vegetation and land-use determination is annotated with source publication, source date, and source reliability. Extensive documentation of sources was developed during data gathering. A complete listing of published sources used in the compilation is provided, by title, in the Appendix. Publication dates for the sources used in compilation of the data range from 1960 to 1979 with a single source for Costa Rica dated 1953. Map scales range from 1:500 000 to 1:20 million. Multiple sources were compared whenever they were available. Where sources disagreed, data from the more recent or better documented source were recorded. These sources were complemented by a collection of LANDSAT satellite imagery from the NASA, Goddard Institute for Space Studies. The most obvious difficulties encountered in the compilation of these data bases were conflicting data, obsolete data, lack of data at appropriate scales, noncomparability among classification schemes of sources, and unavailability of multiple sources for comparison. Source reliability is a simple, subjective estimate which indicates some of the following: quality or age of the source, agreement/disagreement with other available sources, and confidence of "translation" of source legend into UNESCO classification. There are 9 reliability classes; class 1 is least reliable, class 9 is most reliable. This component of the file allows one to isolate geographical areas associated with the highest classification error.

f, LANDSAT confirmation

At this writing, preliminary stages of a comparison check of the vegetation and land-use data with available LANDSAT imagery have been completed to determine, in a qualitative way, the reliability of the data gathered. While neither the specifics of vegetation types nor of crop combinations can be determined from visual interpretation of these images, the presence or absence of human-induced geometries can be indicative of the spatial extent and intensity of modifications to the natural vegetation.

4. Discussion

The data bases discussed here possess several important theoretical and logistical characteristics required in a global land-cover information system. They are accessible, digital files of fine resolution with flexibility in regard to aggregation to coarser resolutions. The hierarchical classification schemes allow the data to be structured in a variety of forms appropriate to several different research areas. Each independent vegetation and land-use designation is encoded according to well documented classification schemes, and annotated with source information and reliability estimates allowing for efficient modification and targeting of areas associated with greatest error.

Fig. 2 is a gray-scale map of the vegetation data base (unmodified by cultivation) at the original resolution of 1° latitude by 1° longitude. The major vegetation types shown here are generally equivalent to formation classes defined in the UNESCO scheme. However, unvegetated desert, ice, and cultivated land[1] have been appended and the tropical rainforest formation group has been distinguished from the more comprehensive forest formation class. The latitudinal banding of these major vegetation types results primarily from large-scale climatic conditions. Equatorial rainforest in zones with small seasonal differences in temperature and precipitation are bounded to the north and south by tropical and subtropical dry woodland and grassland, associated with larger intra-annual temperature variations and distinct wet and dry seasons. The Sahara and the Arabian Peninsula along with the southern African and Australian deserts, clearly show the subtropical position of most major desert areas. Poleward of the deserts, tree-, shrub-, and grass-dominated formations prevail, with latitudinal vegetation bands in the north temperate zones showing longitudinal variations regulated primarily by precipitation. Arid areas in the rainshadows east of the Coast Ranges, the Rocky Mountains, the Andes, and Himalayas are dominated by desert, shrubland, and grassland. These vegetation types also predominate in the extreme continental climates of the Eurasian interior due to limited precipitation, very hot summers and very cold winters. The arctic tree-line, or forest-tundra boundary, shows different geographical and vegetational characteristics in the eastern and western hemispheres. In eastern Canada, the boundary (~50°N) is about 2000 km south of the position of the Eurasian boundary (~70°N), and gradational woodlands between the forest and tundra in Canada are a much less significant feature than those in Eurasia.

Fig. 3 is a grayscale map of cultivation intensities derived from the land-use data base and Table 1. It is presented here to indicate, in conjunction with the vegetation map (Fig. 2), the types of ecosystems modified by agricultural activities of varying intensity. The highest intensities of 5 form a wide north-to-south band extending from south-central Canada to the southern border of the United States, defining a region of large-scale commercial farming. They also appear in the intensive rice-growing regions of southwest and southeast Asia, and in the wheat regions of Australia. Western and Eastern Europe, completely dominated by small-scale commercial farming and dairying, are characterized by intensities of 4, as is the eastern United States and the Soviet wheat areas. Large portions of India and North China, with extensive subsistence farming, are also in this group. A significant part of Africa extending southward from about 20 °N, where low intensity rudimentary agriculture is practiced, is denoted by cultivation intensities of 2 as is the southern rim of the Mediterranean Sea. Cultivation intensities of 1 indicate little or no modification of the natural vegetation. In Africa, this group delineates quite well the outlines of the Sahara, as well as the Somalian Desert in east central Africa and Kalahari and Namibian Deserts in the south. The tropical rainforests in Africa are also generally defined by 1 's, with some intrusion of farming into this ecosystem in the western equatorial region.

The land-cover data base, derived from integration of the vegetation and land-use data, is mapped in Fig. 4. The cultivation category here includes all areas modified by agricultural activities (cultivation inten-

[1] Limited areas in Asia, with long use histories and for which reliable vegetation data could not be acquired, have unavoidably been designated as cultivated land in the vegetation data base.

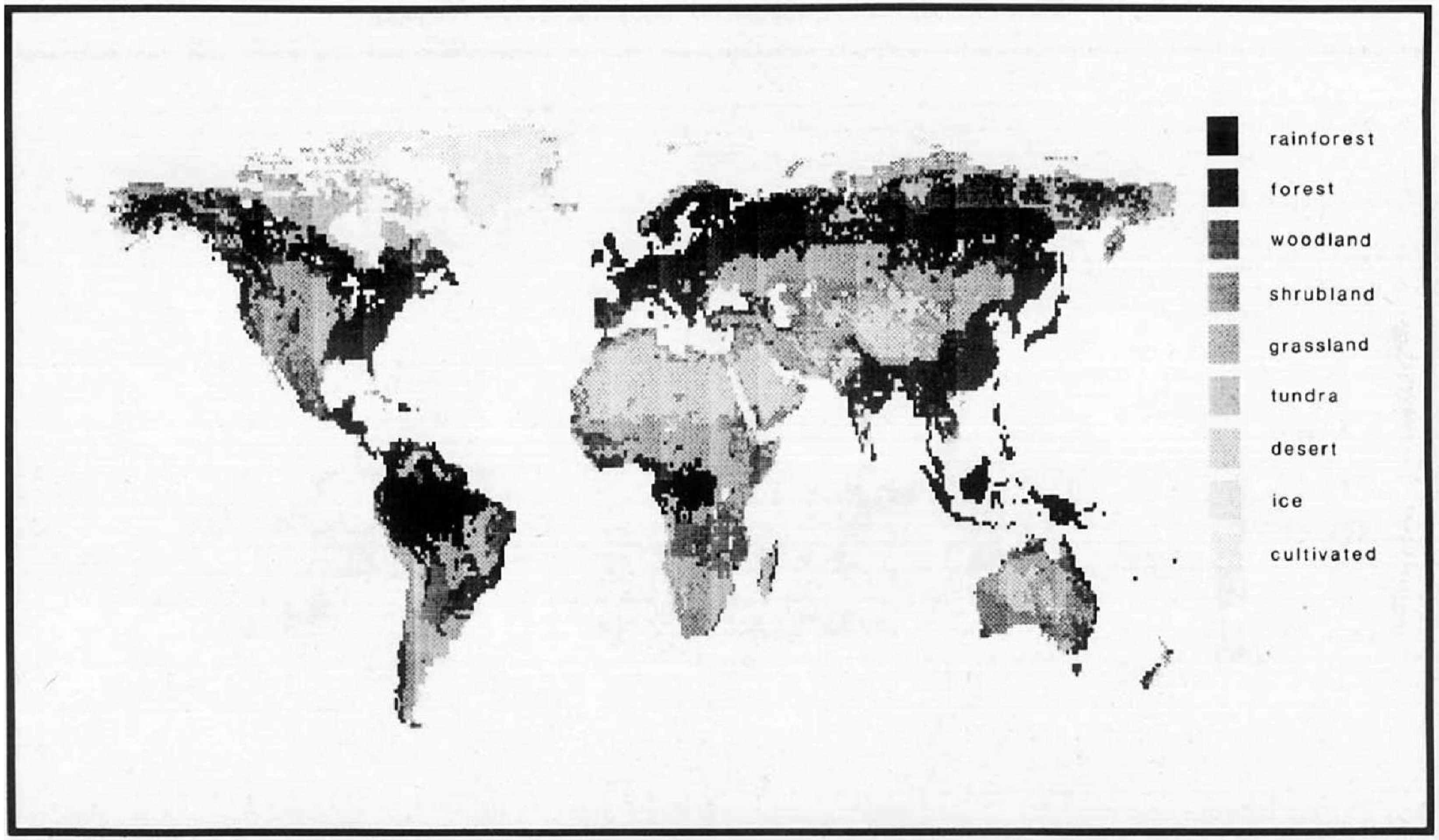

FIG. 2. Gray-scale map of nine major ecosystems (at the original resolution of 1° latitude by 1° longitude) derived from the vegetation data base.

FIG. 3. Gray-scale map of cultivation intensities derived from the land-use data base.

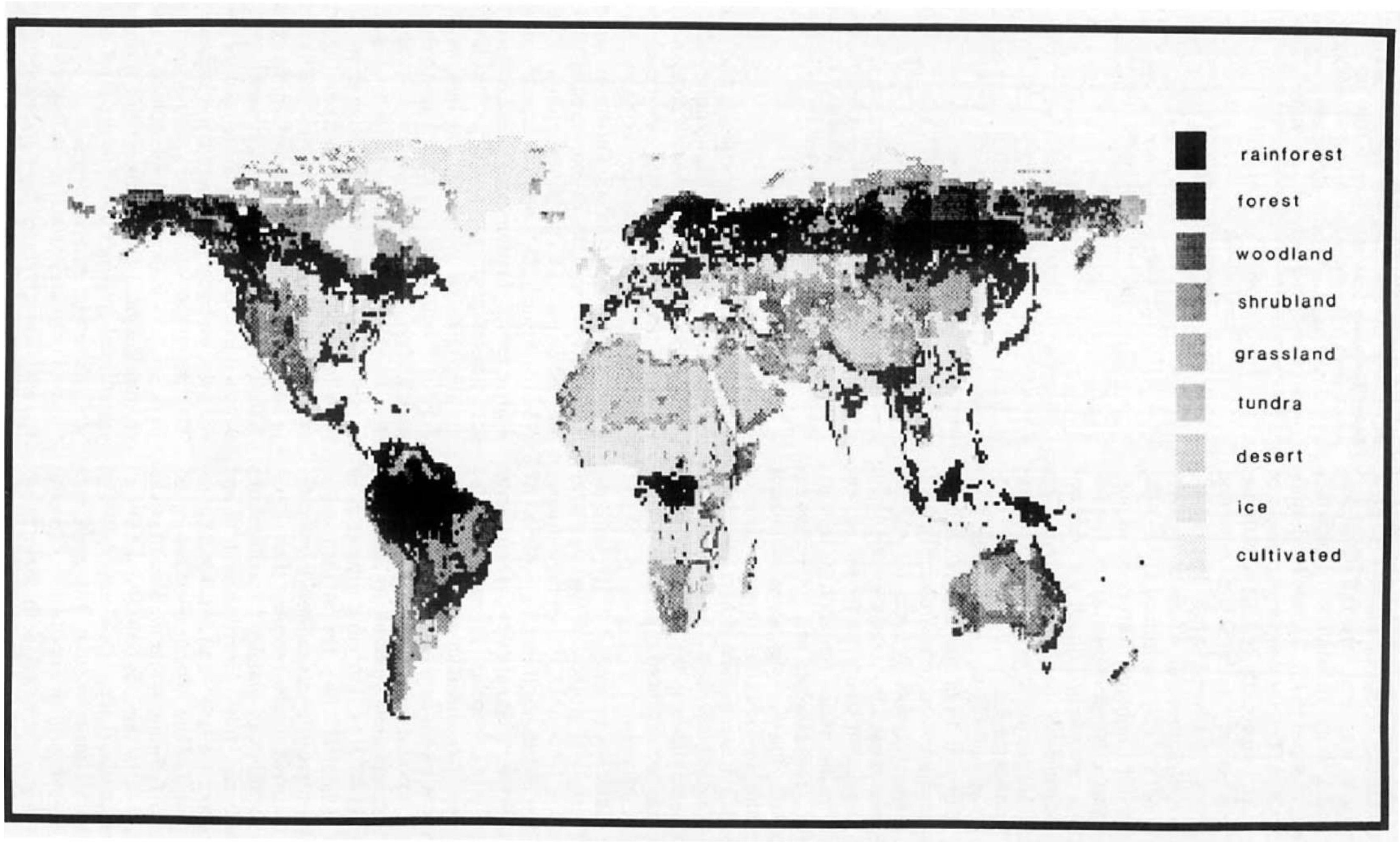

FIG. 4. Gray-scale map of nine major ecosystems derived from the integrated land-cover data base.

sities 2-5 from Fig. 3) regardless of the intensity of modifications, and therefore appears quite extensive. The map indicates, in a general way, the global pattern of agricultural activity. In addition, it indicates which ecosystems, mapped in Fig. 2, have been modified by these activities. The most extensive blocks of cultivated regions are, expectedly, in East Asia, India, eastern and western Europe, central Soviet Union and mid-western and eastern United States. The low intensity subsistence agriculture in Africa also covers large areas south of 20°N as mentioned above. The natural vegetation still dominates in areas of low population densities and in non-inhabited areas. The impact of agricultural activities in South America appears to be far less extensive than that in Africa. This results, in part, from the scarcity of land-use documentation for South America.

Areal estimates of major ecosystems derived from the vegetation data and from the integrated land-cover data discussed here are compared in Table 2. As mentioned earlier (Section 3), areas for original extent of ecosystems derived from the vegetation data base reflect the vegetation landscape for the present climate prior to modifications (reductions) by agricultural activities. The absolute area of ecosystem reductions produced by the integration of present cultivation provides an indication of the extent to which ecosystems, relative to each other, have been modified by agricultural activities. The ecosystem reduction percentages highlight the extent to which each ecosystem has been reduced relative to its original (pre-agricultural) extent.

The greatest reduction in area (7 X 10^6 km^2) occurred within forests, with tropical rainforests declining by only ~0.5 X 10^6 km^2 (3.75% of their original area) and all other forests declining by ~6.5 X 10^6 km^2 or ~ 19.5% of their original extent. The clearing of deciduous forests in Europe and the eastern United States for small-scale commercial farming, and of temperate evergreen forests in Asia for intensive subsistence farming, account for most of the change in forest area. Grasslands show patterns, in both absolute area cleared (6.47 X 10^6 km^2) and percentage of original extent cleared (19.1%), almost identical to those of the non-tropical forests, although grassland modifications occurred more recently than forest clearance. The locations of grassland modifications are predominantly the North American prairies and the Eurasian steppes for large- and small-scale commercial agriculture, and the African savannas for extensive subsistence farming. While the area of woodland cleared (2.13 X 10^6 km^2) is only about 1/3 that of forests or grasslands, it represents almost 14% of the original extent of this ecosystem. The major area affected is the dry African miombo where extensive subsistence farming is practiced, with some reductions throughout the Mediterranean basin for extensive subsistence farming, and for mediterranean and

TABLE 2. Comparison of areal estimates of major ecosystems derived from the newly compiled vegetation and land-cover data bases. Ecosystem reduction figures indicate the extent to which ecosystems have been modified, through agricultural activities, relative to each other, and relative to their respective original extents. Ice-covered land is not included. Total area is 132.4 X 10^6 km^2.

	(Pre-agricultural) Vegetation data	(Present) Land cover data	Ecosystem reduction	
	Area (10" km^2)	Area (10^6 km^2)	Area (10^6 km^2)	Percent total ecosystem
Total forest	46.28	39.27	7.01	15.15
Tropical rainforest	12.77	12.29	0.48	3.75
Other forest	33.51	26.98	6.53	19.5
Woodland	15.23	13.10	2.13	13.8
Shrubland	12.99	12.12	0.87	6.7
Grassland	33.90	27.43	6.47	19.1
Tundra	7.34	7.34	0.0	0.0
Desert	15.82	15.57	0.25	1.6
Cultivation	0.93*	17.56	-16.63	—

* As mentioned in the discussion (Section 4), limited areas with long use histories and for which reliable vegetation data could not be acquired have unavoidably been designated as cultivated in the vegetation data base.

small-scale commercial agriculture, and in Australia for large-scale commercial agriculture.

While original areal extents of ecosystems are calculated directly from the vegetation data base, land-cover areas are partially controlled by the land-use types with their associated cultivation intensities (cf. Table 1). For example, an ecosystem of 10 X 10^6 km^2 affected primarily by small-scale commercial farming (75% cultivated, 25% natural vegetation) will show a larger areal reduction than an ecosystem of the same area affected predominantly by extensive subsistence farming (50% cultivated, 50% natural vegetation)—7.5 X 10^6 and 5.0 X 10^6 km^2 respectively. By comparing vegetation and land-use associations in these data bases, it is possible, in a general way, to pair ecosystems with agricultural activities most likely to occur in them. As can be seen from Table 1, forests and some grasslands are the most likely ecosystems in which to find more intensive farming systems (75-100% cultivation, 0-25% natural vegetation). In other words, if forests or grasslands are used for agriculture, they will probably be subjected to extensive clearing. The less intense subsistence activities are more likely to occur in woodland, shrubland and grassland (including savanna) communities while the least intense agricultural activities occur in the most extreme desert and tundra environments.

Areal estimates of major ecosystems from the integrated land-cover data base discussed here are compared in Table 3 with those of Lieth (1975), which are extensively employed in carbon studies, and those

TABLE 3. Global areal estimates of major ecosystems.

Vegetation type	Area (10^6 km^2) Lieth* (1975)	Hummel and Reck (1979)	This study (land cover)
Total forest	48.5	37.4	39.3
Tropical rain forest	17.0	15.1	12.3
Other forest	31.5	22.3	27.0
Woodland	7.0		13.1
Shrubland	19.5	14.6	12.1
Tropical woodland and grassland	–	6.6	–
Grassland	24.0	–	27.4
Tundra	8.0	11.7	7.3
Desert (rock & sand)	8.5	4.8	15.6
Marsh/Swamp	2.0	3.0	–
Cultivated	14.0	56.6**	17.6
Total	131.5	134.7	132.4

* 1.5 X 10^6 km^2 of chaparral, included in the forest category in Lieth's table, has been included in the shrubland category here according to UNESCO (1973).

** The total of 56.6 X 10^6 km^2 includes 25.5 X 10^6 km^2 of intensively cultivated land and 31.1 X 10^6 km^2 of less modified grazing and marginal farm lands.

of Hummel and Reck (1979), used in global albedo studies. (A comparison with Olson and Watts' data base, which includes numerous vegetation types along with identification of their geographic location, is not within the scope of this preliminary discussion and is being considered for future work.) The area for total forest from Lieth is about 25% higher than this work while that of Hummel and Reck is quite similar. However, the tropical rainforest areas show a considerable spread, with the strict biome definition used in this work resulting in the lowest estimate. Rainforest areas are about 40% higher in Lieth, and about 25% higher in Hummel and Reck, than in the present work. This work shows almost twice the woodland area of Lieth and about twice the tropical woodland and grassland estimate of Hummel and Reck. Combining the forest and woodland areas from Lieth and from this work produces figures of 55.5 X 10^6 and 52.4 X 10^6 km^2, respectively. This similarity indicates the possibility that some portion of these areal discrepancies may result from differences in ecosystem definition. There is a difference of about 3.5 X 10^6 km^2 between the grassland estimates of Lieth (24.0 X 10^6 km^2) and this work (27.4 X 10^6 km^2) which cannot be readily explained. Using a very strict definition of desert, the figure derived from this work is still three times that of Hummel and Reck and almost twice that of Lieth. However, this discrepancy may have resulted from the sometimes difficult and unclear distinction between shrubland and desert, whose combined area in Lieth is within 2% of that in this work. Hummel and Reek's low tropical woodland and grassland estimate, with no temperate woodland or grassland included at all, seems to be balanced by the enormous area in cultivation and grazing equal to about 40% of the ice-free land surface of the globe. Estimates for cultivated area are available from a variety of sources and range from 14 X 10^6 km^2 (Lieth, 1975, reflecting 1950 conditions), to 14.5 X 10^6km^2 (FAO, 1980), 15 X 10^6km^2(Golley, 1972), 18 X 10^6 km^2 (Ajtay *et al.,* 1979, including 2 X 10^6 km^2 urban land), 17.6 X 10^6 km^2 (this work), and 25.5 X 10^6 km^2 (Hummel and Reck, 1979, intensively cultivated only). The 17.6 X 10^6 km^2 for this study includes a contribution of 2.6 X 10^6 km^2 from extensive subsistence agriculture, which goes largely unreported in crop inventories. The remaining 15 X 10^6 km^2 fits very well with the FAO (1980) estimate of 14.5 X 10^6 km^2 for reported global crop acreage although the figures were acquired completely independently of one another using entirely different methods. FAO collected acreage reports from local and national sources, while this work was based on the extent and intensity of agricultural systems. This simple comparison quantifies some basic discrepancies in presently used land-cover data sources. It also highlights the need for critical evaluation of vegetation definitions and classifications, and of compilation sources incorporated into data bases of this kind.

Table 4 demonstrates 32 selected subdivisions, primarily at the UNESCO formation-group level, of the major ecosystems presented in Table 3, using more detailed classification components included in the vegetation file. Abbreviated definitions accompanying the UNESCO codes for each vegetation type identify the subdivisions more fully. Areas are those derived from the integrated land-cover data base. Map symbols refer to Fig. 5. These subdivisions, mapped for North America in Fig. 5, produce a more complex vegetation landscape, at the same spatial resolution, than that apparent in Fig. 4. Longitudinal variations related to precipitation are more detailed in western areas. These patterns reflect the north-south orientation of major topographic features, e.g., mountain ranges with intervening dry basins, and rainshadow plains. Extremely arid areas are classified primarily as xeromorphic woodland or shrubland; there are very limited areas of true un vegetated desert in North America. Along the coast of northern California can be found a narrow discontinuous band of dry evergreen forests. These rare forests, commonly referred to as Mediterranean, are located only in relatively dry areas with a winter rainy season. Major portions of the eastern and midwestern United States as well as central Canada are predominantly cultivated. However, small-scale commercial farms in the previously forested east produce complex agricultural landscapes which retain a greater proportion of the original vegetation than large single-crop farms in the Midwest (refer to Fig. 3 for cultivation intensities).

TABLE 4. Thirty two selected subdivisions of major ecosystems, including areal estimates, derived from the land-cover data base.

Map symbol	UNESCO code	Area (10^6 km^2)	Description
1	1.A.1, 1.A.5	12.29	tropical evergreen rainforest, mangrove forest
2	1.A.2, 1.A.3	3.29	tropical/subtropical evergreen seasonal broad-leaved forest
3	1.A.4	0.19	subtropical evergreen rainforest
4	1.A.6	0.39	temperate/subpolar evergreen rainforest
5	1.A.7	0.81	temperate evergreen seasonal broadleaved forest, summer rain
6	1.A.8	0.47	evergreen broadleaved sclerophyllous forest, winter rain
7	1.A.9	0.49	tropical/subtropical evergreen needleleaved forest
8	1.A.10	9.29	temperate/subpolar evergreen needleleaved forest
9	1.B.1	2.88	tropical/subtropical drought-deciduous forest
A	1.B.2	5.18	cold-deciduous forest, with evergreens
B	1.B.3	3.99	cold-deciduous forest, without evergreens
C	1.C, 2.C	2.68	xeromorphic forest/woodland
D	2.A.1	1.71	evergreen broadleaved sclerophyllous woodland
E	2.A.2	2.51	evergreen needleleaved woodland
F	2.B.1	3.70	tropical/subtropical drought-deciduous woodland
G	2.B.2, 2.B.3	2.50	cold-deciduous woodland
H	3.A.1, 4.A.1, 4.A.2, 4.A.3	1.30	evergreen broadleaved shrubland/thicket, evergreen dwarf shrubland
I	3.A.2	0.67	evergreen needleleaved or microphyllous shrubland/thicket
J	3.B.1, 3.B.2, 4.B.1, 4.B.2	0.83	drought-deciduous shrubland/thicket
K	3.B.3, 4.B.3	0.46	cold-deciduous subalpine/subpolar shrubland, cold-deciduous dwarf shrubland
L	3.C, 4.C	8.86	xeromorphic shrubland/dwarf shrubland
M	4.D, 4.E, 5.C.8	7.34	arctic/alpine tundra, mossy bog
N	5.A.1, 5.B.1, 5.C.1	6.46	tall/medium/short grassland with 10-40% woody tree cover
O	5.A.2, 5.A.4, 5.B.2, 5.B.4, 5.C.2, 5.C.4	3.66	tall/medium/short grassland with <10% woody tree cover or tuft-plant cover
P	5.A.3, 5.B.3, 5.C.3	9.34	tall/medium/short grassland with shrub cover
Q	5.A.5	0.81	tall grassland, no woody cover
R	5.B.5	0.78	medium grassland, no woody cover
S	5.C.5, 5.C.6, 5.C.7	6.10	meadow, short grassland, no woody cover
T	5.D	0.28	forb formations
U	6*	15.57	desert
V	7*	2.44	ice
W	9*	17.56	cultivation

* Not included in UNESCO classification.

5. Final remarks

The status of the changes in natural and managed (cultivated) ecosystems directly affect several climatically important parameters such as albedo, seasonal CO_2 cycling, biomass inventory, hydrologic cycles and surface roughness. While the land-use practices in some areas are stabilized and well documented (e.g. North America, Europe), there exist many regions where such practices are not well documented and

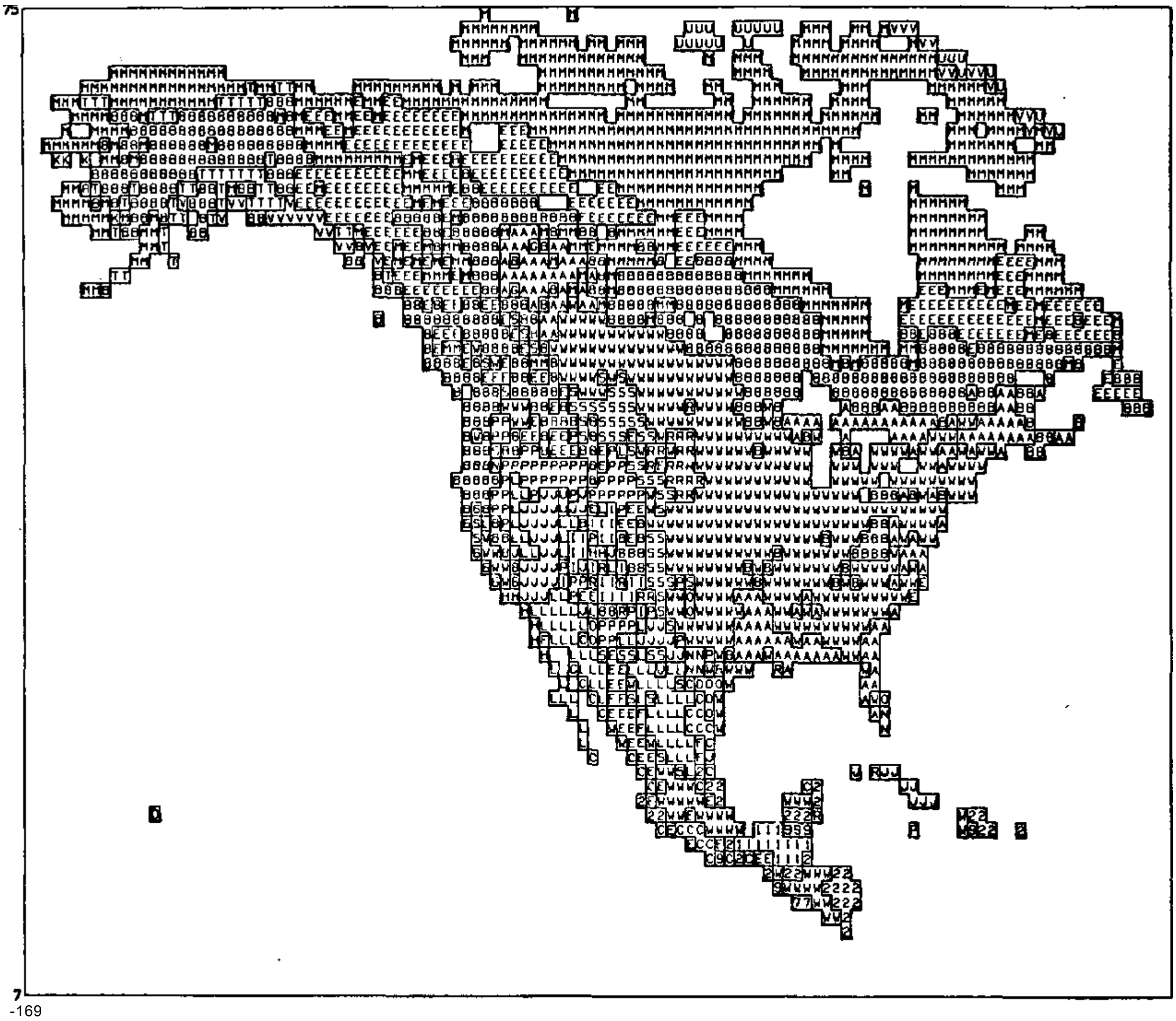

FIG. 5. Land-cover map of North America showing detailed subdivisions of major ecosystems. (Refer to Table 4 for explanation of symbols).

are still undergoing changes in area as well as in intensity of modifications to the natural vegetation (e.g. Africa, South America). This highlights the problem of attempting to inventory the characteristics of evolving natural and cultural (agricultural) systems. With these considerations in mind, the vegetation and land-use data discussed here, integrated into the land-cover data base, provide a reasonable, though not definitive, view of global surface characteristics.

With flexibility in choice of categories and degree of retrievable detail, these vegetation, land-use and land-cover data bases can be tailored to address the variety of climate-related research areas mentioned above. In addition, this series of modifiable inventories, representing both the pre-agricultural (natural) vegetation landscape and the present agriculturally-modified vegetation landscape, provides a useful tool for investigating possible climatic impacts of past and predicted land-cover changes.

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