Popular Summary for:

Reconstructed Historical Land Cover and Biophysical Parameters for Studies of Land-Atmosphere Interactions within the Eastern United States.

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The local environment where we live within the Earth's biosphere is often taken for granted. This environment can vary depending on whether the land cover is a forest, grassland, wetland, water body, bare soil, pastureland, agricultural field, village, residential suburb, or an urban complex with concrete, asphalt, and large buildings. In general, the type and characteristics of land cover influence surface temperatures, sunlight exposure and duration, relative humidity, wind speed and direction, soil moisture amount, plant life, birds, and other wildlife in our backyards. The physical and biological properties (biophysical characteristics) of land cover help to determine our surface environment because they directly affect surface radiation, heat, and soil moisture processes, and also feedback to regional weather and climate. Depending on the spatial scale and land use intensity, land cover changes can have profound impacts on our local and regional environment.

Over the past 350 years, the eastern half of the United States, an area extending from the grassland prairies of the Great Plains to the Gulf and Atlantic coasts, has experienced extensive land cover and land use changes that began with land clearing in the 1600s, led to extensive deforestation and intensive land use practices by 1920, and then evolved to the present-day landscape. Determining the consequences of such land cover changes on regional and global climate is a major research issue. Such research requires detailed historical land cover data and modeling experiments simulating historical climates. Given the need to understand the effects of historical land cover changes in the eastern United States, some questions include:

— What were the most important land cover transformations and how did they alter biophysical characteristics of the land cover at key points in time since the mid-1600s?

— How have land cover and land use changes over the past 350 years affected the land surface environment including surface weather, hydrologic, and climatic variability?

— How do the potential effects of regional human-induced land cover change on the environment compare to similar changes that are caused by the natural variations of the Earth's climate system?

To help answer these questions, we reconstructed a fractional land cover and biophysical parameter dataset for the eastern United States at 1650, 1850, 1920, and 1992 time-slices. Each land cover fraction is associated with a biophysical parameter class, a suite of parameters defining the biophysical characteristics of that kind of land cover. This new dataset is designed for use in computer models of land-atmosphere interactions, to understand and quantify the effects of historical land cover changes on the water, energy, and carbon cycles.

Our approach combined potential vegetation, county-level census data on farmland area and population size, soils data, historical resource statistics, a Landsat-derived land cover classification, and published historical information on land cover patterns and land use activities. We characterized the land cover condition and then reconstructed land-use intensity maps for each time-slice. A mutually consistent set of biophysical parameter classes was developed to encompass the diversity of historical land cover characteristics in the eastern United States. These results were then used to derive time-series maps of land surface albedo (broadband reflectivity for incident sunlight), leaf area index, a deciduousness index, canopy height, surface roughness, and potential saturated soils for the 1650, 1850, 1920, and 1992 time-slices.

Our analysis of reconstructed land cover and biophysical parameters spanned the period from the widespread forests and other natural vegetation patterns of the 1600s to the agriculture, regrowing forest, other semi-natural vegetation, degraded lands, roads, towns, and cities of the 20th century. (1650 was chosen to represent a recent minimum in human land-use intensity across the eastern United States, associated with the tragic declines in populations of Native Americans caused by introduced epidemic diseases.) As a result of repeated land use changes, the biophysical characteristics of the present-day land cover are markedly different from those of either the 1920s or the 1600s time-frames. For example, the effects of these land cover changes are evident in the large quantitative differences in the respective time-series maps of surface albedo, canopy height, and surface roughness parameters at the 1650, 1850, 1920, and 1992 time-slices. Similarly, the maps of potentially water-saturated soils for these time-slices show changes in early season soil moisture that resulted from the expansion of agricultural land area by artificial drainage. Land use changes have all but eliminated entire ecosystems, altered the regrowing forest, changed grassland physiology, increased the impervious surface area, and fragmented the landscape.

This innovative land cover and biophysical parameter dataset for the eastern United States provides the foundation for a new generation of modeling studies of land-atmosphere interactions that will further quantify the consequences of historical land use change, for example, beginning with sensitivity tests on the interrelationships among biophysical parameters and potentially water-saturated soils.

Reconstructed Historical Land Cover and Biophysical Parameters for Studies of Land-Atmosphere Interactions within the Eastern United States

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Abstract

Over the past 350 years, the eastern half of the United States experienced extensive land cover changes. These began with land clearing in the 1600s, escalated to wide-spread deforestation, wetland drainage, and intensive land use by 1920, and then evolved to the present-day landscape of forest regrowth, intensive agriculture, urban expansion, and landscape fragmentation. Such changes alter biophysical properties that are key determinants of land-atmosphere interactions (water, energy, and carbon exchanges). To understand the potential implications of these land use transformations, we developed and analyzed 20-km land cover and biophysical parameter datasets for the eastern United States at 1650, 1850, 1920, and 1992 time-slices. Our approach combined potential vegetation, county-level census data, soils data, resource statistics, a Landsat-derived land cover classification, and published historical information on land cover and land use. We reconstructed land use intensity maps for each time-slice and characterized the land cover condition. We combined these land use data with a mutually-consistent set of biophysical parameter classes, to characterize the historical diversity and distribution of land surface properties. Time-series maps of land surface albedo, leaf area index, a deciduousness index, canopy height, surface roughness, and potential saturated soils in 1650, 1850, 1920, and 1992 illustrate the profound effects of land use change on biophysical properties of the land surface. Although much of the eastern forest has returned, the average biophysical parameters for recent landscapes remain markedly different from those of earlier periods. Understanding the consequences of these historical changes will require land-atmosphere interactions modeling experiments.

1. Introduction

The eastern United States, here defined as the land area to the east of the 97th west meridian, has experienced a series of extensive land cover and land use changes since the arrival of European explorers in the early 1500s [*Williams,* 1989; *Whitney,* 1994]. Regional trajectories of major land cover changes since the 1600s (deforestation, wetlands conversion, agricultural expansion and contraction, and reforestation), when linked with associated changes in biophysical properties, provide a basis for quantifying geophysical consequences of these changes.

The first major land cover transformation was the clearing of the eastern forest, which once extended across most of the eastern United States from the grasslands of the central plains to the marshes and open woodlands of the Atlantic and Gulf coasts. Forest harvest for wood products and clearing for agriculture in the New England and the Atlantic coastal areas was followed by westward expansion across the Appalachians into the Ohio and upper Mississippi River basins, where agriculture was well established by the mid-1800s. By the 1840s, agriculture had peaked in the Northeast and many abandoned farm fields and pasturelands were in the process of forest regeneration [*Williams*, 1989; *Foster and O'Keefe*, 2000]. The late 1800s and early 1900s saw intensive commercial logging of old-growth forests in the Great Lakes states, followed by mechanized logging of the southern pine forests. Agricultural production was increased by the introduction of artificial land drainage systems, such as underground tiles to remove excess water in upper soil layers of Midwestern states (e.g., Indiana and Illinois) [*Whitney*, 1994]. Meanwhile, economically marginal farms were being abandoned in the Southeast. The early 20th century marked the completion of an immense land cover transformation across most of the eastern United States [*Whitney,* 1994].

Reforestation of cleared lands and relocation of intensive agriculture, such as with the drainage of wet prairies in the corn-belt states and floodplains of the lower Mississippi River valley, represented some of the subsequent land cover transformations within the eastern United States. With fluctuations in crop prices, changes in labor markets, and competition with farm products from other regions, farm abandonment continued throughout the East [*Hart,* 1968; *Williams,* 1989]. Efforts to promote forest regrowth received support from an environmental conservation movement that began in the 1880s—motivated by concerns about the negative consequences of land use change, specifically land and water resource degradation associated with deforestation and poor farming practices. A rapidly dwindling supply of saw timber in the eastern United States led to forest management policies that promoted planting of trees and suppression of fires [*Williams,* 1989]. The resiliency of eastern timberlands was underestimated in the 1920s, and by the late 20th century forests had regenerated on much cutover and abandoned land [*Shands and Healy,* 1977; *Clawson,* 1979; *Williams,* 1989; *MacCleery,* 1992]. In most cases, the characteristics of the forest have changed. Previous land clearing, timber management practices, and the inadvertent effects of human activities, such as introduction of the chestnut blight, have left their imprints on the forest. In addition, widespread agricultural and silvicultural drainage throughout much of the eastern United States has altered seasonal soil moisture patterns, in particular the distribution of soils that are saturated in the early growing season. By the mid-20th century, land cover was being transformed by growing urbanization and other land use changes leading to increasing landscape fragmentation. As we show, the biophysical properties of land cover in the late 20th century remained distinct from the land cover that existed at the onset of widespread land cover conversion or during the early 20th century.

Research on land cover and land use change at regional-to-global scales has received increasing emphasis since the early 1990s [*National Research Council,* 1990; *Committee on Earth Science,* 1990; *International Geosphere-Biosphere Program,* 1993; *National Research Council,* 2001; U.S. *Climate Change Science Program,* 2003; *National Research Council,* 2005; and *Foley et al.*, 2005]. Land cover change has been associated with changes in air quality, water quality, hazards potential (such as flooding, landslide, frost occurrence, and drought exacerbation), biological diversity, ecosystem processes, regional weather and climate variability, and other aspects of the biosphere [*Goodchild et al*., 1993; *Meyer and Turner,* 1994; *Steyaert and Pielke,* 2002; and *Gutman et al*., 2004]. Changes in land cover and land use can alter land surface biophysical properties that exert controls over land processes involving the land surface energy, radiation, and soil moisture budgets [*Dickinson,* 1983; *Pielke,* 1984, *Dickinson et al*., 1986; and *Sellers et al.*, 1986]. Therefore, changes in land cover and land use can affect the surface water, energy, and carbon cycles; land surface interactions with the atmospheric boundary layer; convective activity, and precipitation [*Pielke,* 2001]. In addition to the direct effects on the land surface energy budget and land surface forcing [*Pielke,* 2001; *National Research Council,* 2005], land cover change that alters soil moisture or water-saturated soil conditions may have implications for seasonal atmospheric predictions because of potential soil moisture and precipitation feedbacks [*Findell and Eltahir,* 1997; *Fennessy and Shukla,* 1999].

Because of these complex interrelationships, coupled land-atmosphere interactions models are needed to quantify and understand the potential consequences of regional land cover and land use change on land surface biophysical processes, and on hydrologic, weather, and climate variability [*National Research Council,* 1990; *Pielke and Avissar*, 1990; *Sellers et al.*, 1997; *Bounoua et al.*, 2000; *Chen et al.*, 2001; *Kalnay and Cai,* 2003; and *Bronstert et al.*, 2005]. Reconstructed land cover and biophysical parameter data have also been used in modeling sensitivity tests to determine the consequences of long-term land cover change on regional weather and climate [*Copeland et al.*, 1996; *Bonan,* 1997, 1999; *Pielke et al.*, 1997; *Eastman et al.*, 2001; *Narisma and Pitman,* 2003; *Roy et al.*, 2003; and *Marshall et al.*, 2004]. Reconstructed land cover characteristics data were integral to carbon budget studies for the conterminous United States, such as *Houghton et al.* [1999] and *Hurtt et al.* [2002].

Our reconstruction of historical land cover for the eastern United States is rooted in mapping studies from the late 19th century to the mid-20th century that focused on understanding pre-colonial and contemporary vegetation. Early vegetation maps included generalized land cover, woodland density, and timber volume maps of the late 1800s [see *Williams*, 1989]; a "graphic summary of American agriculture" including a map of forest, woodland, and cutover land [*Baker*, 1922]; a map of "Natural Vegetation of the United States" [*Schantz and Zon*, 1924]; and maps of the estimated area of "virgin saw timber forest" in 1620, 1850, and 1920 [*Greeley*, 1925]. The classic syntheses by *Braun* [1950] and *Küchler* [1964] represented fundamental advances in the understanding of regional land cover history within the eastern United States. *Braun* [1950] conducted a comprehensive study of the Deciduous Forest Formation of the eastern United States including the Southeastern Evergreen Forest and Hemlock-White Pine-Northern Hardwood regions. *Küchler* [1964] used a physiognomic approach (vegetation life forms and structural categories) to develop a potential natural vegetation (PNV) map for the United States. This was based on analysis of existing vegetation patterns, including remnant natural vegetation, and extensive review of published studies on both semi-natural and natural vegetation. The Küchler potential natural vegetation was defined as, "the vegetation that would exist today if man were removed from the scene and if the resulting plant succession were telescoped into a single moment" [*Küchler,* 1964].

More recently, U.S. census data have been used to reconstruct historical patterns of agricultural land cover change within the conterminous United States [e.g., *Maizel et al.*, 1998; *Ramankutty and Foley,* 1999a, 1999b; and *Waisanen and Bliss,* 2002]. *Maizel et al.* [1998] used U.S. Census of Population and Housing data (beginning 1790) and U.S. Agricultural Census data (beginning 1850) to map county-level population and percent of land in farms for the conterminous United States. *Ramankutty and Foley* [1999a, 1999b] used a satellite-derived potential vegetation dataset [also see *Loveland et al.*, 2000] and a land-cover change model to disaggregate national and sub-national or U.S. state-level census data, and then reconstruct a regional to global cropland history (5 minute grid). *Waisanen and Bliss* [2002] used county-level census data to develop time-series maps that show the history of population (1790-1990) and agricultural development (1850-1997) for the conterminous United States.

This paper reports the development of a reconstructed historical land cover and biophysical parameter dataset for land-atmosphere interactions modeling studies in the eastern United

States. We reconstructed land use intensity maps including potential saturated soils for the eastern United States and characterized the land cover condition, spatial patterns, and changes in time relative to 1650, 1850, 1920, and 1992 time-slices. In parallel, we defined a coherent set of land cover and biophysical parameter classes to sufficiently resolve and characterize geospatial differences of land cover condition within and changes among the four time-slices. These results were combined to derive biophysical parameter maps and historical land cover data for each time-slice. The methods for geospatial analysis and dataset development are defined in Section 2. The land use intensity analysis, biophysical parameter mapping, and potential implications for land-atmosphere interactions are discussed in section 3.

2. Methods

2.1. Overview of the Analysis

Our analysis for the 1650, 1850, 1920, and 1992 time-slices had three interrelated components: reconstructing land use intensity maps (section 2.3), developing land cover and biophysical parameter classes (Tables 1 and 2, section 2.4), and then combining the land use intensity maps and the set of land cover and biophysical parameter classes to derive biophysical parameter maps and historical land cover data for each time-slice (section 2.5). The set of land use intensity maps for each time-slice depicts major human land-use categories (e.g., regrowing forest, mixed agriculture, and residential-urban). Each map shows the fractional area contribution of the land use category relative to the entire set for the time-slice; the set of fractional areas sum to 1.0. The 1850 and 1920 land use intensity maps were derived from a geospatial analysis of county-level census (population and farmland area) and Küchler PNV data. The 1992 land use intensity maps were based on a Landsat-derived land cover dataset. To address the effects of artificial land drainage on soil moisture and provide a boundary condition for land-atmosphere interactions models, a geospatial analysis of soil suborders and improved farmland area was used to derive potential saturated soils maps for the early growing season in the 1650, 1850, and 1920 time-slices. The Küchler PNV data were used to infer 1650 vegetation types, interpret likely regenerating vegetation composition, and disaggregate county-level census data for the land use intensity analysis. The Küchler PNV map units also provided the spatial framework to develop a temporally-consistent set of land cover classes (Table 1) and associated biophysical parameters (Table 2) that were developed in parallel with the land use intensity analysis for the four time-slices. The standard map projection used throughout this study was the Albers Equal Area Conic.

2.2. Geospatial Data Sources

2.2.1. U.S. Census Data

Our source of county-level spatial data on farmland areas and population size for 1850 and 1920 was the historical database developed by *Waisanen and Bliss* [2002] from U.S. Census records and other sources of information. The 1850 data included county-level areas for "improved land in farms" and "unimproved farmland", while the data for 1920 included areas for "improved land in farms", "unimproved farm woodlands", and "other unimproved farmland".

2.2.2. Potential Natural Vegetation

The PNV was represented with a 1-km digitized version of Küchler's 1964 map of potential natural vegetation of the conterminous United States (scale 1:3.5 million), and interpreted using the Manual to Accompany the Map: Potential Natural Vegetation of the Conterminous United States [*Küchler,* 1964]. In addition to characterizing the composition and geography of each vegetation unit, the manual provides a concise summary of physiognomic information (e.g., vegetation life forms, canopy height class, canopy closure or vegetation density, and deciduousness). Quantitative definitions of structural categories used in these physiognomic summaries appear in related works setting out the vegetation mapping system [*Küchler,* 1955, 1966, 1967], thus providing information critical for inferring biophysical properties of potential vegetation (section 2.4).

Given the appropriate caveats (Text S1 in the supplementary materials[1]), Küchler's PNV map and associated physiognomic characteristics for each vegetation unit provide a starting point for historical land cover reconstruction. Although significant land cover transformations have occurred over the past 400 years, the PNV map units represent a frame of reference to understand and maintain temporal continuity and trajectories of land cover change from pre-colonial vegetation to contemporary semi-natural vegetation. PNV data tend to reflect the underlying constraint on vegetation form and development due to regional geomorphic, soils, and climatic conditions [e.g., *Thompson et al.*, 2005]. *Küchler* [1964] stated that he explicitly considered then available information on the effects of natural disturbance and vegetation likely to develop without on-going human influence. When combined with data on vegetation

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/jd/2006JD008277

changes associated with the intensity of human land use, and updated with current knowledge of prevailing historical disturbance patterns in the eastern United States, these PNV data form a foundation for reconstructing the properties of natural and semi-natural land cover. The spatial resolution of county-level census data and the 1964 PNV map (1:3.5 million) also support some carefully drawn inferences about changes in land cover heterogeneity at scales coarser than 10 km.

We assumed that Küchler's 1964 data represent a reasonable proxy for pre-colonial vegetation physiognomy at 1650. Nevertheless, PNV should differ from vegetation conditions just prior to extensive European settlement in several respects (see Text S1[1]). The influence of land use practices of Native Americans was not included [*Küchler,* 1964]. Because the terrestrial geography used to map PNV was contemporary [*Küchler,* 1964], the historical differences in coastlines and artificial inland water bodies were not represented. Although the PNV explicitly mapped various wetlands regions, some PNV units implicitly include small-scale wetlands inclusions or do not explicitly map extensive wetlands phases in predominantly dry PNV units (e.g., Bluestem prairie, Bluestem-sacahuista prairie, Palmetto prairie, Blackbelt, and Southern mixed forest). The PNV does not include many former wetlands areas (e.g., the tallgrass prairie ecosystem) that were artificially drained and converted to agriculture [*Whitney*, 1994]. Because most of the historical area of water-saturated soils would be missed if predominantly wetland PNV units were used as the sole source of information, we derived a potential saturated soils map for the 1650 time-slice to provide soil moisture information for land-atmosphere interactions modeling in the early growing season (section 2.3.4).

2.2.3. National Land Cover Data (NLCD) 1992

Our source of contemporary land cover data was the 30-m USGS NLCD that was derived from 1992/93 Landsat Thematic Mapper (TM) scenes as described by *Vogelmann et al.* [2001]. The 21 NLCD classes were individually aggregated to obtain the fractional area of each class for 1-km pixels, thereby yielding 21 separate fractional area maps.

2.2.4. Other Spatial Data

A 1-km digital elevation model (DEM) and associated slope data from the USGS HYDRO1k dataset were used in the geospatial analysis.

We used regional forest statistics [*Smith et al.*, 2002], that were summarized by Forest Service region and Forest Cover Type Groups, and related maps to constrain reconstructed trajectories of recovering forest lands (section 2.4.2) and to help derive biophysical properties of semi-natural land cover (section 2.4.4). We also used a digital map of Forest Cover Type Groups [*Zhu and Evans,* 1994; *U.S. National Atlas,* 2000; *Smith et al.*, 2002].

The STATSGO Soils Data [*USDA,* 1994a, 1994b] were the basis for a general soil suborder map from the U.S. Department of Agriculture (USDA) National Resource Conservation Service (NRCS) as published in Chapter 22, Soil Taxonomy, Second Edition [USDA, 1999]. The general soil suborder map data were provided by *S.W. Waltman* [personal communication]. We used these data in a geospatial analysis to derive a potential saturated soils data layer for each of the 1650, 1850, and 1920 time-slices (section 2.3.4).

2.3. Reconstructing and Mapping Land Use Intensity

2.3.1. Geospatial Analysis for 1850

Four land use intensity maps for 1850 were derived from a geospatial analysis of county-level census, PNV, and other spatial datasets. These were: Old-Growth Vegetation, Forest-Village Disturbance, Highland Agriculture, and Lowland Agriculture (see Table 3, section 3.1).

A geographic information system (GIS) overlay operation was used to derive a set of discrete county-PNV polygons. The county-level attributes attached to each county-PNV polygon were converted to 1-km grids that included the fractional areas of improved farmland, unimproved farmland, and non-farmland, as well as population density (persons per km^2). A topographic mask derived from USGS HYDRO1k DEM and slope data was used to split the improved farmland into highland and lowland agriculture components. Online supplemental material (Text S2) provides further details of the geospatial methods for 1850.[1]

The fractional area grids for unimproved farmland and non-farmland were assumed to include a combination of disturbed and relatively undisturbed land cover components, depending on the degree of human activity as of 1850. The unimproved farmland was assumed to represent forests and woodlands, regenerating forests, or intact old-growth vegetation where human activity was minimal (e.g., unimproved portions of frontier land claims). Depending on the stage of settlement, the non-farmland fraction represented either a relatively undisturbed natural landscape or a disturbed mixture of land use types associated with settled lands. We assumed that the land cover of relatively undisturbed fractions of each grid approximated the vegetation reconstructed for 1650.

To separate each grid cell into settled and relatively undisturbed components, we estimated the fraction of land use disturbance due to human activities with a piecewise-continuous linear function of the population density. In this simple model, a population density of zero was assumed to represent negligible human disturbance while a population density of 20 people per km^2 was assumed to be sufficient for 100% human disturbance of the natural landscape. We applied this function separately to the unimproved farmland and non-farm grids, and then summed the results to form two land use intensity maps: a Forest-Village Disturbance map and a map representing the fractional area of the 1850 landscape that was relatively undisturbed by human activities.

2.3.2. Geospatial Analysis for 1920

Seven land use intensity maps were reconstructed for 1920: Remnant Old-Growth, Young Regrowing Forest, Non-Forest Vegetation, Degraded Land, Highland Agriculture, Lowland Agriculture, and Residential-Urban (see Table 3, section 3.1). The initial analysis for 1920 was directly analogous to the approach for 1850 except that the census included unimproved farm woodlands and other unimproved farmland components. Thus, 1-km fractional area grids for improved agriculture, farm woodlots, other unimproved farmland, non-farmland, and population density were derived from the county-level attributes and county-PNV discrete polygons. The fractional area of improved agriculture was split into lowland and highland components according to the topographic-slope conditional mask.

Because of population expansion and the growth of urban areas from 1850 to 1920, we estimated the residential-urban land use intensity (e.g., villages, roads, cities, and urban areas) for each county. Fractional areas were approximated with a piecewise-continuous linear function, which was calibrated with an analysis of non-farm fractional area and population density. This partitioned the non-farm area into a residential-urban category representing high land use intensity and other land-use intensity categories making up the remainder of the non-farm area. (See Text S2 for additional details of our analysis of residential-urban land use intensity in 1920.[1])

As the other extreme of low-intensity land use, we used the *Greeley* [1925] "area of virgin forest 1920" map to estimate the fractional area of remaining virgin forest of saw timber quality in each county. The regional sums of virgin forest area from the Greeley map closely corresponded to the tabular data of virgin forest area for the "1920 USFS regions" [*USDA*, 1925]: 1) New England, 2) Middle Atlantic, 3) Great Lakes States, 4) Central, 5) South Atlantic and Gulf, and 6) Lower Mississippi Valley. Because the remaining virgin forest was mostly located in counties with a low population density and a large non-farm area, the virgin forest was treated as a component of the non-farm area in each county. (For additional information on our analysis of the remaining virgin forest in 1920, see Text S2.[1])

Next, the residual non-farmland area (non-farmland less residential-urban and remnant virgin forest) was split into young forest regrowth, not restocking forest area, or non-forest vegetation depending on the PNV class within each county-PNV polygon. First, the census data were summed by PNV class to obtain totals for the USFS 1920 regions and then analyzed with the USFS regional forest data (USDA, 1925) to estimate the regional ratio of not restocking land to the young regrowing forest on the non-farmland. Second, the regional ratios were used to split the residual non-farmland into non-farmland young forest regrowth and not restocking areas within each county-PNV polygon. Online supplemental material (Text S2) describes the regional analysis necessary to produce estimates consistent with forest area statistics for USFS 1920 regions.[1]

The results for each county-PNV polygon were converted to fractional area grids. A fractional area map for degraded land (i.e., sparse vegetation, scattered shrubs, "scrub" trees, and barren land with poor forest regeneration) was calculated from the sum of the not restocking land and other unimproved farmland categories. Note that by 1920 degraded land was sufficiently extensive to warrant a separate land use intensity category (see Table 3). The fractional area grids for the young forest in farm woodlands and non-farmland were summed to form our land-use intensity category representing young regrowing forest.

2.3.3. Geospatial Analysis for 1992

A geospatial analysis of the 1992 NLCD was used to define a set of 1992 land-use intensity categories (see Table 3, section 3.1) and to infer forest structural information based on a statistical comparison among the USGS NLCD, U.S. Forest Cover Type Groups [*U.S. National Atlas,* 2000], Forest Resources of the United States, 1997 [*Smith et al.*, 2002], and PNV datasets [*Küchler,* 1964].

The NLCD was aggregated to 12 land-use intensity categories expressed as 1-km fractional areas, which summed to 1.0, and consisted of 7 semi-natural vegetation categories and 5 land use categories. The semi-natural categories included the three NLCD forest classes plus the NLCD woody wetlands, emergent herbaceous wetlands, shrublands, and grasslands classes. The higher land-use intensity categories included inland water bodies, the NLCD transitional class, mixed agriculture (NLCD classes for pasture/hay, row crops, small grains, fallow, urban/recreational grasses, and non-natural woody vegetation such as orchards and vineyards), low intensity residential, and urban/built-up/impervious (NLCD classes for high intensity residential, commercial/industrial/transportation, bare rock/sand/clay, and quarries/strip mines/gravel pits).

Spatial distributions of the seven semi-natural land cover classes then were compared with USFS forest cover data and PNV data. We selected the 1-km pixels where a NLCD semi-natural class was at least 50% of the area, and then cross-tabulated their dominant NLCD classification with their PNV unit and their mapped Forest Cover Type Group. This statistical analysis informed our selection of the most appropriate biophysical land cover classes to use for NLCD classes occurring in various PNV units (see section 2.4).

2.3.4. Geospatial Analysis of Potential Saturated Soils

A geospatial analysis of the NRCS STATSGO soils dataset was used to derive fractional area maps of potential saturated soils during the early growing season for the 1650, 1850, and 1920 time-slices. In contrast to the much more complex problem of wetlands characterization and mapping [*National Research Council,* 1995], we adopted a conservative approach in order to infer the distribution of potentially water-saturated soils (not addressed by Küchler PNV data); to account for changes caused by artificial drainage for agriculture in the1850 and 1920 time-slices; and maintain temporal continuity with potential saturated soils inferred from the 1992 NLCD wetlands classes. We also restricted this analysis to the early peak growing season, when preceded by normal weather. Because land-atmosphere interactions processes are sensitive to soil moisture levels, incorporating the fractional area of saturated soils into modeling experiments would represent a first-order approximation to account for effects on soil moisture and energy budgets.

We used data from STATSGO on the fractional abundance of different soil suborders to derive an estimated saturated soils moisture map for 1650 and then used census farmland data to adjust the 1650 baseline map to estimate saturated soils maps for the 1850 and 1920 time-slices. Our methods for 1650 were consistent with *Dahl* [1990] who used aquic and organic soil suborders [*USDA*, 1975] as one of his approaches to estimate the original wetlands area within the conterminous United States at the 1700s time-frame. This approach was in part based on the concept that hydric soils, such as the aquic suborders, can retain distinctive soil profile characteristics even after drainage [*Dahl,* 1990; *NRC*, 1995]. For our analysis, we combined organic (Histosols, excluding Folists) and aquic suborders [*USDA,* 1999] to estimate the fractional area of potential saturated soils during the early growing season for the 1650 time-slice. Conversion of wetlands to agriculture by artificial drainage was the dominant reason for wetlands losses and directly contributed to the expansion of farmland crop area well into the 20th century [*Dahl,* 1990; *Whitney,* 1994]. To estimate the fractional area of potential saturated soils for the 1850 and 1920 time-slices, we used improved farmland data from the agricultural census of 1850 and 1920, respectively. If the fractional area of improved farmland exceeded the fractional area classified as other soil suborders (non-aquic, non-organic), then the difference was used to decrease the area of potential saturated soils.

2.4. Biophysical Land Cover Classes and Parameters

2.4.1. Establishing a Consistent Set of Land Cover Classes

This study required a suite of land cover classes and associated biophysical parameters to characterize the range of land cover conditions needed to represent 1650, 1850, 1920, and 1992 time-slices across the eastern United States (see Table 1). Our analysis built on heritage land cover classes for modeling land-atmosphere interactions and their biophysical parameter tables [e.g., *Dickinson et al.*, 1986; and *Sellers et al.*, 1986], and the parameters for the Land Ecosystem-Atmosphere Feedback Model (LEAF-2) model [*Lee,* 1992; *Walko et al.*, 2000]. We extended those class sets to represent the greater range in some biophysical properties needed for historical land cover, and we updated parameter estimates using published reviews of field observations and recent observations with Earth remote-sensing satellites.

A set of land cover classes and their associated biophysical parameters can be viewed as a biophysical parameter class table, where the rows are functionally distinct types of land cover and columns specify parameters directly related to land surface processes (e.g., see Table 2). Parameters important for land-atmosphere interactions include: estimates of the characteristic solar broadband albedo, emissivity, leaf area index (*LAI*), fractional vegetation cover (*VF*), aerodynamic surface roughness length (z_0), zero-plane displacement height (D), rooting depth (d_r), canopy height (h), and the amounts of seasonal change in LAI (ΔLAI) and in VF (ΔVF).

Although parameters for some intensive land use classes, such as crop/mixed farming, were adapted from the LEAF-2 biophysical parameters, sites representative of much historical land cover are uncommon or nearly absent from the modern landscape. Given the limitations of available parameter sets, we began with physiognomic information for Küchler's PNV units. We developed a consistent suite of land cover classes to represent the full range of biophysical properties important to modeling 1650 land cover, grouping PNV units with the same or similar average physiognomy. We then analyzed properties of semi-natural vegetation common in other time slices. Classes were added when no class defined for an earlier time-slice could parsimoniously represent a land cover condition that had become widespread (see section 3.1). Classes were combined when the differences in their estimated biophysical parameters were smaller than uncertainties in the parameter estimates.

The approach was conservative in that we sought to represent land cover change, where possible, without defining distinct classes for different historical periods. It was also iterative, in that it required us to estimate biophysical parameters for many different types of vegetated historical and recent land cover, to combine types of vegetation having similar biophysical properties, and then to confirm or refine our estimates of characteristic parameters for the classes in light of the historical record (see section 3.1). Repeating this process, as we extended our analysis across the four time slices, produced a consistent suite of classes appropriate for modeling the effects of wide-spread historical changes in properties of land surfaces of the eastern United States.

2.4.2. Plant Life Forms

For vegetated land cover, definitions of dominant life forms or plant functional types provide key assumptions needed to derive biophysical parameters (e.g., differences in leaf lifespan, leaf reflectance, or typical crown shapes of trees). Characteristic plant life forms also were used in an informal way to help develop descriptive class names (Table 1) and convenient short-hand names (Table 2) for parameter classes. Information on prevailing mixtures of vegetation life forms was from PNV physiognomy [*Küchler,* 1964] or from regionally-derived changes associated with human land use (see section 3.1). We developed information on the characteristics and composition of managed forests using summary tables published in Forest Resources of the United States, 1997 [*Smith et al.*, 2002]. Additional insights into regional differences in patterns of life form dominance during forest regeneration, regrowth, and continued harvesting were provided by statistical cross-tabulations in which forest cover type data [*Zhu and Evans,* 1994; and *U.S. National Atlas*, 2000] were compared to the 1992 NLCD and Küchler 1964 PNV datasets, as well as by results from the cross-tabulation of 1992 NLCD and PNV data. We relied on two further assumptions about the predictability of ecosystem responses to disturbance: (1) Forest composition, as mapped with forest type groups and measured in forest inventories from 1953 to 1997, developed through predictable successional processes consistent with 1920 land cover. (2) Trajectories of plant succession remain sufficiently stable within a PNV unit to use 20th century composition and dynamics in estimating the average characteristics of disturbed semi-natural forests in 1850.

2.4.3. Land Cover Classes to Characterize Historical Land Cover

A suite of 36 land cover classes was sufficient to summarize the types of biophysically distinct land surfaces that were important components of historical and modern land cover in the eastern United States (Table 1). Most (22) are represented in the PNV of the eastern United States and were present in the land cover of 1650. Some classes with sparse vegetation and/or low stature (e.g., #31 Open Infertile Grassland; #45 Low Mixed Open Forest) were restricted to unusual soils in 1650, but also represent biophysical properties that became much more common as intensive human land use became more widespread (see section 3.1). Classes representing land cover of agricultural, residential, and urban settings were not used for the 1650 time-slice, as they represented negligible land area at that time. As discussed below (section 3.1), these are associated with types of intensive land use that later came to dominate the land cover of the eastern United States. A set of taller forest classes essential for characterizing the land cover of 1650 became progressively less important in later time periods (Table 1).

2.4.4. Canopy Height (*h*)

For purposes of vegetation mapping, *Küchler* [1955, 1966] established the following forest height classes, defined by the average height of the uppermost canopy surface: low (2-10 m), medium tall (10-25 m), tall (25-35 m), and very tall (greater than 35 m). For physiognomic data provided as ranges, it is simplest to assume a uniform distribution of likely values and to use the mid-range as the characteristic value. Any other assumption is more complicated, requiring additional information or prior knowledge. *Küchler* [1955, 1966] also provided numerical ranges for height categories of herbaceous vegetation and rules for categorizing shrubs and very low trees, as well as numerical ranges for coverage terms such as "continuous" and "rare". When physiognomic summaries [*Küchler,* 1964] listed multiple forest or grassland height classes for a vegetation unit, we developed aggregated characteristic values using the coverage information provided. When the physiognomic summary described multiple distinct layers, for example, "tall grass with scattered groves of low trees", we used structural information about those layers, including distinct height strata and relative cover estimates, in modeling other biophysical properties of the vegetation unit [*R. Knox and L. Steyaert,* manuscript in preparation, 2007].

Average canopy heights for modern forest cover type groups in various Forest Service regions were derived from published forest inventory statistics [*Smith et al.*, 2002], and appropriate allometric equations for tree height, to develop area-weighted averages. We then used that information to estimate characteristic heights of distinct types of forest regeneration and stages of forest regrowth important for the 1850, 1920, and 1992 time-slices (see section 3.1).

2.4.5. Shortwave Broadband Solar Albedo

The total shortwave broadband solar albedo (peak growing season) for most of the land cover classes was updated based on an analysis of the MODIS-derived albedo data summarized by *Gao et al*. [2005] and *Jin et al.* [2003]. The white-sky albedo data summaries of *Gao et al.* [2005; Table 1 and Figure 5] were interpolated to refine the total shortwave broadband albedo values for related groups of land cover classes (Table 2). In some cases (e.g., wetlands), published albedo data from field studies were used. In addition, time-series of observed shortwave broadband albedo (local solar noon) that were measured at selected Surface Radiation Budget Network (SURFRAD) stations plus associated MODIS-derived actual broadband albedos (combined black-sky and white-sky estimates based on the direct and diffuse components from SURFRAD data) as summarized by *Jin et al.* [2003] were used for comparison. We also analyzed multi-year time-series of MODIS-derived albedos (black-sky, white-sky, and combined blue-sky) that were available for subsets within the EOS Validation Core Sites located in our study area. In general, the MODIS-derived broadband surface albedo estimates were towards the low-end of the range of reported field measurements, for example, see tabulated albedo data and field data sources as summarized by *Pielke* [1984]. The Urban/Built-up/Impervious Surface (class #25) was assigned an albedo of 0.15 [*Offerle et al.*, 2003, *Jin et al.*, 2005]. Classes with bare soil exposed beneath plant cover that is sparse, close-cropped, or discontinuous were assigned higher average albedo values (0.2, 0.22). The albedo for Residential/Urban Trees and Grass (class #26) was retained from the corresponding LEAF-2 class.

2.4.6. Emissivity

Longwave (thermal) emissivity estimates varied modestly among different living plant materials: 0.95 for broadleaf canopies, 0.97 for needleleaf canopies, and intermediate values for grasses and mixed forests (Table 2). Larger differences are attributable to non-living surfaces such as water (0.99) and bare ground (0.86). Emissivity parameters for classes with mixed surface types derive from the aggregate effects of those surfaces. A higher fraction of bare soil or impervious surface lowered the emissivity estimate, whereas water exposed at or above the soil surface raised the emissivity parameter.

2.4.7. Leaf Area Index (*LAI*)

The estimated total column leaf area index (LAI), i.e. the average ratio of living leaf area (one-sided convention) to corresponding ground area, for the land cover classes was based on the biome/land cover type summaries of LAI provided by *Scurlock et al.* [2001]. We rounded their averages to the nearest 0.5 and used those for total LAI of semi-natural vegetation, except in cases where unusually low values of LAI are associated with early forest regeneration, mangrove, and some vegetation types confined to poor/shallow soils as discussed by *Barbour and Billings* [1988]. For classes characterized by open canopies resulting from a history of intensive human land use, we reduced the peak LAI to reflect a greater amount of exposed soil (Table 2). LAI values for some classes characterized by intensive human land use were retained from heritage class sets.

2.4.8. Differences in LAI from Dormant to Peak Season (ΔLAI)

We estimated the dynamic component of the peak season LAI from the fraction of the cover in deciduous life forms (12.5%, 50%, and 87.5% for nominally evergreen, mixed, and deciduous forest and shrub types). We multiplied these fractions by the peak LAI and then rounded back to units of 0.5 LAI. For the dormant season LAI of forest understory plants, grasslands, and dependent or epiphytic plants, we adjusted for the fact that these plants tend to be more evergreen where winters are less severe. If a parameter class represented vegetation of warm temperate or subtropical portions of the eastern United States, we reduced the seasonal dynamics of the portion of the leaf area associated with those plant types or layers.

2.4.9. Fractional Vegetation Cover (*VF*)

Estimates of the fractional area covered by vegetation were based on the satellite-derived analysis of *Zeng et al.* [2000]. We used these data conservatively, adjusting up or down from the corresponding IGBP class value when the physiognomic description (e.g., dense, sparse) or historical information emphasized a departure from the most widespread modern condition (Table 2). In using those estimates for historical vegetation as well, we assumed that recurrent disturbances, such as intense fire, landslides, severe winds, patchy feeding by herbivores, and human land use (see section 3.1.2), would have created open disturbed area comparable to un-vegetated area within modern semi-natural vegetation that is distant from urbanized and agricultural lands. Parameter values for classes representing the most intensive land uses were drawn from the literature. Estimates were rounded to the nearest 0.05 unit of fractional cover.

2.4.10. Differences in Fractional Vegetation Cover for the Dormant Season (ΔVF)

We developed parameter values consistent with estimated LAI dynamics for the class and with approaches used in heritage land cover classes for land-atmosphere models (Table 2). Note that dormant season fractional cover values do not drop linearly with changes in LAI. That is both because total cover is a non-linear, saturating function of LAI and because perennial woody plants retain living stems above ground although their leaves may be fully deciduous.

2.4.11. Aerodynamic Surface Roughness Length (z_0) and Zero-Plane Displacement Height (*D*)

Structural aerodynamic parameters were estimated using the approach developed by *Schaudt and Dickinson* [2000]. We developed a spreadsheet model implementing their equations and developed ancillary calculations needed to derive required structural variables from physiognomic properties of vegetation layers and phases characteristic of a vegetation unit or type of land cover [*R. Knox and L. Steyaert,* manuscript in preparation, 2007]. The resulting parameters estimate aerodynamic properties for momentum exchange that are typical of the growing season. This model was used for most land cover classes (#33-59). Values for the remaining classes were estimated from published measurements of structurally analogous land cover (Table 2).

As would be expected, grassland classes present much less aerodynamic roughness than shrub and tree classes. Nonetheless, native tall grasslands and sparsely wooded grasslands (#33, 34, 35, 51) had modeled roughness lengths 2 to 12 times those of crops and cleared grasslands under intensive agricultural use (#28-#32). Among the forest classes, estimated roughness lengths varied from 0.7 m to 3 m. Forests were hardly homogeneous in this property. Differences among classes dominated by the trees with similar leaf shapes and duration/seasonality (e.g., broadleaf deciduous) greatly exceeded those between classes with similar average canopy heights but dominated by trees with contrasting leaf characteristics. Note that estimated roughness lengths for the two tallest physiognomic groups (Medium-Tall/Tall Forest, as well as Tall Forest) were greater than values typically measured in present-day forests of the temperate zone.

2.4.12. Vegetation Rooting Depth (d_r)

We derived the effective depth of vegetation rooting zones from revised estimates for the most closely analogous BATS classes [*Zeng,* 2001]. Rooting zone depths (Table 2) were 2 m for deciduous, mixed forests, native medium-tall grassland, and most wetlands, and were slightly shallower for evergreen needleleaf forests (1.8 m). Effective rooting zones of tall grasslands and the sparsely wooded grasslands typical of more water-stressed environments were somewhat deeper (2.4 m), as were the low mixed open forest class (2.4 m) and shrubland classes, #44 and #53 (2.5 m). Rooting depths for herbaceous plant layers of crops, highland pasture, open bog or marsh classes were 1 m. Other pastures and hayfields were 1.5 m. More extensively modified bare/transitional, residential, and urban classes were assigned rooting depths less than 1 m. These rooting depths varied inversely with the intensity of land use. Modelers should be aware that absolute maximum depths of woody plants can be much deeper [*Canadell et al.*, 1996], and that rooting depths will adapt to the soil moisture and nutrient conditions present [*Stone and Kalicz,* 1991].

2.5. Geospatial Analysis to Derive Biophysical Parameter and Land Cover Data

The land use intensity maps (section 3.1) and biophysical parameter classes (see Tables 1 and 2) were combined to derive biophysical parameter and land cover data at each time-slice (1650, 1850, 1920, and 1992). A land cover change trajectory within each PNV unit was defined by assigning a biophysical land cover class (therefore, associated set of biophysical parameters) for each land-use intensity category of each time-slice. The result is a land cover change trajectory table where the rows are PNV classes, the columns are land use intensity categories, and the elements biophysical land cover classes (see Tables S1, S2, and S3).[1] A particular column (i.e., land use intensity category) within a trajectory table corresponds to a land use intensity map, as well as, a biophysical land cover map (i.e., as defined by the set of biophysical land cover classes within the column) and its associated set of parameter maps.

Within a particular time-slice, the land use intensity maps are expressed as fractional areas that sum to 1.0 at each location.

An average biophysical parameter map for a particular time-slice is derived from the joint set of land use intensity and parameter maps. That is, multiplying values of a biophysical parameter by the corresponding fractional areas, and summing the results at each location, produces a map of weighted averages. This approach was applied to derive biophysical parameter maps by time-slice for albedo, leaf area index, fractional vegetation cover, and canopy height. The average surface roughness value for each pixel was estimated with a weighted average of log-transformed roughness lengths [cf. *Shuttleworth,* 1998]. In addition, a relative deciduousness index was mapped using a ratio of the max-min change in LAI divided by the total LAI, for LAI > 0.0. These results are reported in section 3.2.

Analogously, the land cover trajectory tables and the land use intensity maps were combined in a geospatial analysis to derive a set of data layers for biophysical land cover classes that are expressed as fractional areas for each time-slice. The column of land cover classes for each land use intensity category defines a land cover map, which is converted to a fractional area land cover map using fractional areas in the associated land use intensity map. The fractional areas of each land cover class occurring in each 20-km cell, in a given time-slice, were summed. The result is a set of land cover classes expressed as fractional area layers for each time-slice. The fractional area land cover layers (Table 1) and the biophysical parameters (Table 2) can be ingested into the land surface component of land-atmosphere interactions models.

3. Results and Discussion

3.1. Historical Land Cover Condition: Spatial Patterns and Changes over Time

3.1.1. Overview

The landscape of the eastern United States was transformed from the pre-colonial vegetation of 1650 to present-day land cover by increasing levels of human land use intensity (Table 3, Figures 1-4). As evident from the decreasing percentage of remnant old-growth vegetation, the relatively minimal human disturbance in 1650 had grown to 30% human disturbance by 1850, 93% by 1920, and, except for small isolated patches, effectively 100% by 1992 (Table 3). These land-use intensity categories demonstrate the initial theme of "clearing the forest", with the primary drivers of land use change being agricultural expansion, commercial logging, and wood-cutting for fuel and other products. They also illustrate subsequent transformations through farmland abandonment, forest regeneration, and increasing urbanization and landscape fragmentation with the growing population [*Williams,* 1989; *Whitney,* 1994]. The old-growth vegetation of 1650 was spatially heterogeneous as illustrated by the examples of variable physiognomic characteristics in Figure 1. By 1850, although 70% of the landscape remained relatively undisturbed by humans (Figure 2a), intensive land uses representing 50-100% fractional areas were common in many parts of the country (Figure 2b-d). The 1920 time-slice was characterized by intensive land use categories (Table 3) that represented the approaching end of the saw timber logging in old-growth "virgin forests" (Figure 3a) and shows the impacts of massive land use transformations that led to regenerating forests (Figure 3b), degraded land

(Figure 3c), and extensive agriculture (Figure 3d-e). The 1992 time-slice represents recent land use patterns (Table 3) that were primarily associated with a regrowing forest (Figure 4a), residual wetlands and contemporary inland water bodies (Figure 4b), shifting agricultural patterns (Figure 4c), and a growing residential-urban component of the landscape (Figure 4d). Additional insights on changes in land use intensity since 1650 are illustrated by the fractional area distribution of potential saturated soils (Figure 6a-d).

3.1.2. The 1650 Landscape

The 1650 landscape of the eastern United States was characterized by spatially heterogeneous vegetation patterns at multiple spatial scales. There was spatial heterogeneity in terms of species composition, age, and structure associated with: 1) regional-scale geologic history, climate, and ecological constraints [*Braun,* 1950]; 2) sub-regional scale vegetation inclusions and mosaics; and 3) the land management activities of Native Americans [*Williams,* 1989; and *Delcourt et al.*, 1993]. The pre-colonial forest was "not a vast, silent, unbroken, impenetrable and dense tangle of trees, nor was it in a state of static equilibrium" [*Williams,* 1989].

The PNV units defined by *Küchler* [1964] encompass regional-scale heterogeneity and structural information of importance to land-atmosphere interactions studies. To illustrate, Figure 1 shows broad physiognomic categories (canopy height and dominant life forms) that are aggregated from PNV units: non-forest vegetation and low trees (< 10 m average canopy height); vegetation "height" mosaics consisting of closed forest (> 10 m canopy height) with extensive inclusions (1-5 km size) of lower vegetation dominated by the same life forms (e.g., tall pine forests and shrubby pine barrens mapped in one vegetation unit); more continuous closed forests (> 10 m average canopy height); and vegetation "type" mosaics where the different phases are of distinct life forms (e.g., grassland-forest mosaics).

Variations in wetlands characteristics, site productivity, and natural disturbance contributed to sub-regional scale heterogeneity that is not fully resolved in the PNV map, yet is directly relevant to the understanding and parameterization of the 1650 landscape. Wetlands complexes with variable hydroperiods (i.e., seasonal onset, duration, water inundation depth, degree of soil saturation, and inter-annual variability) were a dominant component of the land cover within the Atlantic and Gulf coastal plains, Florida, the lower Mississippi River valley, tallgrass prairie ecosystem, and the northern forests [*Dahl,* 1990; *Whitney*, 1994]. In fact, the total area of wetlands in 1650 was probably twice as large as the area of present-day wetlands [*Dahl*, 1990]. Site productivity differences contributed to a wide range in the average size of old-growth trees [*Braun,* 1950], such as found in many accounts of tall, large-diameter trees in the original forest [e.g., see *Whitney*, 1994; *Davis,* 1996], versus the recently-reported small old-growth trees that are located in remote, low productivity sites such as the "Middleburgh" red cedars or chestnut oaks [*Krajick,* 2003]. Severe weather events (e.g., hurricanes, tornados, flooding, and winter storms), drought, fire, pests, and disease affect the forest species composition, age, and canopy structure depending on the spatial scale, severity, and return interval of the disturbance [*Braun,* 1950; *Whitney,* 1994; *Davis,* 1996; *Runkle*, 1996; *Greenberg et al.*, 1997; and *Foster et al.*, 2004]. Large-scale disturbances caused by lightning-ignited fire and blowdowns from hurricanes are common in the northeastern and southeastern forests [*Runkle,* 1996; *Foster et al.*, 2004], while disturbance and gap dynamics are more prevalent in the central mesophytic forests [*Runkle,* 1996; *Greenberg et al.*, 1997]. Frequent disturbance by lightning-ignited fires maintained open southern pine forests, eastern shrublands, tallgrass prairie, and other ecosystems.

The spatial heterogeneity of the 1650 landscape was influenced by the activities of Native Americans prior to 1492 and by the tragic decline of the Native American population as a result of widespread disease and massive epidemics that began in the early 1500s following contact with European explorers [e.g., see reviews by *Williams,* 1989; *Delcourt et al.*, 1993; *Whitney,* 1994; *Allen et al.*, 1996; *Hicks,* 1998; *White et al.*, 1998; *Carroll et al.*, 2002; *Foster et al.*, 2004]. Native Americans lived in villages, cultivated crops and used fire as a tool to manage the landscape throughout much of the eastern United States. The population decline was documented during the 1500s and 1600s in New England [*Whitney,* 1994; *Foster et al.*, 2004] and Mississippi River Valley [*Delcourt et al.*, 1993]. Although there is ample evidence of Native American influence on historical land cover, sources of regional geospatial data are not available for reconstructing the circa 1500 land cover.

We chose 1650 as a time-slice when direct human influences on land cover of the eastern United States probably reached a (recent) minimum. *Allen et al.* [1996] hypothesized that by the early 1800s, the decline in the native population would have led to "50- to 150-year-old, relatively even-aged stands that were presumably perceived as being pristine by the European settlers". *Hicks* [1998] suggested that the central hardwood forests had probably regenerated for 150-250 years by the mid-1700s and early 1800s when naturalists described the forest condition. *Carroll et al.* [2002] suggested that climate and fire including the use of fire by

Native Americans are the two most important factors that "shaped the pre-European flora and fauna" in the Southeast prior to extensive fire suppression.

3.1.3. The 1850 Landscape

The 1850 landscape of the eastern United States was in transition from the pre-colonial vegetation patterns of 1650 to regenerating forests, villages and cities, and farmlands (Table 3, Figure 2a-d). Old-growth/pre-settlement vegetation still characterized approximately 70% of the eastern United States and fractional areas of 50% old-growth vegetation were common at many other locations (Figure 2a).

The forest-village disturbance accounted for approximately 17% of the eastern United States (Table 3). The spatial patterns and fractional areas for this land-use intensity category (Figure 2b) represent recovering or regenerating vegetation in disturbed or cleared forests on non-farmland; farm woodlots with selective logging for fuel, buildings and fences and/or livestock grazing; or a small component consisting of roads, villages, and cities depending on population density. In general, this disturbed vegetation (Figure 2b) corresponds to the 1650 vegetation types, but with altered biophysical parameters (section 3.2). Specifically, forest recovery was underway in New England, New York, and northern Ohio where commercial logging was coming to a close [*Whitney,* 1994]. Elsewhere, groundcover, shrubs, and small trees in farm woodlots were disturbed by livestock grazing. Forest disturbance was widespread near populated areas because of extensive annual wood-cutting to provide fuel for home heating. Sparse vegetation and scrubby oaks characterized parts of central and eastern Pennsylvania, eastern Maryland, the Blue Ridge Mountains in Virginia, and southeastern Ohio because of intensive wood-cutting to support charcoal-fired blast furnaces for iron making [*Williams,* 1989]. Vegetation on floodplains of major rivers was disturbed by fuelwood cutting for steamboats or selective logging utilizing water transport [*Williams,* 1989]. By 1850, white pine was regenerating on abandoned croplands in New England [*Foster et al.*, 2004].

Lowland mixed agriculture (Figure 2c) was diverse, including row crops, grain crops, pasture, and hay. Cotton was primarily grown in the southern Piedmont and Blackbelt regions. Highland agriculture (Figure 2d) was characterized by pasture and hay at locations where climate, topography, and soil were typically not ideal for row and grain crops [*Williams,* 1989; *Whitney*, 1994; *Foster et al.*, 2004].

3.1.4. The 1920 Landscape

By 1920, approximately 90% of the eastern United States had been transformed by intensive land use (Table 3, Figures 3a-f). The landscape was characterized by remnants of old-growth vegetation (7%; Figure 3a), a young regenerating forest (28%; Figure 3b), degraded land (14%; Figure 3c), extensive mixed agriculture (44%; Figure 3d-e), and growing population centers (5%; Figure 3f). The highly disturbed state of the 1920 landscape was the result of intensive commercial logging, extensive mixed agriculture including management of woodlots, and environmental degradation due to soil erosion and farming on marginal lands [e.g., see *Greeley*, 1925; *Shands and Healy,* 1977; *Williams,* 1989; *Whitney,* 1994; and *MacCleery,* 1992].

The remnant old-growth vegetation was mainly located in northern Maine, the Great Lakes states, Florida, and especially in the states of the lower Mississippi River basin where most of the remaining saw-timber quality forests of economic value were located (Figure 3a). The forest composition and structure for these sites generally corresponded to 1650 vegetation.

Disturbed and regenerating forests consisted of second or third growth saw timber, cordwood, young trees, tree root sprouts, disturbed farm woodlots, and regrowth on abandoned croplands (Figure 3b). Across the northern states, young deciduous trees followed intensive logging with the old-growth pines and hemlock trees replaced by cherry and maple trees in Pennsylvania and by aspen and birch trees in the Great Lakes states [*Whitney,* 1994]. The land use intensity is illustrated by the cutting of second and third growth trees for low-quality box and veneer products, and by the abundance of young broadleaf trees because of stump sprouts that were coppiced for firewood [*Whitney,* 1994]. Although the species composition of trees in farm woodlots resembled the original forest, these woodlots had been changed by long-term culling of saw timber, woodcutting for fuel, and extensive grazing by farm livestock especially hogs. By 1920, regenerating deciduous trees were replacing the recently logged white pine stands on abandoned croplands in New England [*Foster et al.*, 2004]. Also by 1920, a lasting ecological change was underway in New England and the Mid-Atlantic states as the chestnut blight had infected more than 80% of the trees and the disease was spreading to the south and west.

Similar patterns existed across the central and southern states. Shortleaf pine and scrub oak followed the clear-cutting of old-growth longleaf and/or slash pine that grew extensively in the coastal plain from Virginia to Texas; the cutover land was characterized as approximately 33%

regenerating saw timber, 33% scrubby cordwood, and the remainder barren [*Williams,* 1989]. Following recent logging, early regeneration was underway in the Appalachians and the hardwood regions of the lower Mississippi River basin. Saw timber baldcypress trees had been extracted from wetlands of Louisiana and Florida. Loblolly pine was regenerating on abandoned cotton or tobacco fields in the Piedmont region and elsewhere [*Williams,* 1989].

Sparse vegetation, scattered shrubs, "scrub" trees and barren land cover characterized 15-20% or more of the landscape across the northern and southern tiers of states (Figure 3c); this degraded land had poor forest regeneration [*Shands and Healy,* 1977; *Williams,* 1989; *Whitney,* 1994]. In the colder north, many cutover lands did not regenerate and remained barren or with open, bushy regrowth [*Williams,* 1989]. Regeneration was also slowed by failed crop farming attempts on unsuitable logged-over lands and by extensive wildfires such as in Maine, the Adirondacks, Pennsylvania, Michigan, Wisconsin, and Minnesota. Approximately 33% of the southern pine land was characterized as barren. Intensive fire, flooding, and soil erosion contributed to not restocking forest land in the Blue Ridge Mountains, southern Appalachians, and Monongahela Mountains. Over-grazing and soil erosion on marginal farmland also led to sparse vegetation and poor regeneration [*Williams,* 1989; *Whitney,* 1994; and *Foster et al.*, 2004].

The components of lowland and highland agriculture on improved farmland reflected intensive land use practices to produce food for home and the market (Figures 3d-e). The upper Midwest was the primary region for production of row and grain crops with secondary production regions in the southeast and the Mississippi River bottomlands (Figure 3d). Pasture grasses and hay were grown in the north and in the highland regions (Figure 3e). Although climate and soil conditions generally determined suitable agricultural crops, diverse farming was widely practiced in a largely rural economy. The online supplemental material (Text S3) provides additional details on agricultural practices for 1920.[1]

3.1.5. The 1992 Landscape

The 1992 land cover was broadly characterized by a regrowing forest, decreasing rates of annual wetlands losses, continuing relocation of agricultural production according to land suitability, and increasing fragmentation of the landscape, due in part to the growth and spread of residential areas, urbanized complexes, and transportation networks, frequently at the expense of forest and agricultural land. The land-use intensity categories for the regrowing forest (43%; Figure 4a), wetlands and inland water bodies (11%; Figure 4b), mixed agriculture and grasslands (42%; Figure 4c), and residential and urban land use (3%; Figure 4d) represented approximately 99% of the eastern United States (Table 3, Figures 4a-d).

Forest regrowth was widespread and fractional areas > 70% were common within the Appalachian Mountains and parts of the lower Mississippi River basin (Figure 4a). Overall, the "rebirth" of the eastern forest represents a remarkable land cover transformation given the low expectations of many experts in the early 1920s for the regeneration of saw timber-quality forest or the potential recovery of degraded landscapes [*Clawson,* 1979; *Williams,* 1989; *MacCleery,* 1992; *Whitney,* 1994; and *Smith et al.*, 2002]. In referring to the recovery of the U.S. National Forests in the eastern United States, *Shands and Healy* [1977] suggested that many conservationists and foresters of the early 1900s would be surprised at the recovery of these "lands that nobody wanted". Eastern timberland was dominated by hardwood tree cover types with 80% coverage in the northern region and more than 50% coverage in the southern region [*Smith et al.*, 2002]. Both natural and planted pine silivculture are major sources of landscape dynamics in the south [*Allen et al.*, 1996; *Alig and Butler,* 2004]. Pine plantations in the south accounted for approximately 14% of the forest area; timber management represented a major source of human disturbance [*Alig and Butler,* 2004]. In contrast, the forest was also becoming more fragmented, while residential-urban development resulted in a slight net loss of forest land along the eastern seaboard [*Riitters et al.*, 2002].

The remaining wetlands were predominately located in the lower Mississippi River valley, Florida, Gulf and Atlantic coasts, and the northern parts of the Great Lakes states as indicated in Figure 4b, which also depicts the larger inland water bodies.

Primary agricultural production was in the Upper Midwest and the lower Mississippi River valley (fractional areas of 70-90%), while secondary mixed farmland regions such as the southeastern coastal plain represented fractional areas on the order of 20-40% (Figure 4c). Pastureland as a fraction of total farmland was typically 20% or less, but increased to 40% or more on the less suitable farmland within the Piedmont and Appalachian states, and up to 60-80% of total farmland in pasture throughout most of Florida and to the west of the lower Mississippi River valley [*U.S. Department of Commerce,* 1993]. The online supplemental material (Text S3) provides additional details on agricultural practices in 1992.[1]

The residential and urban land use was geographically variable with the highest land use intensities associated with large cities and dense population centers, such as within the Boston to Washington, D.C. corridor (Figure 4d). Regional contributions at the state-level varied from 1-2% for states with low population densities to 17-20% in the Northeast. Rural population densities within the eastern United States had increased from about 25 persons/km^2 in 1920 to 100 persons/km^2 and frequently more than 700 persons/km^2 by 1990, as the total population of the conterminous United States increased from approximately 105.3 million persons in 1920 to 243.7 million persons in 1990 [*Waisanen and Bliss*, 2002]. Recent studies have estimated the total developed area within the conterminous United States for the 1990s time-frame in the range of 1-2% [*Imhoff et al.*,1998; *Vogelmann et al.*, 2001; and *Elvidge et al.,* 2004].

Land use suitability was perhaps the dominant controlling factor that determined the 1992 patterns of agricultural production, wetlands, and the regrowing forest in the eastern United States. If the artificial drainage of wetlands for agriculture is considered, the Suitability of Relief and Soil for Crops Map (Figure 5) from *Hart* [1968] and *Barnes and Marschner* [1958] represents a first-order land use suitability analysis to help understand how the recent patterns have evolved over the past century. Figure 5 incorporates regional climate, topography, and soil as determinants of Generalized Land Resource Areas with emphasis on the favorability of land for crops [*Barnes and Marschner,* 1958]. Historically, the "poorly drained" land suitability category was often viewed as a candidate for artificial drainage to permit improved agricultural crop farming. In fact, significant portions of the "very favorable" land suitability category within the Upper Midwest (Figure 5) included pre-settlement wet prairie wetlands that were artificially drained during the late 1800s or early 1900s [*Whitney,* 1994; *Dahl*, 1990].

Artificial drainage was also used to convert "poorly drained" wetlands to agricultural cropland in the lower Mississippi River valley, Florida, and the southeastern coastal areas. These are also the areas where irrigated agriculture in 1992 was most common. Therefore, Figure 5 helps to explain the agricultural patterns of 1920 (Figures 3 d-e) and their transformation to 1992 patterns, including intensive, highly mechanized row and grain crop production areas (Figure 4c). The intensive and secondary agricultural production areas in 1992 (Figure 4c) generally correspond to the very favorable and medium favorable cropland suitability categories. The less favorable crop suitability categories were associated with low economic returns and abandoned farmland that reverted to forest or land that was placed in conservation reserve programs [*Hart,* 1968; *USDA,* 2000]. According to Figures 4a and 5, the 1992 forest was generally associated with the less suitable land categories for crops throughout the eastern United States.

3.1.6. Major Land Cover Changes Since 1650

Land cover changes since 1650 have significantly modified the properties of the land surface, therefore affecting land-atmosphere interactions involving the water, energy, and carbon cycles. Land use activities have: fundamentally altered vegetation regions; modified the forest species composition and structure; reduced the area of potential saturated soils during the early growing season; shifted patterns of C3/C4 vegetation; and modified land surface properties through fragmentation of the landscape and the construction of impervious surfaces.

For example, the tallgrass prairie region of 1650 has been almost entirely converted [*Whitney,* 1994] to row and grain crop agriculture or to intensively grazed pasture dominated by nonnative plants. Only sparse remnants of longleaf and slash pine-dominated communities remain in the Southeast [*Williams,* 1989, *Ware et al.*, 1993; *Frost,* 1993; and *Early,* 2004]. Land use changes have contracted the distribution of several less extensive types including: Pocosin, Elm-ash forest, Everglades, and fire-dependent pine-barrens (formerly typical of sand plains and sand ridges in glaciated regions and across the Atlantic coastal plain). Because of intensive land uses or modified disturbance regimes (e.g., fire, flooding), the basic dynamics and structure of recovering ecosystems often diverge from characteristic properties of the former land cover.

Logging practices, fire suppression, changed patterns of wild fire, farmland abandonment (after soil modification by cultivation), livestock grazing, deer browsing, insect outbreaks, and novel diseases represent some of the many factors that have contributed to changes in the forest composition and structure since 1650 [*Williams,* 1989; *Whitney,* 1994; *Greenberg et al.*, 1997]. Following logging, aspen, birch and other deciduous trees have generally replaced the extensive old-growth pine forests in the Great Lakes states [*Whitney,* 1994; *Cole et al.*, 1998]. Browsing by large deer populations has affected the forest understory and regeneration [*Whitney,* 1994]. By the late 20th century, introduced insects and pathogens frequently killed canopy fir, hemlock, oak, and white pine trees; most of the large American elms are gone and nearly all native chestnuts and chinquapins have met a similar fate. These factors contributed to persistent changes in vegetation physiognomy.

Artificial land drainage resulted in major differences between the 1650 and 1992 spatial patterns of potential saturated soils for the eastern United States (Figure 6). In 1650, potential saturated soils during the early summer growing season ("normal" or typical preseason precipitation) were widespread throughout the Atlantic and Gulf coastal areas, lower Mississippi River valley, prairie grasslands, and across the northern forest states (Figure 6a). Because artificial drainage was not yet pervasive, the patterns of potential saturated soils for 1650 and 1850 are quite similar (Figures 6a and 6b). By 1920, the widespread introduction of artificial drainage systems had led to major reductions within the Midwestern corn-belt states with more modest changes elsewhere (Figure 6c). The 1992 map of potential saturated soils contrasts sharply with the maps for earlier time-slices (Figure 6d).

The results from our analysis of potential saturated soils for the 1650 time-slice are consistent with the estimated area of total wetlands for the conterminous United States as reported by *Dahl* [1990] and *NRC* [1995]. For example, *Dahl* [1990] provided state-by-state estimates of the wetlands area in the 1780s and 1980s for the conterminous United States. Based on the state-by-state estimates of *Dahl* [1990] for the 31 states entirely in our study area, wetlands have been reduced from approximately 20% of the land area during the 1780s to 8% of the land area by the 1980s. By 1992, irrigated cropland had increased to 1.4% of this same area as estimated from [*Vesterby and Krupa*, 1997]. Information on the spatial distribution, timing, and quantity of crop irrigation may be important to some modeling studies particularly those focused on Florida or the lower Mississippi River valley.

Conversion of natural vegetation to agricultural crops and pasture/hay grasses (section 3.1) has changed the distribution of vegetation having C3 versus C4 photosynthetic pathways. The C3 grasses/crops tend to be more active at cool temperatures, less active at high temperatures, use water less efficiently, and be less tolerant of drought than C4 grasses/crops [see the species tabulation and review of *Waller and Lewis,* 1979]. In general, agricultural production has introduced extensive C3 (cool season) vegetation into the eastern United States including C3 crops (e.g., wheat, soybeans, barley, oats, rye, rice, cotton, and peanuts) and C3 pasture/hay (e.g., alfalfa, orchard grass, fescue, perennial ryegrass, and Kentucky bluegrass). In contrast, the major C4 crop is corn (maize) with contributions from sorghum and sugarcane. The conversion of the C4 (warm season) dominated grasslands of the tallgrass prairie has led to large near-homogeneous blocks of corn and soybeans, while corn also has replaced forest trees (C3). Both warm and cool season turf grasses are grown and irrigated in residential areas [*Milesi et al.*, 2005].

3.2. Biophysical Parameter Maps

3.2.1. Changes in Broadband Solar Albedo

The significant changes in patterns of peak-season land surface albedo among the 1650, 1850, 1920, and 1992 time-slices (Figure 7a-d) relate to patterns of change in land use intensity (section 3.1). The typical albedo for the 1650 pre-settlement vegetation ranged from 0.09-0.10 in evergreen needleleaf forests of the northern Great Lakes states, higher mountains, and coastal Maine, to 0.14-0.15 for the central deciduous broadleaf forest region, wooded grasslands and grassland prairies. Higher values (≥ 0.2) were restricted to barrier islands and some Florida sand ridges.

The albedo pattern for 1850 (Figure 7b) is analogous to patterns in the 1850 land use intensity maps (Figure 2a-d). Relative to 1650, the average albedo for 1850 increased by about 0.02 in disturbed and regenerating forests, with comparable or larger albedo increases where forests were converted to mixed agriculture.

In 1920 (Figure 7c), the difference in albedo from 1650 was quite dramatic throughout most of the eastern United States, with average albedo typically between 0.16 and 0.19. Contrasted with 1850, the effects of recent deforestation, land degradation, and intensive agricultural production are quite evident across the southern tier of states from the Carolinas to the states in the lower Mississippi River basin. The relatively high peak-season albedo values are associated with the highly disturbed landscape of 1920 (see section 3.1.4.).

By 1992 (Figure 7d), return to lower albedo (0.12-0.15) across much of the region was caused by forest regrowth and the return of closed forest cover on former agricultural lands, especially across the southern states. Across the corn (maize) and soybean belt of the Midwest, average albedo remained elevated (0.18); average albedo values characteristic of intensive agriculture became common in the lower Mississippi valley.

The widespread decreases in average albedo from 1920 to 1992 have clear implications for direct radiative forcing and land-atmosphere interactions across the eastern United States.

3.2.2. Changes in Average Leaf Area Index (*LAI*)

Relatively high peak-season leaf areas (3.6 to 5.5 times the ground area) were typical of all four time-slices (Figure 8a-d), as expected for vegetated land in a humid temperate climate. Forest dominated landscapes had LAI between 4.6 and 5.5. Native grasslands and many landscapes dominated by agriculture had average LAI between 3.1 and 4.5. These average values were common in the northeastern states by 1850 (Figure 8b) and in 1920 were typical across the eastern United States, except in portions of the South, in northern peatlands, and Maine (Figure 8c). The LAI map for 1992 (Figure 8d) displays local features attributable to urban centers and inland water bodies. It also shows larger areas of reduced average LAI associated with intensive agriculture in former tall grasslands, formerly forested areas of Indiana and Ohio, and formerly flood-prone bottomlands of the lower Mississippi River valley.

3.2.3. Changes in the Relative Deciduousness of Leaf Area

An index of relative deciduousness (average ΔLAI divided by the average LAI for LAI > 0.0) indicated an increase in the average fractional cover of seasonally deciduous life forms after 1650 (Figure 9a-d). In 1650, evergreen and mixed evergreen-deciduous forests and shrublands dominated the region of the Great Lakes states, northern New England, New York, and the Southeast (Figure 9a). A belt of cold-deciduous forest extended from southern New England to the west and then southwest to the prairie grasslands at the western edge of our study area. Predominantly deciduous forest (broadleaf and needleleaf) dominated southern river floodplains and swamp forests. Winter loss of 70% to 80% of peak season LAI was also characteristic of wooded grasslands of south Florida, of prairie-forest transition areas, and of the Blackbelt. Note that this deciduousness index describes the aggregate dynamics of all layers of green vegetation, not just the upper canopy or the economically important species. Hence these maps may appear somewhat different from maps derived by classification of named biomes (e.g., needleleaf evergreen forests) or from characteristics of trees making up a plurality of the stocking in Forest Type Groups [see definitions in *Smith et al.*, 2002].

In most of the eastern United States, average deciduousness tended to increase with increasing population and agricultural development. The map for 1850 (Figure 9b) shows pervasive changes along the Atlantic coast, east of the Appalachian Mountains, and in the Ohio River drainage and the region of the lower Great Lakes. Along with the effects of continued westward expansion of widespread agriculture, the 1920 map (Figure 9c) reflects the harvest of nearly all economically valuable old-growth forests. In response to initial cutting, deciduous trees capable of regenerating from cut stumps or residual roots became dominant in many northern conifer forests. Southern long-leaf pine woodlands, once very extensive, were semi-deciduous with their frequently burned understories of grasses, perennial herbs, broadleaf shrubs, and/or small deciduous trees [*Frost,* 1993]. The maps for 1920 (Figure 9c) and 1992 (Figure 9d) indicate an increase in deciduousness along the southeastern coastal plain, consistent with removal of this slow-to-regenerate pine and release of competing deciduous vegetation.

Although forest recovery by 1992 contributed to a reduction in the average deciduousness of green leaf area (Figure 9d) compared with 1920, persistent differences from 1650 remained, not only in agricultural and residential areas, but also in the forests. Evergreen vegetation continued to be less important than in 1650.

3.2.4. Changes in Average Canopy Height (*h*)

Across the eastern United States, there were pervasive changes in the average height of vegetation during the intervals spanned by 1650, 1850, 1920, and 1992 (Figure 10a-d). The pattern in 1650 (Figure 10a) was characterized by extensive areas of tall forest (average 30 m) and medium-tall to tall forest (average 24 m). Even in mountainous regions, shorter forests growing in shallow soils of steep slopes and ridges would be complemented by taller forests of sheltered coves and valleys [*Braun,* 1950]. In contrast, the upper Great Lakes region had large areas of vegetation with heights averaging from 9 to 18 m, as well as forests with average heights greater than 20 m. Wooded grasslands of the prairie-forest transition commonly had groves of low to medium tall trees (< 25 m) in those locations protected from frequent intense fires. Where intense fire was more prevalent, trees became multi-stemmed shrubs, similar in stature to the dominant tall or medium-tall grasses (1-2.5 m). Shorter vegetation was also found in marshes and bogs, on some unusual soil types, and as vegetation fringing the Atlantic and Gulf coasts.

By 1850, short canopies associated with agriculture had become the dominant cover of areas with dense settlement and extensive agriculture (Figure 10b). Forested landscapes with average heights of 24 m or more remained in less accessible highlands, in thinly settled parts of the South, in parts of northern New England and the upper Great Lakes region, and west of the Mississippi River (Figure 10b). Few of these large blocks of tall old-growth forest survived to 1920. Landscapes with average canopy heights greater than 15 m were rare (Figure 10c). In 1920, most landscapes of the eastern United States had average canopy heights less than 10 m.

The interval from 1920 to 1992 saw recovery of forest cover, with limited recovery of forest stature. By 1953 timberland area had expanded to near current levels, most of this land had adequate tree populations, and the "non-stocked" portion steadily declined from 1953 to 1997 [*Smith et al.*, 2002]. By 1992, average canopy heights of at least 7 m were typical in most of the eastern United States (Figure 10d). Yet, we identified no extensive areas with average heights greater than 18 m in 1992 (Figure 10d). Areas supporting large-scale agriculture were characterized by average heights of 3 m or less. In contrast with the resilience of leaf area index, average canopy stature had not recovered.

3.2.5. Changes in Aerodynamic Surface Roughness Length (z_0)

The spatial patterns and changes in surface roughness and zero-plane displacement (not shown) broadly paralleled the patterns and changes in vegetation canopy height, which along with canopy density and morphology, determines aerodynamic roughness properties governing momentum exchange.

To provide insight into likely consequences for land-atmosphere energy exchanges, we mapped average roughness lengths on log scales (Figure 11a-d). In 1650, tall and medium-tall to tall forests over most of the eastern United States had roughness lengths of at least 170 cm. Shorter roughness lengths appear in the Great Lakes region, along the prairie-forest transition, along coastal fringes, and sporadically in the interior (Figure 11a). Roughness of 30 cm or less was found in grassland or tall marsh vegetation. Some open bogs and coastal marshes averaged less than 12 cm.

By 1850, densely settled regions had average aerodynamic properties more characteristic of grassland or wooded grassland than of forest (Figure 11b). By 1920, vast areas with characteristic roughness lengths of 5-10 cm appeared (Figure 11c), extending from the former tallgrass prairies to the east across Ohio and even, sporadically, through the mid-Atlantic region. Average roughness greater than 150 cm became rare and roughness greater than 90 cm was uncommon (Figure 11c).

Extensive areas of low-roughness land cover remained in 1992, both in regions where large-scale agriculture was the dominant land use and also scattered through the rest of the eastern United States (Figure 11d). Roughness length reveals the fragmented character of forest vegetation at this time. Landscapes with characteristic roughness lengths of 100 to 150 cm were mixed with areas that retained non-forest aerodynamic properties. A few large contiguous blocks with roughness typical of medium-tall closed forests emerged, for example, in the Allegheny highlands of West Virginia and eastern Kentucky (Figure 11d). These patterns in roughness at 10-km spatial scales are consistent with distributions of forest fragmentation at finer scales [see *Riitters et al.*, 2002]. The least fragmented forests at finer scales were in the same areas as our contiguous blocks having characteristic roughness lengths greater than 90 cm. In 1992, much of the eastern United States exhibited the discontinuous texture once typical of the prairie-forest transition (e.g., southwest of Lake Michigan in 1650 or 1850). The potential influence on weather patterns from changes in fragmentation of land cover deserves further exploration [for example, see *de Goncalves et al.*, 2004].

3.3. Implications for Land-atmosphere Interactions

Our reconstructed land cover and biophysical parameter dataset for the eastern United States at a nominal 20-km grid scale presents new opportunities for coupled land-atmosphere interactions modeling experiments. A consistent set of biophysical land cover classes characterizes the massive land use transformations across the 1650, 1850, 1920, and 1992 time-slices. This new dataset can be viewed as a set of land cover fractional areas (Table 1)—with an associated biophysical parameter table (Table 2), where each time-slice is represented with a subset of the land cover classes that are weighted according to the fractional areas in the corresponding land-use intensity categories (Figures 1-4). We have also developed a potential saturated soils data layer (peak growing season for normal preseason precipitation) for each time-slice (Figure 6) as a basis to prescribe soil moisture boundary conditions in land-atmosphere interactions sensitivity tests. In contrast with the parameter-by-parameter averages discussed above (section 3.2), the final biophysical land cover data layers preserve the combination of parameter values characteristic of each distinct surface type. These layers will support modeling experiments either using sub-grid mosaics [e.g., *Koster and Suarez,* 1992] or formal parameter scaling with the fractional abundances [e.g., *Shuttleworth,* 1998]. Therefore, the combined effects of dramatic historical changes in albedo (e.g., widespread decreases from 1920 to 1992), land surface roughness, rooting depths, and potentially saturated soils can be quantified and the feedbacks understood.

Some of the potential implications for land-atmosphere interactions modeling studies include:

1) The land cover condition analysis and land use intensity maps (Section 3.1; Figures 1-4, 6) quantify the magnitude of historical land use transformations, establish the foundation for the reconstructed historical land cover data, and provide information for land surface parameterization in coupled land-atmosphere interactions modeling experiments that are designed to quantify the effects of historical land cover and land use change over the past 350 years.

2) The biophysical parameter maps (Figures 7-11) quantify significant changes across the 1650, 1850, 1920, and 1992 time-slices due to these large land cover transformations. The differences reflect the progressive alteration of the 1650 vegetation to the intensive land use conditions of 1920 and the transformation to 1992 land use patterns (Section 3.1). In addition to agricultural and residential-urban land use, the biophysical characteristics of the 1992 land cover reflect large changes in the structure and composition of forests.

3) Sensitivity tests with coupled land-atmosphere interactions models are needed to investigate the complex interrelationships and consequences of the historical land cover and biophysical parameter changes on the land surface energy, radiation, surface hydrology, and carbon budgets; on fluxes and exchanges between the land surface and the lower atmosphere; on atmospheric boundary layer processes; on convective precipitation patterns; and landscape forcing of mesoscale- to synoptic-scale wind circulations [cf. *Copeland et al.*, 1996; *Bonan,* 1999; and *Roy et al.*, 2003].

4) The potential saturated soils data layers for the 1650, 1850, 1920, and 1992 time-slices (Figure 6) provide the basis for a new generation of land-atmosphere interactions sensitivity tests to investigate the effects of soil moisture availability on land processes, regional weather and climate variability, interactions with historical changes in biophysical parameters, and

precipitation feedbacks. In addition, such sensitivity experiments can also investigate the effects of artificial inland water bodies (reservoirs, lakes, and ponds) which were extracted from the 1992 NLCD as a separate data layer.

5) These land cover and biophysical parameter data for the 1650, 1850, 1920, and 1992 time-slices represent an opportunity to refine carbon budget models for the eastern United States, as related to the role of land use change in carbon dynamics and using a variety of approaches [e.g., *Houghton et al.*, 1999; *Hurtt et al.*, 2002; or *Eastman et al.*, 2001]. These data may also support research on coupled carbon, climate, and land use dynamics.

4. Concluding Remarks

This reconstructed 20-km land cover and biophysical parameter dataset for the eastern United States will support studies of coupled land-atmosphere interactions to investigate the consequences of historical land cover change on the water, energy, and carbon budgets; surface hydrology; regional weather and climate variability; and ecosystem dynamics. Reconstructed land use intensity maps, including potential saturated soils, characterize the spatial patterns of historical land cover condition and changes in time for the 1650, 1850, 1920, and 1992 time-slices. Mutually consistent land cover and biophysical parameter classes were combined with the results of the land use intensity analysis to map historical biophysical land cover and parameters in each time-slice. The effects of historical land cover change are evident in the time-series maps of average biophysical parameters for land surface broadband solar albedo, leaf area index, an index of deciduousness, canopy height, and surface roughness. These historical land cover and land use changes potentially affect land-atmosphere interactions, altering the water, energy, and carbon cycles.

The eastern-half of the Unites States has experienced extensive land cover transformations over the past 350 years. Land use change has fundamentally altered the land cover of entire vegetation regions (e.g., wetland forests in the lower Great Lakes region and lower Mississippi River floodplain, tallgrass prairie, and southeastern pine savannas and open woodlands). Forest management practices, pests, and disease have modified forest composition and structure. Wetlands have been converted by intensive agriculture, plantation forestry, flood control, navigable waterway development, and urban development. Few areas of the eastern United States have escaped considerable alteration by human land management. (Even these have been exposed to increases in the average partial pressure of atmospheric CO_2, enhanced nitrogen deposition, and changing distributions of anthropogenic aerosols, as well as numerous human-introduced pests, pathogens, and invasive exotic competitors.) Although semi-natural vegetation re-established on many former cut-over or agricultural lands during the 20th century, it typically persists in landscapes fragmented by transportation corridors, residential-urban development, agriculture, industrial forestry, and other intensive land uses. Recent land cover provides an insufficient basis for understanding the functional responses and feedbacks of historical land cover. Modeling experiments and sensitivity tests incorporating coupled land-atmosphere interactions are needed to understand and quantify the feedbacks, inter-regional connections, and integrated consequences of these land cover and land use changes.

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References

Alig, R.J. and B.J. Butler (2004), Area Changes for Forest Cover Types in the United States, 1952 to 1997, with Projections to 2050, *General Technical Report PNW-GTR-613*, 106 pp., United States Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Allen, A.W., Y.K. Bernal, and R.J. Moulton (1996), Pine Plantations and Wildlife in the Southeastern United States: An Assessment of Impacts and Opportunities, *Information and Technology Report 3*, 23 pp., National Biological Service, U.S. Department of Interior, Washington, D.C.

Baker, O.E. (1922), A graphic summary of American agriculture based largely on the census of 1920, *USDA Yearbook 1921*, pp. 407-506, U.S. Department of Agriculture, Bureau of Agricultural Economics, Government Printing Office, Washington, D.C.

Barbour, M.G., and W.D. Billings (Eds.) (1988), *North American Terrestrial Vegetation*, 434 pp., Cambridge University Press, Cambridge.

Barnes, C.P., and F.J. Marschner (1958), Our wealth of land resources, Land, *Yearbook of Agriculture 1958*, pp. 10-18, U.S. Department of Agriculture, Washington, D.C.

Bonan, G.B. (1997), Effects of land use on the climate of the United States, *Clim. Change*, *37*, 449-486.

Bonan, G.B. (1999), Frost followed the plow: impacts of deforestation on the climate of the United States, *Ecol. Appl.*, 9, 1305-1315.

Bounoua, L., G.J. Collatz, S.O. Los, P.J. Sellers, D.A. Dazlich, C.J. Tucker, and D.A Randall (2000), Sensitivity of Climate to Changes in NDVI, *J. Clim.*, *13*, 2277-2292.

Braun, E.L. (1950), *Deciduous Forests of Eastern North America*, 596 pp., Blakiston Co., Philadelphia.

Bronstert, A., J. Carrera, P. Kabat, and S. Lutkemeier (Eds.) (2005), *Coupled Models for the Hydrological Cycle: Integrating Atmosphere, Biosphere, and Pedosphere*, 345 pp., Springer, Berlin.

Canadell, J., R.B. Jackson, J.R. Ehleringer, H.A. Mooney, O.E. Sala, and E.D. Schulze (1996), Maximum rooting depth of vegetation types at the global scale, *Oecologia*, *108*, 583-595.

Carroll, W.D., P.R. Kapeluck, R.A. Harper, and D.H. Van Lear (2002), Chapter 24: Background Paper: Historical Overview of the Southern Forest Landscape and Associated Resources, in *Southern Forest Resource Assessment, Gen. Tech. Rep. SRS-53*, edited by D.N.

Wear and J.G. Greis, pp. 583-606, U.S. Department of Agriculture, Forest Service, Southern Research Station Asheville, NC.

Chen, F., R.A. Pielke Sr., and K. Mitchell (2001), Development and application of land-surface models for mesoscale atmospheric models: problems and promises, in *Land Surface Hydrology, Meteorology and Climate: Observations and Modeling*, edited by V. Lakshmi, J. Albertson, and J. Schaake, pp. 107-135, Water Science and Applications, Vol. 3, AGU, Washington D.C.

Clawson, M. (1979), Forests in the long sweep of American history, *Science*, *204*, 1168-1174.

Cole, K.L, M.B. Davis, F. Stearns, G. Guntenspergen, and K. Walker (1998), Historical landcover changes in the Great Lakes region. Chapter 6, in *Perspectives on the Land-use History of North America: A Context for Understanding Our Changing Environment*, edited by T.D. Sisk, 104 pp., U.S. Geological Survey, Biological Resources Division, Biological Science Report USGS/BRD/BSR 1998-0003 (Revised September 1999).

Committee on Earth Science (1990), Our Changing Planet: A U.S. Strategy for Global Change Research, A Report by the Committee on Earth Sciences, 38 pp., Washington, D.C.

Copeland, J.H., R.A. Pielke, and T.G.F. Kittel (1996), Potential climatic impacts of vegetation change: A regional modeling study, *J. Geophys. Res.*, *101*, 7409-7418.

Dahl, T.E. (1990), Wetlands Losses in the United States 1780's to 1980's, U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C. (available online at Northern Prairie Wildlife Research Center, version 16 July 1997, http://www.npwrc.usgs.gov/resource/wetlands/wetloss/wetloss.htm).

Davis, M.B. (Ed.) (1996), *Eastern Old Growth Forests, Prospects for Rediscovery and Recovery*, 383 pp., Island Press, Washington, D.C.

de Goncalves, L.G.G., E.J. Burke, W.J. Shuttleworth, C.S. Chan, and J.A. Marengo (2004), Application of improved ecosystem aerodynamics in regional weather forecasts, *Ecol. Appl.*, *14*, S17-S21.

Delcourt, P.A., H.R. Delcourt, D.F. Morse, and P.A. Morse (1993), History, evolution, and organization of vegetation and human culture, in *Biodiversity of the Southeastern United States: Lowland Terrestrial Communities*, edited by W.H. Martin, S.G. Boyce, and A.C. Echternacht, pp. 47-79, Wiley and Sons, NY.

Dickinson, R.E. (1983), Land surface processes and climate, surface albedos and energy balance, in *Advances in Geophysics*, *25*, pp. 305-353, Academic Press, New York.

Dickinson, R.E., A. Henderson-Sellers, P.J. Kennedy, and M.F. Wilson (1986), Biosphere-Atmosphere Transfer Scheme (BATS) for the NCAR Community Climate Model, *NCAR Technical Note NCAR/TN-275+STR*, 69 pp., NCAR, Boulder, CO.

Early, L.S. (2004), L*ooking for Longleaf, The fall and rise of an American Forest*, 322 pp., The University of North Carolina Press, Chapel Hill, NC.

Eastman, J .L., M.B. Coughenour, and R.A. Pielke Sr. (2001), The regional effects of CO2 and landscape change using a coupled plant and meteorological model, *Global Change Biol.*, *7*, 797-815.

Elvidge, C.D., C. Milesi, J.B. Dietz, B.J. Tuttle, P.C. Sutton, R. Nemani, and J.E. Vogelmann (2004), U.S. constructed area approaches the size of Ohio, *Eos Trans. AGU, 85(233).*

Fennessy, M.J., and J. Shukla (1999), Impact of initial soil wetness on seasonal atmospheric prediction, *J. Clim.*, *12*, 3167-3180.

Findell, K.L., and E.A.B. Eltahir (1997), An analysis of the soil moisture-rainfall feedback, based on direct observations from Illinois, *Water Resour. Res., 33*, 725-735.

Foley, J.A. and Coauthors (2005), Global consequences of land use, review, *Science*, *309*, 570-573.

Foster, D.R. and J.F. O'Keefe (2000), *New England Forests Through Time, Insights from the Harvard Forest Dioramas*, 67 pp., Harvard University Press, Cambridge, MA.

Foster, D., G. Motzkin, J. O'Keefe, E. Boose, D. Orwig, J. Fuller, and B. Hall (2004), The environmental and human history of New England, in *Forests in Time, The Environmental Consequences of 1,000 years of Change in New England*, edited by D.R. Foster and J.D. Aber, pp. 43-100, Yale University Press, New Haven.

Frost, C.C. (1993), Four centuries of changing landscape patterns in the longleaf pine ecosystem, in *The Longleaf Pine Ecosystem: Ecology, Restoration and Management*, edited by S. Herman, Proceedings 18th Tall Timbers Fire Ecology Conference, pp. 17-43, Tall Timbers Research, Inc., Tallahassee, Florida.

Gao, F., C.B. Schaaf, A.H. Strahler, A. Roesch, W. Lucht, and R. Dickinson (2005), MODIS bidirectional reflectance distribution function and albedo Climate Modeling Grid products and the variability of albedo for major global vegetation types, *J. Geophys. Res.*, *110(D1)*, D01104, doi:10.1029/2004JD005190.

Goodchild, M. F., B.O. Parks, and L.T. Steyaert (Eds.) (1993), *Environmental Modeling with GIS*, 488 pp., Oxford University Press, Oxford.

Greeley, W.B. (1925), The relation of geography to timber supply, *Econ. Geogr.*, *1*, 1-14.

Greenberg, C.H., D.E. McLeod, and D.L. Loftis (1997), An Old-Growth Definition for Western and Mixed Mesophytic Forests, *General Technical Report SRS-16*, 14 pp., Southern Research Station, U.S. Department of Agriculture, Forest Service, Asheville, NC.

Gutman, G., A.C. Janetos, C.O. Justice, E.F. Moran, J.F. Mustard, R.R. Rindfuss, D. Skole, B.L. Turner II, and M.A. Cochrane (Eds.) (2004), *Land Change Science: Observing, Monitoring and Understanding Trajectories of Change on the Earth's Surface*, 459 pp., Kluwer Academic Publishers, Dordrecht.

Hart, J.F. (1968), Loss and abandonment of cleared farm land in the eastern United States, *Ann. Assoc. Am. Geographers*, *58*, 417-440.

Henderson-Sellers, A. and A.J. Pitman (1992), Land-surface schemes for future climate models: specification, aggregation, and heterogeneity, *J. Geophys. Res.*, *97(D3)*, 2687-2696.

Hicks Jr., R.R. (1998), *Ecology and Management of Central Hardwood Forests*, 412 pp., John Wiley and Sons, New York.

Houghton, R., J.L. Hackler, and K.T. Lawrence (1999), The U.S. carbon budget: contributions from land use change, *Science*, *285*, 574-578.

Hurtt, G. C., S.W. Pacala, P.R. Moorcroft, J.P. Casperson, E. Shevliakova, R.A. Houghton, and B.I. Moore (2002), Projecting the future of the U.S. carbon sink, *Proc. Natl. Acad. Sci. USA*, *99*, 1389-1394.

Imhoff, M.L., W.T. Lawrence, D. Stutzer, and C. Elvidge (1998), Assessing the impact of urban sprawl on soil resources in the United States using nighttime "city lights" satellite images and digital soils maps, in *Perspectives on the Land-use History of North America: A Context for Understanding Our Changing Environment*, edited by T.D. Sisk, 104 pp., U.S. Geological Survey, Biological Resources Division, Biological Science Report USGS/BRD/BSR 1998-0003 (Revised September 1999).

International Geosphere-Biosphere Programme (1993), Relating Land Use and Global Land-Cover Change, A Proposal for an IGBP-HDP Core Project, *International Geosphere-Biosphere Programme Report No. 24*, 65 pp., IGBP, Stockholm.

Jin, Y., C.B. Schaaf, C.E. Woodcock, F. Gao, X. Li, A.H. Strahler, W. Lucht, and S. Liang (2003), Consistency of MODIS surface bidirectional reflectance distribution function and albedo retrievals: 2 validation, *J. Geophys. Res.*, *108* (*D5*). 4159, doi:10.1029/2002JD002804.

Jin, M., R.E. Dickinson, and D.L. Zhang (2005), The Footprint of urban areas on global climate as characterized by MODIS, *J. Clim.*, *18*, 1551-1565.

Kalnay, E., and M. Cai (2003), Impact of urbanization and land-use change on climate, *Nature*, *423*, 528-531.

Koster, R.D., and M.J. Suarez (1992), Modeling the land surface boundary in climate models as a composite of independent vegetation stands, *J. Geophys, Res.*, *97*(D3), 2697-2715.

Krajick, K. (2003), Methuselahs in our midst, Ecology, News Focus, *Science, 302*, 768-769.

Küchler, A.W. (1955), A comprehensive method of mapping vegetation, *Ann. Assoc. Am. Geographers*, Vol. *XLV*, No. *4*, 404-415.

Küchler, A. W. (1964), *Manual to Accompany the Map Potential Natural Vegetation of the Conterminous United States (with separate map at scale 1:3,168,000)*, *Special Publication 36*, 154 pp., American Geographical Society, Princeton Polychrome Press, Princeton, NJ.

Küchler, A. W. (1966), Analyzing the physiognomy and structure of vegetation, *Ann. Assoc. Am. Geographers*, *56*, No. *1*, 112-127.

Küchler, A.W. (1967), *Vegetation Mapping*, 472 pp., The Ronald Press Company, New York.

Lee, T. (1992), The impact of vegetation on the atmospheric boundary layer and convective storms, Ph.D. dissertation, 137 pp., Department of Atmospheric Science, Colorado State University, Fort Collins, CO.

Loveland, T.R., B.C. Reed, J.F. Brown, D.O. Ohlen, Z. Zhu, L. Yang, and J.W. Merchant (2000), Development of a global land cover characteristics database and IGBP DISCover from 1-km AVHRR data, *Int. J. Remote Sens.*, *21*, 1303-1330.

Maizel, M., R.D. White, S. Gage, L. Osborne, R. Root, S. Stitt, and G. Muehlbach (1998), Historical interrelationships between population settlement and farmland in the conterminous United States, 1790 and 1992, Chapter 2, in *Perspectives on the Land Use History of North America: A Context for Understanding Our Changing Environment*, edited by T. D. Sisk, 104 pp., U.S. Geological Survey, Biological Resources Division, Biological Sciences Report USGS/BRD/BSR-1998-0003 (Revised September, 1999).

MacCleery, D.W. (1992), American Forests, A History of Resiliency and Recovery, *FS_540*, 58 pp., USDA Forest Service, (revised edition 2002, Forest History Society, Durham, NC).

Marshall, C.H., R.A. Pielke Sr., L.T. Steyaert, and D.A. Willard (2004), The impact of anthropogenic land-cover change on the Florida Peninsula sea breezes and warm season sensible weather, *Mon. Wea. Rev., 132*, 28-52.

Martin, W.H., S.G. Boyce, and A.C. Echternacht (1993), *Biodiversity of the Southeastern United States, Lowland Terrestrial Communities*, 502 pp., John Wiley and Sons, New York.

Meyer, W.B., and B.L. Turner (Eds.) (1994), *Changes in Land Use and Land Cover: A Global Perspective*, 537 pp., Cambridge University Press, Great Britain.

Milesi, C., S.W. Running, C.D. Elvidge, J.B. Dietz, B.T. Tuttle, and R.R. Nemani (2005), Mapping and modeling the biogeochemical cycling of turf grasses in the United States, *Environ. Manag.*, *36*, 426-438.

Narisma, G.T., and A.J. Pitman (2003), The impact of 200 years of land cover change on the Australian near-surface climate, *J. Hydrometeorol.*, *4*, 424-436.

National Research Council (1990), Research Strategies for the U.S. Global Change Research Program, Committee on Global Change, 291 pp., National Academy Press, Washington, D.C.

National Research Council (1995), Wetlands Characteristics and Boundaries, 307 pp., National Academy Press, Washington, D.C.

National Research Council (2001), Grand Challenges in Environmental Sciences, 96 pp., National Academy Press, Washington, D.C.

National Research Council (2005), Radiative Forcing Of Climate Change: Expanding the Concept and Addressing Uncertainties, Committee on Radiative Forcing Effects on Climate Change, Climate Research Committee, Board on Atmospheric Sciences and Climate, Division on Earth and Life Studies, 207 pp., National Academies Press, Washington, D.C.

Offerle, B., C.S.B. Grimmond, and T.R. Oke (2003), Parameterization of net all-wave radiation for urban areas, *J. Appl. Meteorol.*, *42*, 1157-1173.

Pielke, R.A. (1984), *Mesoscale Meteorological Modeling*, 599 pp., Academic Press, New York.

Pielke, R. A., Sr. (2001), Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall, *Rev. Geophys.*, *39*, 151-177.

Pielke, R.A., and R. Avissar (1990), Influence of landscape structure on local and regional climate, *Landsc. Ecol.*, *4,* 133-155.

Pielke, R. A., T.J. Lee, J.H. Copeland, J.L. Eastman, C.L. Ziegler, and C.A. Finley (1997), Use of USGS-provided data to improve weather and climate simulations, *Ecol. Appl.*, *7*, 3-21.

Ramankutty, N., and J.A. Foley (1999a), Estimating historical changes in land cover: North American croplands from 1850 to 1992, *Global Ecol. Biogeogr.*, *8*, 381-396.

Ramankutty, N., and J.A. Foley (1999b), Estimating historical changes in global land cover: Croplands from 1700 to 1992, *Global Biogeochem. Cycles*, *13*, 997-1027.

Riitters, K. H., J.D. Wickham, R.V. O'Neill, K.B. Jones, E.R. Smith, J.W. Coulston, T.J. Wade, and J.H. Smith (2002), Fragmentation of continental United States forests, *Ecosystems*, *5*, 815–822.

Roy, S.B., G.C. Hurrt, C.P. Weaver, and S.W. Pacala (2003), The impact of historical land cover change on the July climate of the United States, *J. Geophys. Res.*, *108(D24)*, 4793, doi:10.1029/2003JD003565.

Runkle, J.R. (1996), Central mesophytic forests, in *Eastern Old Growth Forests, Prospects for Rediscovery and Recovery*, edited by M.B. Davis, pp.161-177, Island Press, Washington, D.C.

Schantz, H.L., and R. Zon (1924), Natural Vegetation, in *USDA Atlas of American Agriculture. Pt. 1: The Physical Basis of Agriculture, Sec. E* , Sup. of Docs., U.S. Government Printing Office, Washington, D.C.

Schaudt, K.J., and R.E. Dickinson (2000), An approach to deriving roughness length and zero-plane displacement height from satellite data, prototyped with BOREAS data, *Agric. For. Meteorol.*, *104*, 143-155.

Scurlock, J.M.O., G.P. Asner, and S.T. Gower (2001), Worldwide Historical Estimates of Leaf Area Index, 1932-2000, *ORNL/TM-2001/268*, 23 pp., Oak Ridge National Laboratory, Oak Ridge, TN.

Sellers, P.J., Y. Mintz, Y.C. Sud, and A. Dalcher (1986), A simple biosphere model (SiB) for use within general-circulation models, *J. Atmos. Sci.*, *43*, 505-531.

Sellers, P.J., R.E. Dickinson, D.A. Randall, A.K. Betts, F.G. Hall, J.A. Berry, G.J. Collatz, A.S. Denning, H.A. Mooney, C.A. Nobre, N. Sato, C.B. Field, and A. Henderson-Sellers (1997), Modeling the exchanges of energy, water, and carbon between continents and the atmosphere, *Science*, *275*:5299, 502-509.

Shands, W.E., and R.G. Healy (1977), *The Lands Nobody Wanted*, 267 pp., The Conservation Foundation, pp. 267, Washington, D.C.

Shuttleworth, W.J. (1998), Combining remotely sensed data using aggregation algorithms, *Hydrol. Earth Syst. Sci.*, *2*(*2-3*), 149-158.

Smith, W.B., J.S. Vissage, D.R. Darr, and R.M. Sheffield (2002), Forest Resources of the United States, 1997, *Gen. Tech. Rep. NC222*, 127 pp., Forest Service, U.S. Department of Agriculture, St. Paul, MN.

Steyaert, L.T., and R.A. Pielke Sr. (2002), Using Landsat-derived land cover, reconstructed vegetation, and atmospheric mesoscale modeling in environmental and global change research, paper presented at 53rd International Astronautical Congress, World Space Congress, 12 pp., Houston, Texas, 10-19 October.

Stone, E.L., and P.J. Kalicz (1991), On the maximum extent of tree roots, *For. Ecol. Manag.*, *46*, 59-102.

Thompson, R. S., S.L. Shafer, K.H. Anderson, L.E. Strickland, R.T. Pelltier, P.J. Bartlein, and M.W. Kerwin (2005), Topographic, bioclimatic, and vegetation characteristics of three ecoregion classification systems in North America: comparisons along continent-wide transects, *Environ. Manag.*, *34*, Suppl. 1, S125-S148.

U.S. Climate Change Science Program (2003), Strategic Plan for the U.S. Climate Change Science Program, A Report by the Climate Change Science Program and the Subcommittee on Global Change Research, 202 pp., Climate Change Science Program, Washington, D.C.

U.S. Department of Agriculture (1925*), USDA Yearbook of Agriculture 1924*, 1005 pp., Government Printing Office, Washington, D.C.

U.S. Department of Agriculture (1975), Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys, *U.S. Dep. Agric. Handbook 436*, 754 pp., Soil Survey Staff, Soil Conservation Service, U.S. Government Printing Office, Washington, D.C Washington, D.C.

U.S. Department of Agriculture (1994a), State soil geographic (STATSGO) data base: data use information, *Miscellaneous Publication Number 1492*, Soil Conservation Service.

U.S. Department of Agriculture (1994b), State soil geographic (STATSGO) data base national collection, digital maps and associated attribute tables (CD-ROM media), Natural Resources Conservation Service.

U.S. Department of Agriculture (1999), Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys, 2nd Edition, U.S. Dep. Agric. Handbook 436, 871 pp. and fold out color map, Natural Resources Conservation Service, U.S. Government Printing Office, Washington, D.C.

U.S. Department of Agriculture (2000), Summary Report 1997 National Resources Inventory (revised December 2000), 94 pp., National Resources Conservation Service and Iowa State University Statistical Laboratory, Washington, D.C.

U.S. Department of Commerce (USDOC) (1993), 1992 Census of Agriculture, v. 1, Geographic Area Series, part 51, United States, Summary and State Data, Economics and Statistics Administration, Bureau of the Census, AC92-A-51. Washington, D.C.

U.S. National Atlas (2000), Forest Cover Types, Map: 1:7,500,000, *Compiled by the USDA Forest Service*, U.S. Department of Interior and U.S. Geological Survey, U.S. Department of Agriculture, U.S. Forest Service, Reston, VA.

Vesterby, M., and K.S. Krupa (2001), Major Uses of the Land in the United States, 1997, *Statistical Bulletin No. 973*, 47 pp., United States Department of Agriculture, Economic Research Service, Washington, D.C.

Vogelmann, J. E., S.M. Howard, L.M. Yang, C.R. Larson , B.K. Wylie, and N. Van Driel (2001), Completion of the 1990s national land cover dataset for the conterminous United States from Landsat Thematic Mapper data and ancillary data sources, *Photogramm. Eng. Remote Sens.*, *67*, 650-662.

Waisanen, P.J., and N.B. Bliss (2002), Changes in population and agriculture land in conterminous United States counties, 1790 to 1997, *Global Biogeochem. Cycles, 16(4),* 1137, doi:10.1029/2001GB001843.

Walko, R.L., L.E. Band, J. Baron, T.G.F. Kittel, R. Lammers, T.J. Lee, D. Ojima, R.A. Pielke, C. Taylor, C. Tague, C.J. Tremback and P.L. Vidale (2000), Coupled atmosphere-biophysics-hydrology models for environmental modeling, *J. Appl. Meteorol.*, *39*, 931-944.

Waller, S.S., and J.K. Lewis (1979), Occurrence of C3 and C4 photosynthetic pathways in North American grasses, *J. Range Manag.*, *32*, 12-28.

Ware, S., C. Frost, and P.D. Doerr (1993), Southern mixed hardwood forest: the former longleaf pine forest, in *Biodiversity of the Southeastern United States, Lowland Terrestrial Communities*, edited by W.H. Martin, S.G. Boyce, and A.C. Echternacht, pp. 447-493, John Wiley and Sons, New York.

White, P.S., S.P. Wilds, and G.A. Thunhorst and contributing authors (J.M. Alderman, M. Barnett-Lawrence, J. Whitfield Gibbons, T.C. Gibson, D.S. Lee, M.R. Pelton, D. Penrose, and J.D. Williams) (1998), Southeast, in *Part 2-Regional Trends in Biological Resources, Status and Trends of the Nation's Biological Resources*, *2 VOLS,* edited by M.J. Mac, P.A. Opler, C.E. Puckett-Haecker, and P.D. Doran, U.S. Department of Interior, U.S. Geological Survey, Reston, VA.

Whitney, G.G. (1994), *From Coastal Wilderness to Fruited Plain, A History of Environmental Change in Temperate North America from 1500 to the Present*, 451 pp., Cambridge University Press, Cambridge, UK.

Williams, M. (1989), *Americans and Their Forests, A Historical Geography*, 599 pp., Cambridge University Press, New York.

Zeng, X., R.E. Dickinson, A. Walker, M. Shaikh, R.S. DeFries, and J. Qi (2000), Derivation and evaluation of global 1-km fractional vegetation cover data for land modeling, *J. Appl. Meteorol.*, *39*, 836-839.

Zeng, X. (2001), Global vegetation root distribution for land modeling, *J. Hydrometeorol.*, *2*, 525-530.

Zhu, Z., and D.L. Evans (1994), U.S. forest types and predicted percent forest cover from AVHRR data, *Photogramm. Eng. Remote Sens.*, *60*, 525-531.

Table 1. Biophysical Land Cover Classes. Usage by time-slice: (A) abundant, accounting for > 3% of the study area or a least 100,000 km^2; (+) required to depict the range of distinct land cover types important at the time.

Description and/or Vegetation Physiognomy	Class ID	Time-Slice 1650	1850	1920	1992
Urban/Built-up/Impervious Surface	25				+
Residential/Urban Trees and Grass	26			A	+
Bare Ground/Transitional	27				+
Crop/Mixed Farming	29		A	A	A
Highland Pasture/Hay/Some Crops	30		A	A	+
Open Infertile Grassland	31	+	+	+	+
Well-grazed Tall Grass Pasture/Hay	32		+	+	+
Medium-Tall Grass	33	+	+		
Tall Grass/Sparsely Wooded Grassland	34	A	A	+	+
Open Deciduous Broadleaf Wooded Grassland	35	A	A		
Low/Medium-Tall Evergreen Needleleaf Forest	36	+	+	+	+
Medium-Tall Evergreen Needleleaf Forest	37	+	+	+	+
Low/Tall Evergreen Needleleaf Forest	38	+	+	+	+
Low Deciduous Broadleaf Forest Regeneration	39		+		+
Low/Medium-Tall Deciduous Broadleaf Forest	40		A	A	+
Medium-Tall Deciduous Broadleaf Forest	41	+	A	+	A
Medium-Tall/Tall Deciduous Broadleaf Forest	42	A	A	+	
Tall Deciduous Broadleaf Forest	43	A	A	+	
Eastern Mixed Shrubland	44			A	+
Low Mixed Open Forest	45	+	+	+	+
Low Mixed Forest/Early Forest Regeneration	46		+	+	
Low/Medium-Tall Mixed Forest	47		A	A	+
Medium-Tall Mixed Forest	48	+	+	+	A
Medium-Tall/Tall Mixed Forest	49	A	A	+	
Tall Mixed Forest	50	A	A	+	
Marsh with patches of evergreen or deciduous trees	51	+	+	+	+
Low Mixed Trees/Shrubs Bog	52			+	
Low Evergreen Wooded/Shruby Wetland	53	+	+	+	+
Marsh with low deciduous trees	54		+		+
Low/Med.-Tall Evergreen Broadleaf Forested Wetland	55	+	+	+	+
Semi-open, Semi-deciduous Bog	56	+	+	+	+
Medium-Tall Deciduous Swamp Forest	57	+	+	+	A
Medium-Tall/Tall Deciduous Swamp Forest	58	A	A	+	
Open Bog or Marsh	59	+	+	+	+
Lakes, Rivers, Streams and Inland Waters	60	+	+	+	A

Table 2: Parameter Table for Biophysical Land Cover Classes. Symbols: *ID* = numeric identifier for the class; *Albedo* = shortwave broadband land surface albedo; *Emissivity* = land surface emissivity for longwave radiation; *LAI* = vegetation leaf area index (m^2/m^2); *ΔLAI* = difference in LAI between peak and dormant seasons; *VF* = maximum fractional vegetation cover; *ΔVF* = difference in fractional vegetation cover between peak and dormant seasons; z_0 = aerodynamic roughness length (m); *D* = zero-plane displacement height (m); d_r = vegetation rooting zone depth (m); *h* = average height of the tallest vegetation layer (m).

ID	*Albedo*	*Emis-sivity*	*LAI*	*ΔLAI*	*VF*	*ΔVF*	z_0	*D*	d_r	*h*	Summary Description
25	0.15	0.86	0.0	0.0	0.00	0.00	2.00	12.0	0.0	20.0	Urban/Built-up/Impervious Surface
26	0.15	0.90	4.0	3.0	0.70	0.40	0.80	6.3	0.8	10.0	Residential/Urban Trees & Grass
27	0.16	0.86	0.7	0.6	0.07	0.03	0.05	0.2	0.5	0.3	Bare Ground/Transitional
28	0.16	0.95	6.0	5.5	0.80	0.60	0.06	0.7	1.0	1.1	Irrigated Crop
29	0.18	0.95	4.0	3.5	0.85	0.60	0.06	0.7	1.0	1.1	Crop/Mixed Farming
30	0.20	0.96	3.0	2.5	0.70	0.40	0.06	0.3	1.0	0.5	Highland Pasture/Hay/Some Crops
31	0.22	0.96	2.0	1.5	0.70	0.30	0.02	0.2	1.5	0.3	Open Infertile Grassland
32	0.18	0.96	3.0	2.5	0.70	0.30	0.06	0.2	1.5	0.3	Grazed Grass Pasture/Hay
33	0.16	0.96	4.0	3.5	0.70	0.20	0.15	1.0	2.0	1.3	Med.-Tall Grass
34	0.16	0.96	4.0	3.5	0.80	0.30	0.30	1.5	2.4	2.5	Tall Grass/Sparsely Wooded Grassl.
35	0.16	0.96	4.0	3.0	0.85	0.25	0.70	3.0	2.4	9.0	Open Decid. Brdlf. Wooded Grassl.
36	0.09	0.97	5.5	1.0	0.90	0.10	0.80	8.0	1.8	12.0	Low/Med.-Tall Evrgr. Ndlf. Forest
37	0.10	0.97	5.5	1.0	0.90	0.10	1.00	11.0	1.8	15.0	Med.-Tall Evrgr. Ndlf. Forest
38	0.10	0.97	5.5	1.0	0.90	0.10	1.70	11.0	1.8	18.0	Low/Tall Evrgr. Ndlf. Forest
39	0.15	0.95	4.0	3.0	0.85	0.35	0.85	3.0	2.0	6.0	Low Decid. Brdlf. Forest Regen.
40	0.15	0.95	5.0	4.0	0.90	0.40	1.30	8.0	2.0	13.0	Low/Med.-Tall Decid. Brdlf. Forest
41	0.15	0.95	5.0	4.0	0.90	0.40	1.70	11.0	2.0	18.0	Med.-Tall Decid. Brdlf. Forest
42	0.15	0.95	5.0	4.0	0.90	0.40	2.40	15.0	2.0	24.0	Med.-Tall/Tall Decid. Brdlf. Forest
43	0.15	0.95	5.0	4.0	0.90	0.40	3.00	19.0	2.0	30.0	Tall Decid. Brdlf. Forest
44	0.20	0.96	2.0	1.0	0.70	0.20	0.60	1.5	2.5	3.0	Eastern Mixed Shrubland
45	0.20	0.96	2.5	1.0	0.70	0.20	0.60	2.5	2.4	4.0	Low Mixed Open Forest
46	0.13	0.96	4.0	2.0	0.85	0.25	0.70	3.5	2.0	6.0	Low Mix. Forest/Early Forest Regen.
47	0.13	0.96	5.5	2.5	0.90	0.20	1.00	8.0	2.0	12.0	Low/Med.-Tall Mixed Forest
48	0.13	0.96	5.5	2.5	0.90	0.20	1.40	11.0	2.0	16.0	Med.-Tall Mixed Forest
49	0.13	0.96	5.5	2.5	0.90	0.20	2.00	16.0	2.0	24.0	Med.-Tall/Tall Mixed Forest
50	0.13	0.96	5.5	2.5	0.90	0.20	2.40	20.0	2.0	30.0	Tall Mixed Forest
51	0.14	0.98	4.0	3.0	0.85	0.45	0.20	1.5	2.0	2.1	Marsh with patches of trees
52	0.14	0.97	5.0	2.5	0.85	0.20	0.50	2.5	2.0	4.0	Low Mixed Trees/Shrubs Bog
53	0.14	0.97	4.0	1.0	0.85	0.10	1.00	3.0	2.5	6.0	Low Evrgr. Shruby Wetland
54	0.15	0.97	4.0	3.0	0.85	0.35	0.90	3.0	2.0	6.0	Marsh with low Decid. trees
55	0.14	0.96	5.0	1.0	0.85	0.10	0.90	5.0	3.0	9.0	Low/Med.-Tall Evrgr. Brdlf. Wetl.
56	0.15	0.97	5.5	2.5	0.85	0.20	1.20	7.0	2.0	12.0	Semi-open, Semi-decid. Bog
57	0.15	0.95	5.0	4.0	0.90	0.40	1.90	11.0	2.0	18.0	Med.-Tall Decid. Swamp Forest
58	0.15	0.95	5.0	4.0	0.90	0.40	2.30	15.0	2.0	24.0	Med.-Tall/Tall Decid. Swamp Forest
59	0.12	0.98	4.0	3.5	0.80	0.40	0.03	1.0	1.0	1.5	Open Bog or Marsh
60	0.14	0.99	0.0	0.0	0.00	0.00	0.00	0.1	0.0	0.2	Inland Waters

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Table 3. Land-Use Intensity (LUI) Categories, Percent of Study Area, and Descriptive Information for the 1650, 1850, 1920, and 1992 time-slices within the Eastern United States. Categories in each time-slice are ordered according to increasing LUI.

Time-Slice	Land-Use Intensity Category	Area	Description
1650	Old-Growth Vegetation	100%	Pre-settlement 1650 vegetation
1850	Old-Growth Vegetation	70%	Remaining pre-settlement 1650 vegetation
	Forest-Village Disturbance	17%	Regrowing forest, farm woodlots, villages, cities
	Highland Agriculture	3%	Highland agriculture limited by soils and climate
	Lowland Agriculture	10%	Mixed agriculture in lowland areas
1920	Remnant Old-Growth	7%	Remnant veg./old-growth saw timber
	Young Regrowing Forest	28%	Regrowing saw timber and cordwood forests
	Non-Forest Vegetation	3%	Semi-natural vegetation on non-farm lands
	Degraded Land	14%	Not restocking logged forest/abandoned farmland
	Highland Agriculture	5%	Highland agriculture limited by soils and climate
	Lowland Agriculture	39%	Mixed agriculture in lowland areas
	Residential and Urban	5%	Estimated non-farm residential and urban area
1992	Regrowing Forest	43%	Regenerating/regrowing forests (mix of stages)
	Woody Wetlands	6%	Wetlands with forest or shrub cover
	Emergent-Herbaceous Wetlands	2%	Wetlands with non-woody/herbaceous cover
	Shrubs	0%	Semi-natural shrub cover
	Grasslands	3%	Semi-natural grass/herbaceous cover
	Inland Water Bodies	3%	Excludes Great Lakes
	Transitional	1%	Disturbed land due to clearing, logging, etc.
	Mixed Agriculture	39%	Row, grain, pasture, hay, and other crops
	Residential and Urban	3%	Residential, urban, built-up, impervious surfaces

Figure captions

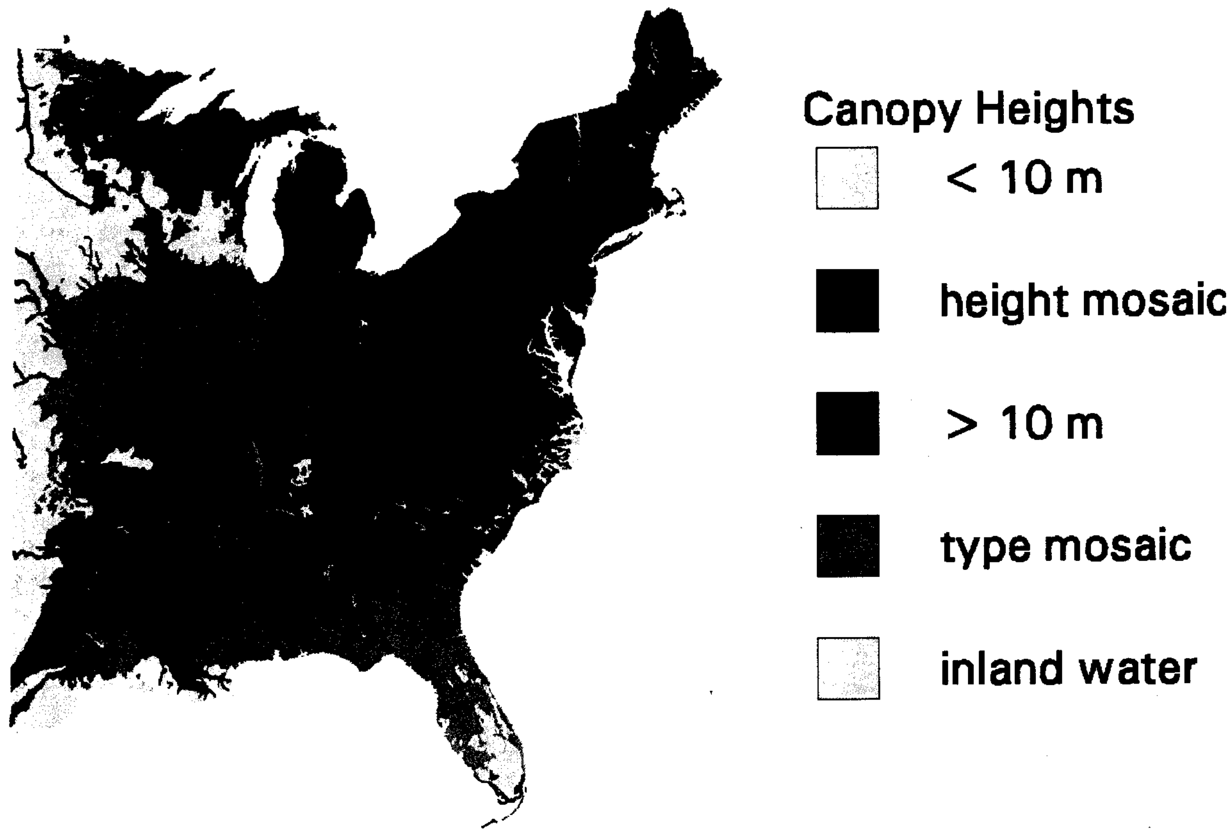
Figure 1. Major physiognomic variability and spatial heterogeneity in reconstructed land cover for 1650. Although most of the eastern United States was dominated by closed forests having average canopy heights greater than 10 m, shorter non-forest vegetation and low trees of less than 10 m canopy height dominated to the west and along much of the coast. Landscapes consisting of mosaics of tall forests mixed with patches of much shorter trees of the same life form (height mosaics) were regionally important. The southeastern coastal plain and prairie-forest transition zone were characterized by mosaics of grassland or wooded grassland and closed forest (type mosaics).

Figure 2. Reconstructed 10-km land use intensity maps for 1850 expressed as fractional areas (%) within the eastern United States including (a) Old-Growth Vegetation, (b) Forest-Village Disturbance, (c) Lowland Agriculture, and (d) Highland Agriculture. High fractional area values near 80-100% for old-growth vegetation imply minimal human disturbance, while the degree of human-induced land cover change corresponds to the sum of fractional area values in panels b-d.

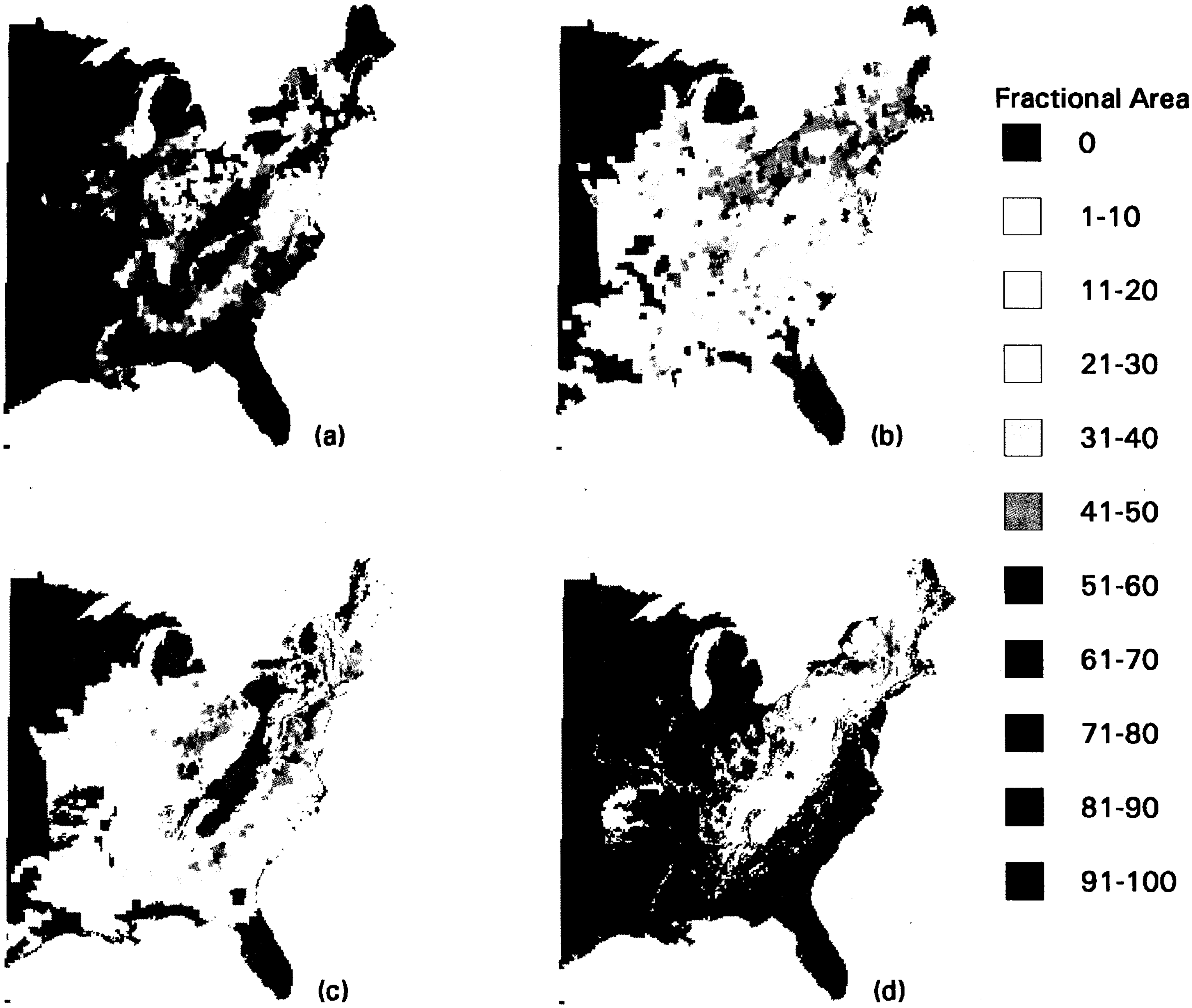
Figure 3. Reconstructed 10-km land use intensity maps for 1920 expressed as fractional areas (%) within the eastern United States including (a) Remnant Old-Growth, (b) Young Regrowing Forest , (c) Degraded Land, (d) Lowland Agriculture, (e) Highland Agriculture, and (f) Residential and Urban. Large fractional area values for agriculture, young regrowing forest, and degraded land illustrate the combined effects of intensive land use.

Figure 11. Patterns of aerodynamic surface roughness length (cm), as 10-km characteristic values displayed using a logarithmic color scale. Maps for (a) 1650, (b) 1850, (c) 1920, and (d) 1992 time slices. Characteristic roughness lengths track changes and patterns of land use, including settlement patterns in 1850 and the fragmented distribution of recovering forests of 1992.

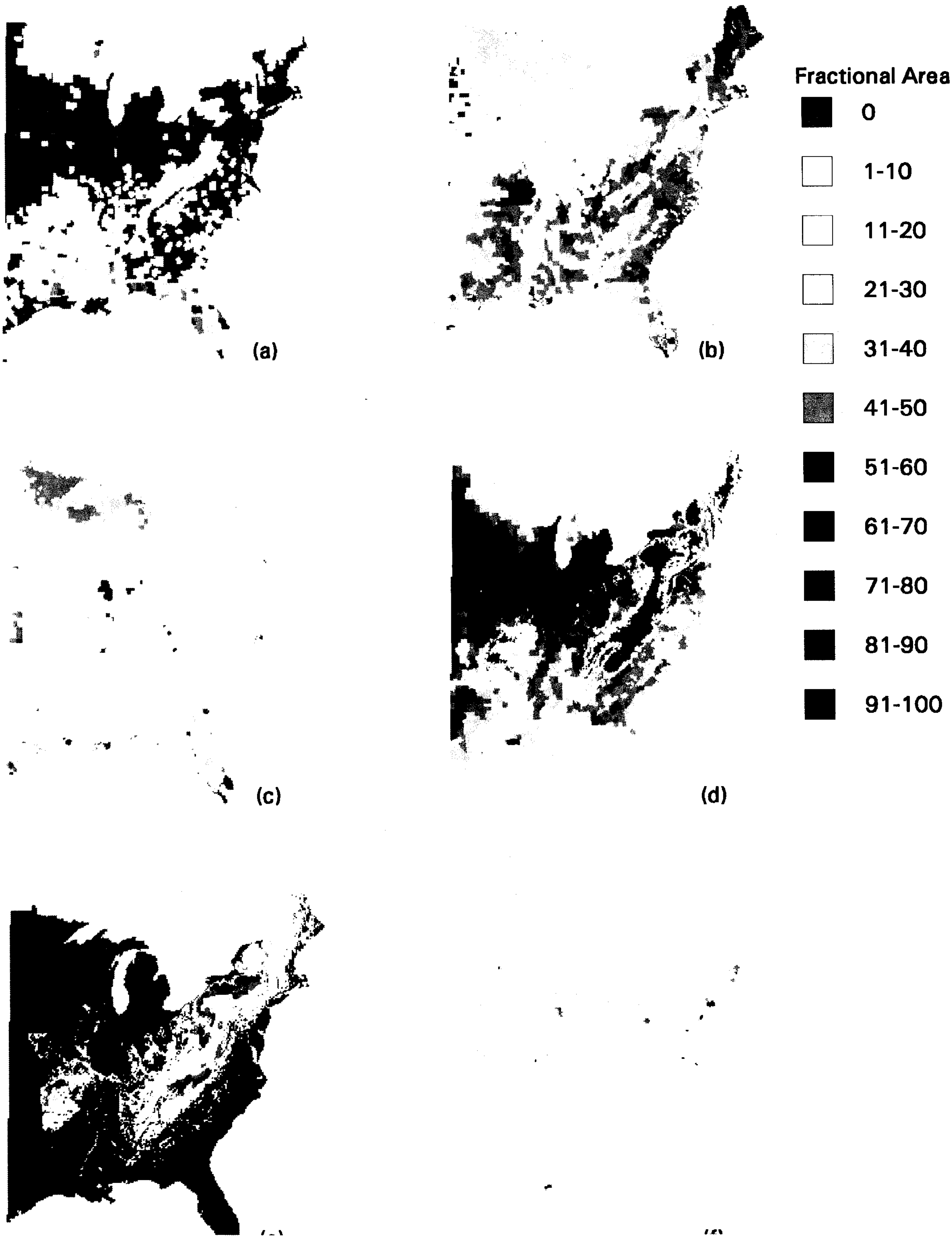
Variable PNV Physiognomy



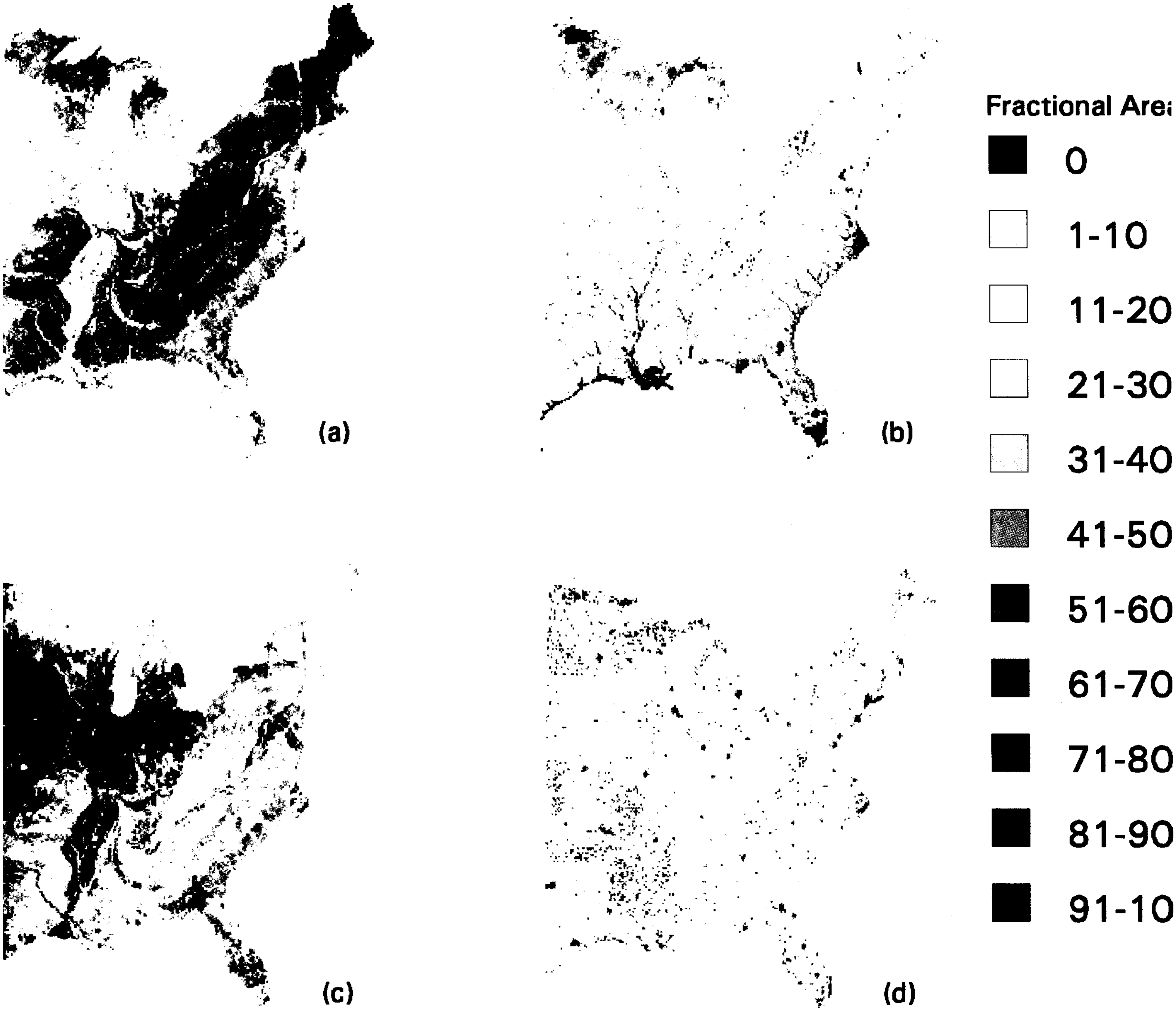
Land Use Intensity: 1850

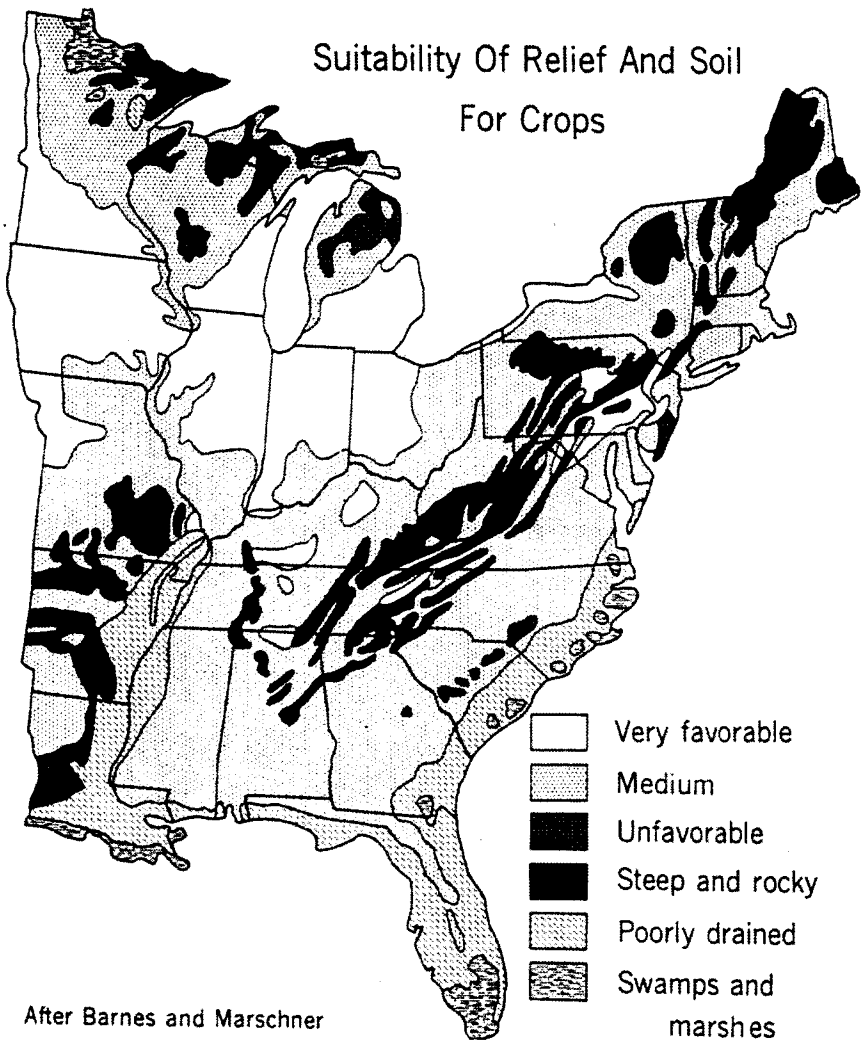


Land Use Intensity: 1920



Land Use Intensity: 1992

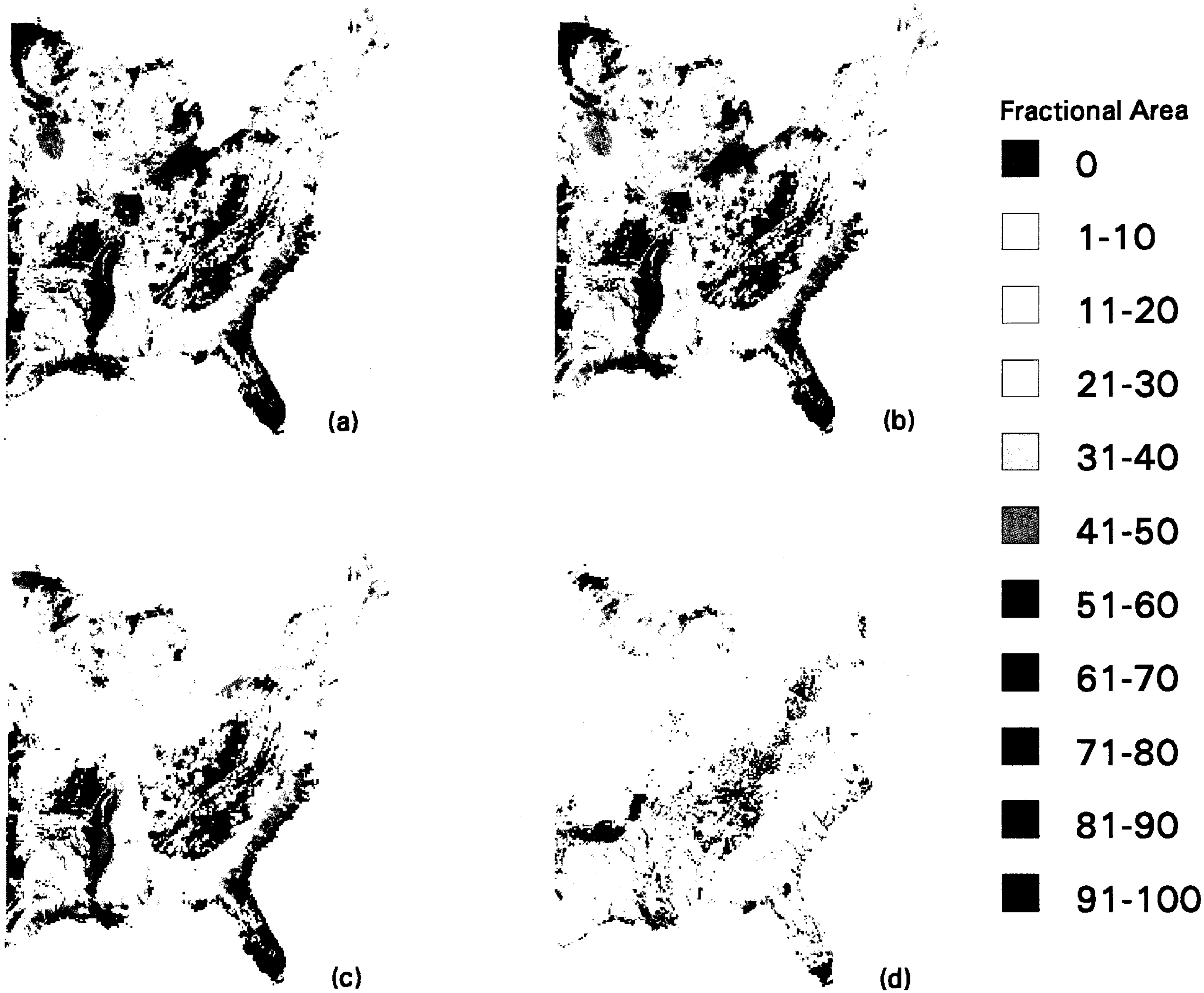




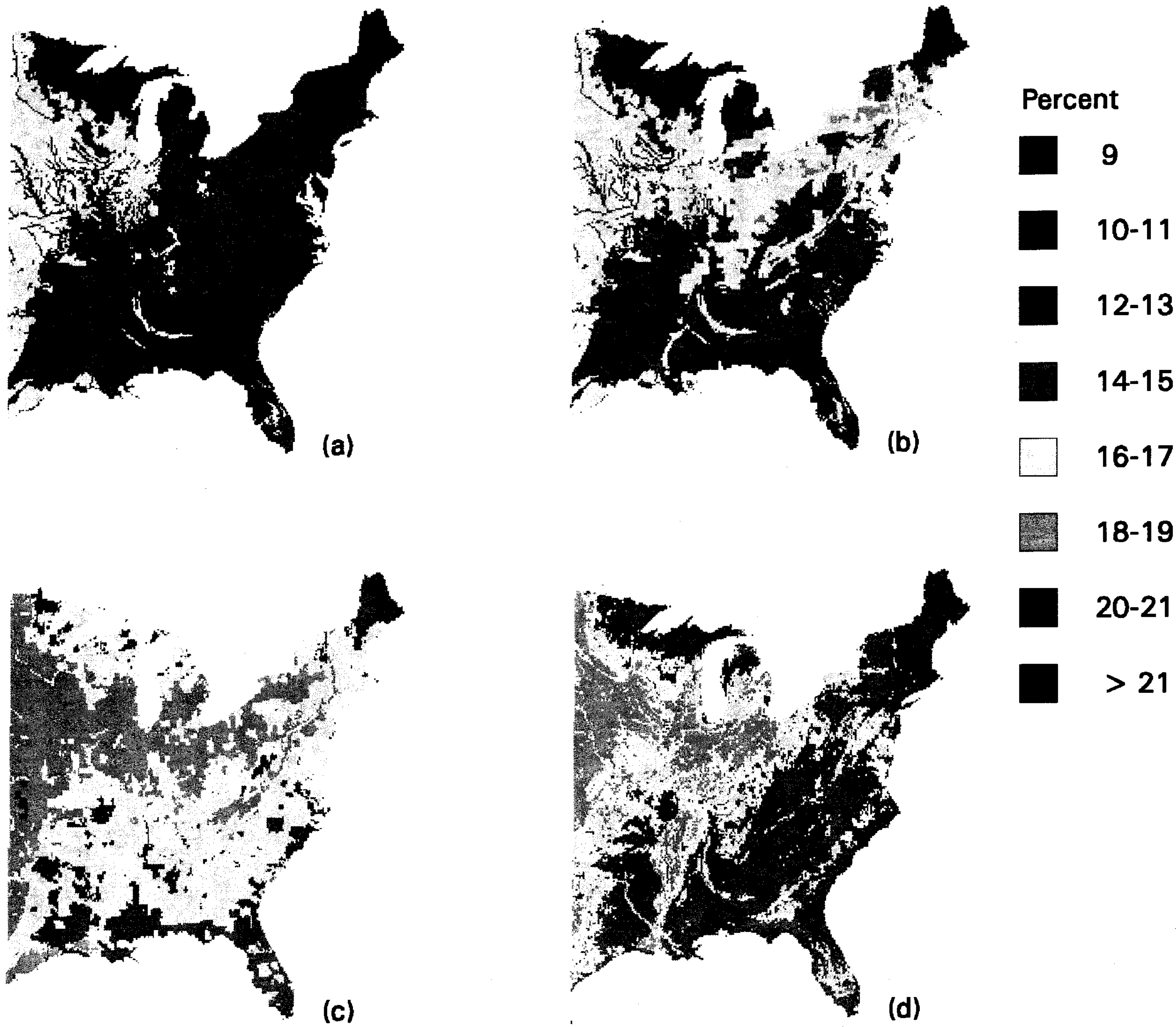
After Barnes and Marschner

Potential Saturated Soils: 1650, 1850, 1920, 1992

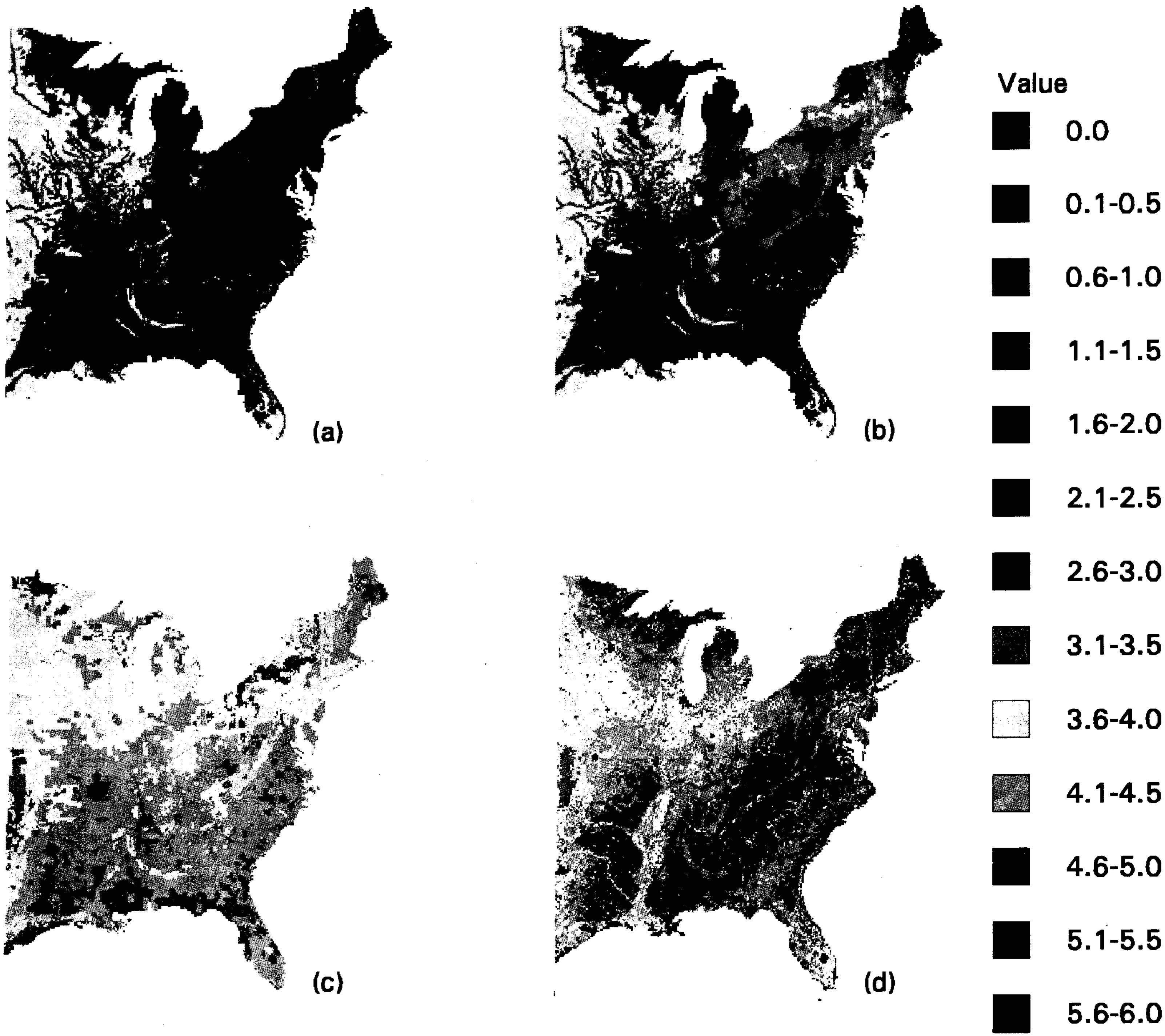
Early Summer: June



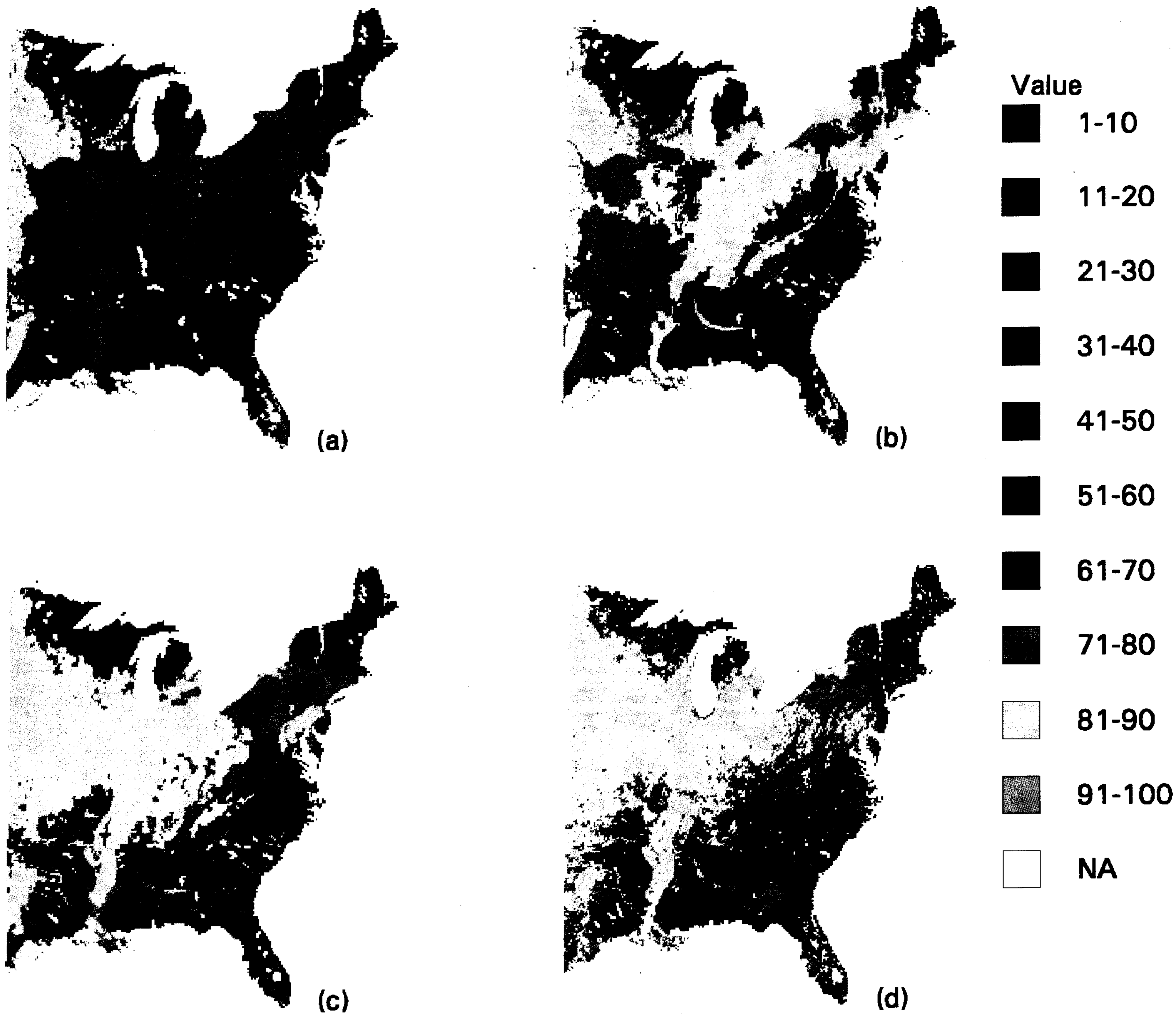
Albedo: 1650, 1850, 1920, 1992



Leaf Area Index: 1650, 1850, 1920, 1992



Deciduousness Index: 1650, 1850, 1920, 1992



Canopy Height: 1650, 1850, 1920, 1992

Surface Roughness: 1650, 1850, 1920, 1992