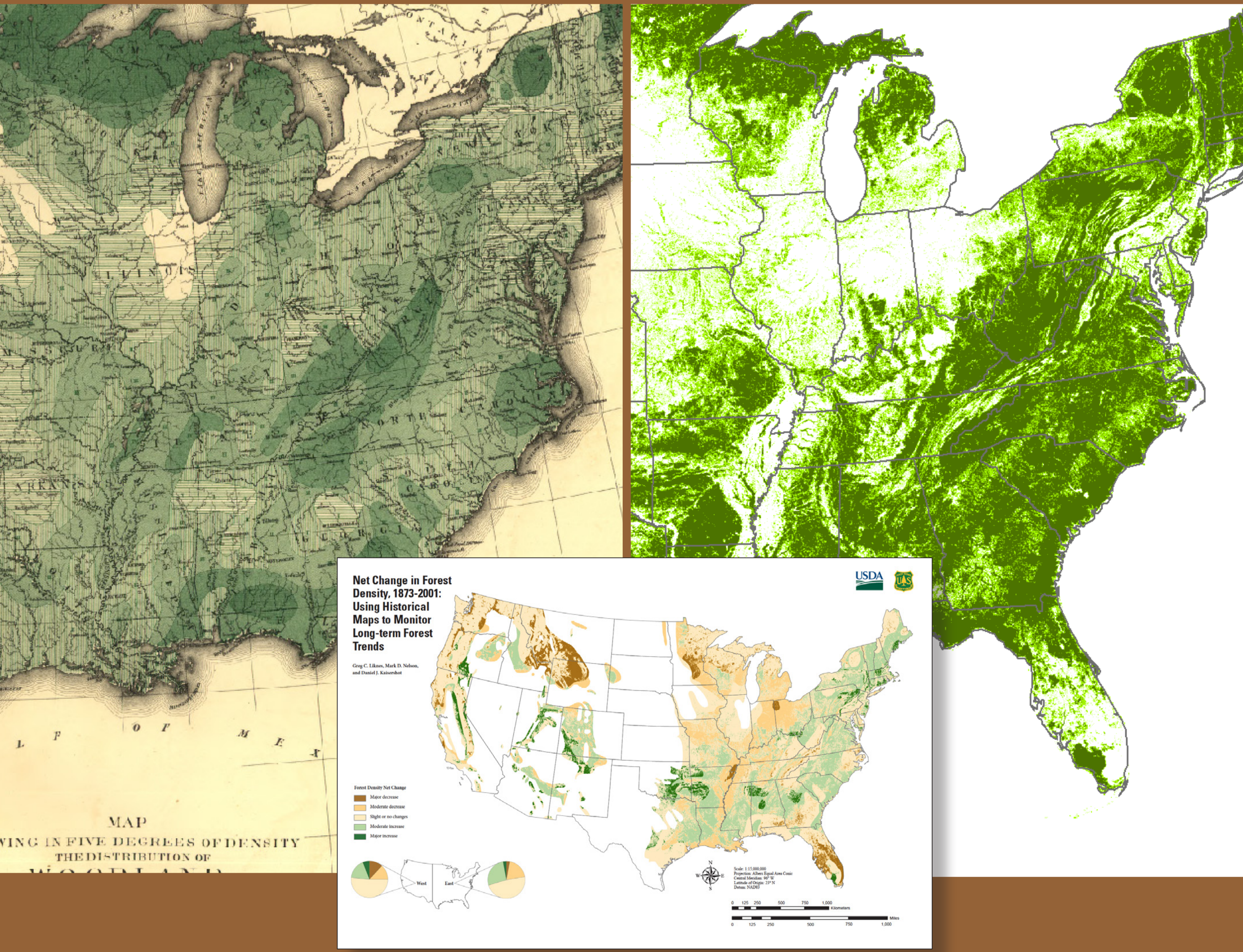
Net Change in Forest Density, 1873-2001: Using Historical Maps to Monitor Long-term Forest Trends



United States Department of Agriculture

Forest Service

Research Map NRS-4

Abstract

European settlement of the United States and utilization of forests are inextricably linked. Forest products fueled development, providing the building blocks for railroads, bridges, ships, and homes. Perhaps because of the importance of its forests, the United States has a rich cartographic history documenting its resources. Long-term, broad-scale monitoring efforts for forests focus on relatively simple measures, such as forest area, change in forest area over time, and proportion of forest land. We demonstrate how historical cartographic products could be effectively used to produce information about the change of forests over time at regional or national scales. We georeferenced and digitized a map of U.S. woodland density circa 1873 produced for the first national atlas. Using a contemporary digital forest layer derived from MODIS satellite imagery, we developed density categories that matched the historical map and calculated changes since 1873. A process is presented for combining historical maps with modern data. We discuss challenges with georeferencing of scanned images, lack of metadata, thematic misclassification, and inconsistent definitions, all of which require that historical maps should be used with caution for the purpose of broad-scale monitoring of resources.

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Net Change in Forest Density, 1873-2001: Using Historical Maps to Monitor Long-term Forest Trends

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Figure 1.—Woodland density map (circa 1873) produced by William H. Brewer for the "Statistical Atlas of the United States..." based on results from the ninth census (Walker 1874). Image source: United States Library of Congress.

INTRODUCTION

The development of the United States during the era of European settlement depended on the availability of wood as a raw material. The collective "forest culture" (Cox 1985, Kollmorgen 1969) utilized trees on abundant forest land to build homes, ships, bridges, railroads, and furniture. In addition to harvesting natural resources for raw materials, land was converted for agriculture resulting in the clearing of vast stretches of forest land in the United States. Wood also served as a primary fuel for heating, cooking, and steam-based locomotion. Kellogg (1907) estimated the U.S. annual cut rate to be 20 billion cubic feet (156 million cords) of wood in the beginning of the 20th century. Concerns about the sustainability of such practices began in the late 19th to early 20th century, leading to the acquisition and reporting of tabular lumber statistics in a variety of outlets.

In addition to these historical statistical reports, there is also a rich cartographic history related to the natural resources of North America and the United States. Joseph Henry (1858) developed a nationwide map titled "The Forest and Prairie Lands of the United States" depicting broad categories of evergreen and deciduous forests, and arable and dry prairies. James Cooper (1860) depicted a series of provinces in his North American map titled "Map of the Distribution of North American Forests." William H. Brewer developed an 1873 map of forest density resulting from the ninth U.S. Census (Walker 1874), and Charles Sargent later presented a forest density map based on the tenth census (Sargent 1884). Shantz and Zon (1924) produced a map of natural vegetation in the United States. Each of these maps covers a large spatial extent (national or continental) and represents a temporal snapshot of resources.

Today there is a variety of monitoring and reporting efforts related to forests and the environment that rely on past information to inform current analyses. For example, the Food and Agriculture Organization of United Nations produces a Global Forest Resources Assessment at 5- to 10-year intervals. In the United States, the Forest and

Rangeland Renewable Resources Planning Act (RPA) of 1974 mandates that an assessment be prepared every 10 years. In fulfillment of the RPA, a forest resource assessment was most recently published in 2009 (Smith et al. 2009), which also includes a compilation of 22 maps of contemporary U.S. forest resources. These broad-scale, long-term forest resource monitoring efforts generally rely on relatively simple measures, such as forest area and change in forest area over time. The United Nations' Seventh Millennium Development Goal (environmental sustainability) will use the proportion of land area covered by forests as a primary indicator, and it will be assessed over time (http://millenniumindicators.un.org). To support these applications of trend information in sustainability efforts, we need information on past or baseline conditions.

Our objective was to demonstrate how historical cartographic products can be effectively used to produce information about the change of forests over time at regional or national scales. We georeferenced a scanned image of William H. Brewer's 1873 U.S. map of woodland density, digitized polygons of density classes, and converted the results into a nationwide raster dataset. Using a forest probability layer derived from recent MODIS satellite imagery and *in situ* data from the U.S. Forest Service's Forest Inventory and Analysis (FIA) program, we replicated the mapping unit and categories of woodland density from the 1873 map to facilitate the calculation of change between historical and current dates.

HISTORICAL WOODLAND DENSITY MAP

William H. Brewer produced a U.S. map of woodland[1] density (Fig. 1) in 1873 that was included in the "Statistical Atlas of the United States…" (Walker 1874). Brewer reported that for the eastern United States, the map was largely based on statistics from the ninth census of 1870. He developed density categories based on the ratio of agricultural acreage to forested acreage. For the western United States, Brewer felt the census statistics were inadequate, so he pieced together information from

> *"various reports and documents, from the General, State, and Territorial Governments, reports of surveys of every kind, public and private, journals and narratives of travel, reports of various expeditions, explorations and voyages, various journals, reports and opinions of botanists, the publications of learned societies, scientific periodicals, journals devoted to special industries dependent on wood and lumber, and other published information not necessary here to be enumerated."*

With regard to the definition of the mapped categories, Brewer writes that he attempted to portray

> *"the relative proportions of surface occupied by woodlands and by lands not occupied by trees, so far as the scale chosen will allow, it takes no account of the species which make up the tree-covering of the soil, nor of the density of the forests—that is, of the relative numbers of trees per acre—nor of their size or economic value, or their fitness for sawing or other use or manufacture."*

It is worth emphasizing density portrayed on the map is a macro-scale measure rather than the more familiar trees per acre or basal area per acre. Brewer mapped density in five categories according to the number of 40-acre blocks per square mile (640 acres) that were wooded. The map reflects the cover of the land rather than its use.

A scanned image of the map was acquired from the U.S. Library of Congress (http://memory.loc.gov) in JPEG2000 format. While the map is quite readable (Fig. 1), the original document is not without defects. A line is visible down the center of the map (likely from a fold), and a tear is visible near the bottom center of the map (Fig. 2). Additionally, information about the projection or coordinate system is not provided. In short, the scanned image inherited flaws in the original map and is not accompanied by thorough metadata, a familiar scenario for those working with maps of this vintage.

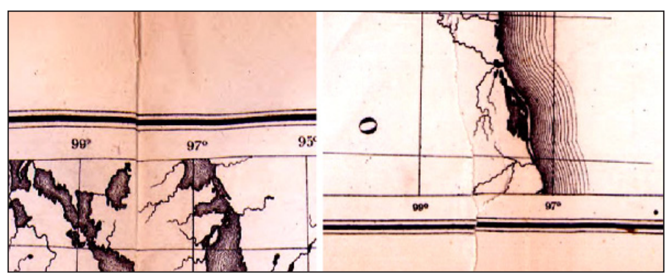

Figure 2.—Examples of flaws in a scanned map: a fold line near the top of the map (left) and a tear in the map (right).

MODERN FOREST DENSITY MAP

To match the mapping unit and density categories of the 1873 map, a modern geospatial dataset was needed with A) full coverage of the United States as of 1873; B) sufficient spatial detail to determine the number of 40-acre blocks per square mile that currently are forested; and C) a flexible forest definition. A forest probability data layer derived primarily from MODIS satellite data and information collected on tens of thousands of ground plots by the FIA program was selected.

[1] Although Brewer uses the term woodland in his map, the description of the categories indicates he is referring to what we would generically now call forest. For clarity, we use only the term forest hereafter unless the term woodland is used in a direct quote.

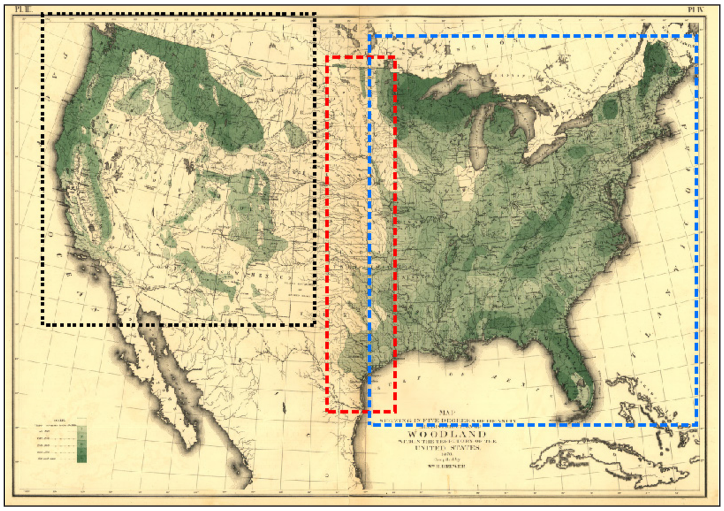

Figure 3.—Three geographic extents clipped from a scanned image of the 1873 Brewer map (outlined in black, red, and blue) to facilitate improved georeferencing. The central extent, outlined in red, contained few woodland areas and had the most distortion due to a fold in the center of the page; it was georeferenced with a rubber sheeting model while the western and eastern extents used a third-order polynomial model.

While the MODIS imagery was primarily from 2001, the resulting product will be referred to as the modern- or present-day map or geospatial dataset This dataset has nationwide coverage (CONUS + Alaska), 250-m spatial resolution (pixel size), and values ranging from 0 to 1 indicating the probability each pixel is forested. The dataset was produced as a forest/nonforest mask in support of a nationwide biomass dataset (Blackard et al. 2008) and is accessible from the Oak Ridge National Laboratory Distributed Active Archive Center (http://webmap.ornl.gov/biomass/biomass.html). It should be noted that while remote sensing approaches focus on land cover, the FIA data used for model training is based primarily on a land use definition of forest land, although both data sources include elements of land cover and land use. Therefore, it is possible some pixels assigned a high forest probability may be in the early stage of forest regeneration and thus have sparse forest cover.

PREPARATION OF DATA FOR CHANGE DETECTION

The initial step in preparing the historical density map was to georeference it to real-world coordinates. The first attempt at georeferencing involved the use of state boundary intersections as reference points (i.e., ground control points) and a third-order polynomial model. This resulted in a reasonably well-registered map, but there were a few large discrepancies, particularly at the U.S.-Canada border. A second attempt was made that involved the creation of a reference graticule layer, since a large number of graticule intersections (2 degree x 2 degree intervals of longitude and latitude) are visible on the map. In this second attempt, a piece-wise polynomial model (a.k.a., rubber sheeting) was used and resulted in a reasonable product. The final output product employed a combination of these two georeferencing approaches and was an improvement on the first two attempts.

The first step in the preparation process was the division of the 1873 forest density map into three separate, rectangular pieces (Fig. 3) and the removal of extraneous geographic extents (oceans, Canada, Mexico) and the map surround. Because the desired output was a map of changes based on derived data rather than a visually-appealing georeferenced historical map, maintaining the map surround and a seamless appearance was not a requirement. Furthermore, by isolating the center of the image where the map fold and tear existed, the overall georeferencing was improved. The western and eastern subset images were georeferenced using primarily state intersections as references with a third-order polynomial model. The center image utilized rubber sheeting and latitude/longitude intersections as reference points. Polynomial transformations are the most flexible of georeferencing options while rubber sheeting should be reserved for the most severely distorted images (Gao 2008).

Once the georeferencing was completed, the density areas on the map were heads-up digitized[2] via a geographic information system while displayed on a computer monitor, and labeled according to their density class as defined on the original map (Fig. 4 on pg. 9). The resulting vector layer of density class polygons (Liknes et al. 2013) was then converted to a raster dataset for subsequent comparison with the modern forest density map.

To prepare a modern map for the comparison, pixels were resampled from approximately 15 acres (250 m x 250 m pixel resolution) to 40 acres, with a weighted average of the associated forest probabilities assigned to the new, larger pixels. A probability threshold of 0.5 was then applied in order to assign each pixel to a “forest” or “nonforest” category. Lastly, a block statistics operation was used to determine the count of forested 40-acre pixels per square mile, simulating the geographic scale and attributes of the 1873 map (Fig. 5 on pg. 9).

(Text continues on pg. 10).

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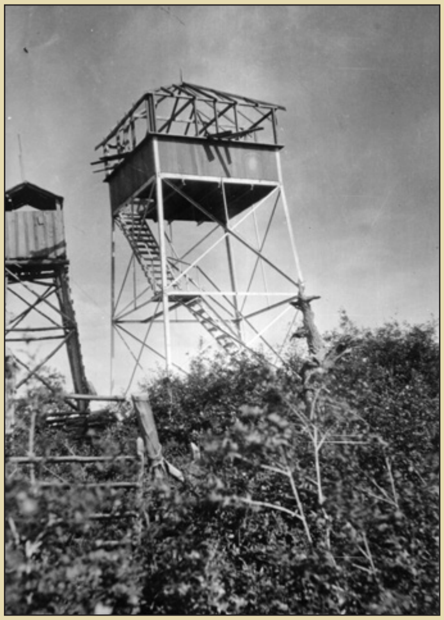
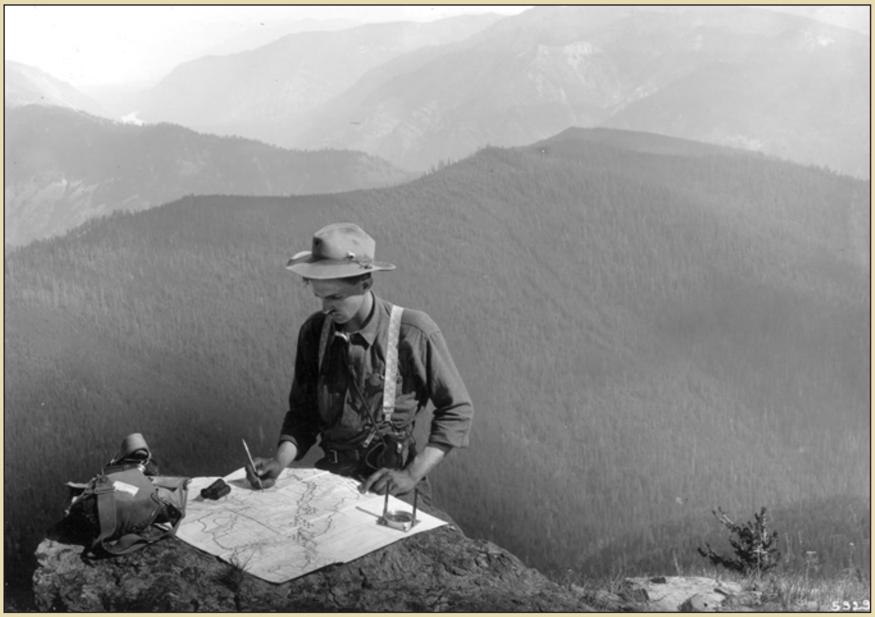
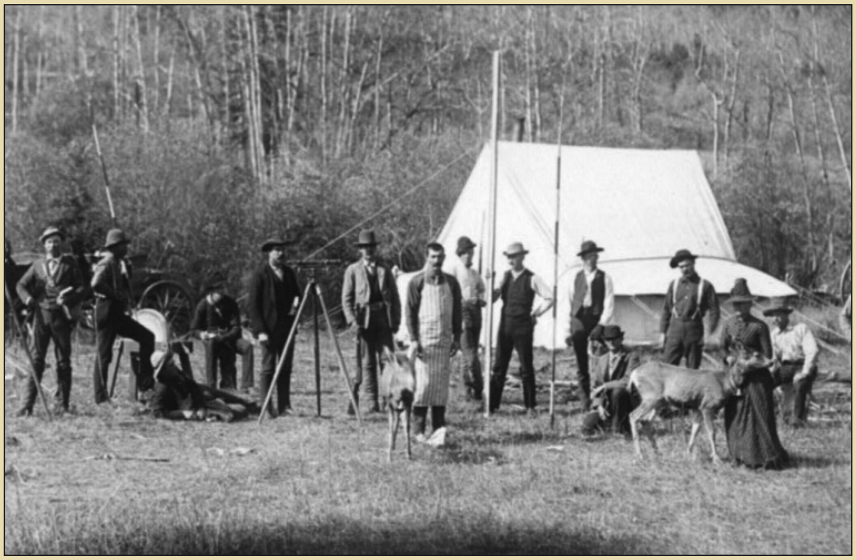
[2] Here we use the term heads-up digitized to refer to the fact geographic features displayed on a computer monitor were traced using a mouse rather than using a digitizing table or similar device.



Fire tower on Gila National Forest, New Mexico. Photo by E.S. Shipp, U.S. Forest Service.



Forest Ranger locating distance to forest fire on map by means of compass. Cabinet National Forest, Montana. Photo courtesy of Forest History Society, Durham, NC.



Forest surveyors and engineers in camp, South Dakota, circa 1889. Photo on file at Library of Congress, photographer John Grabill collection.

Ranger on the Jefferson National Forest is pointing out a tree peeled to make a huckleberry bucket , circa 1940. Photo courtesy of Forest History Society, Durham, NC.

Measuring a ponderosa pine (bottom right) on Gila National Forest, New Mexico. Photo by I.B. Nash, U.S. Forest Service.

Load of logs, Clam River, Minnesota, 1902. Photo courtesy of Forest History Society, Durham, NC.

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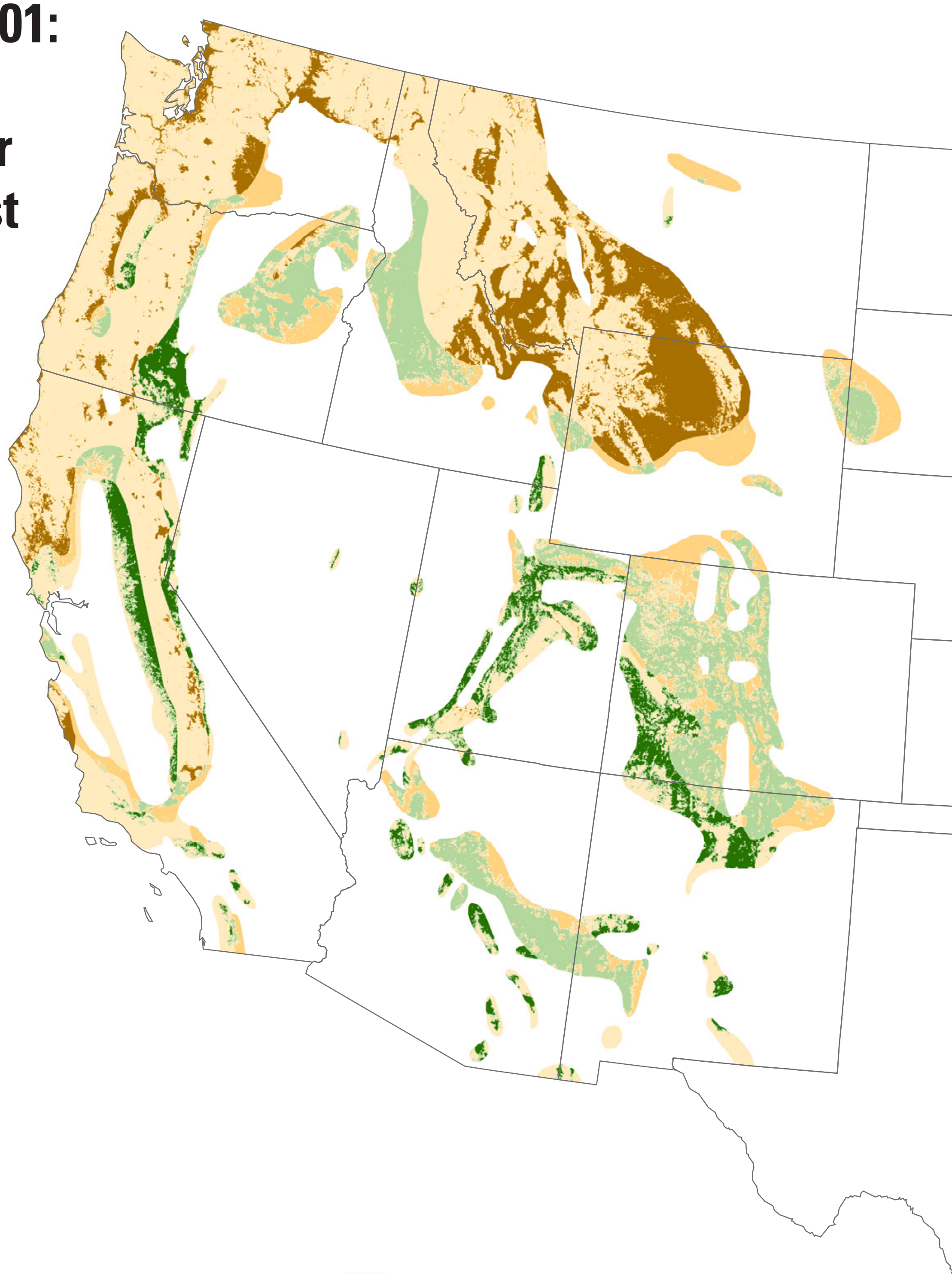
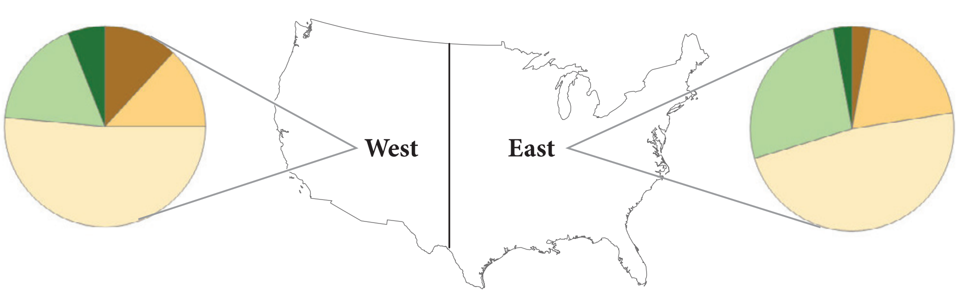
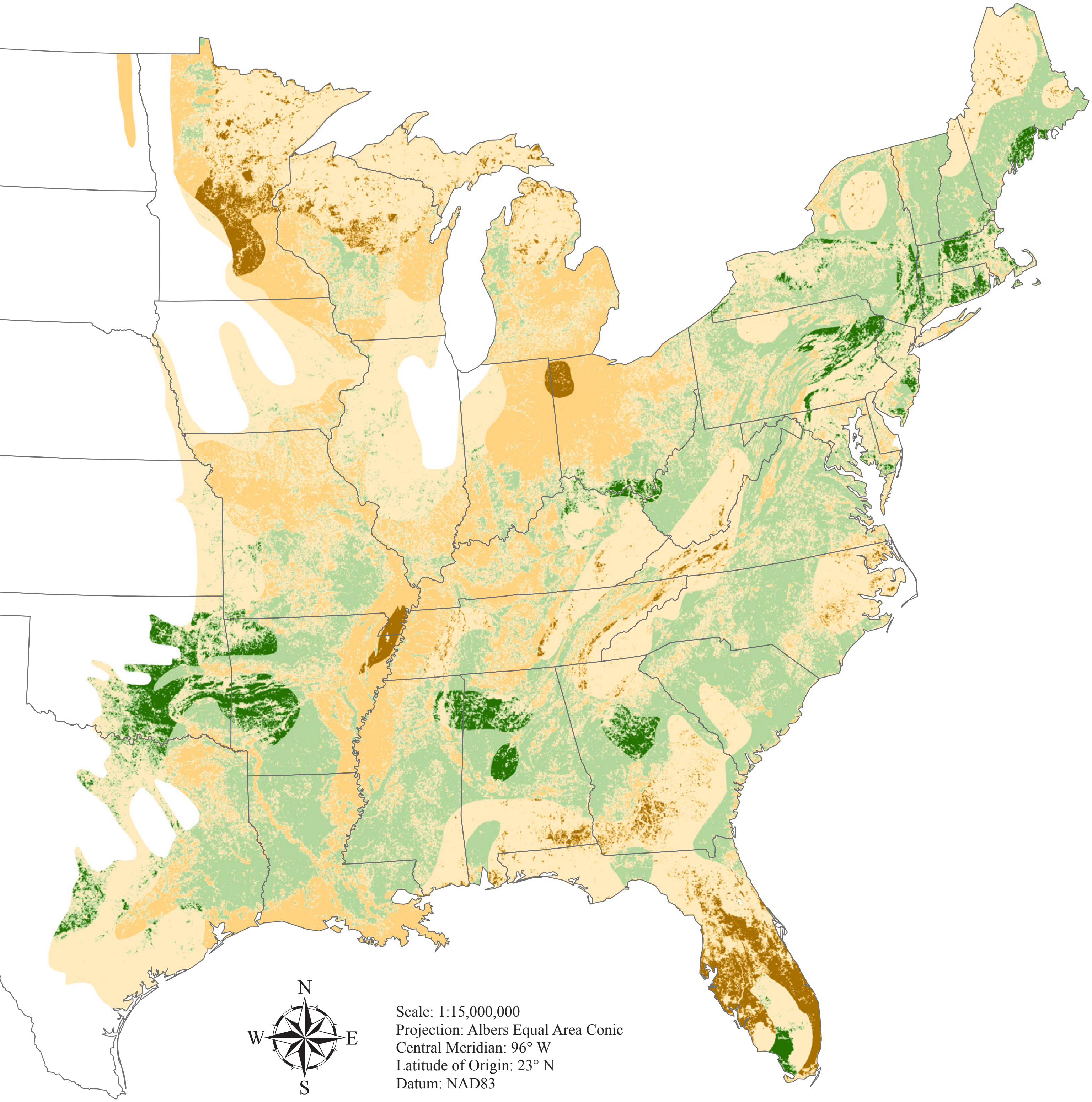


Forest Density Net Change

- Major decrease
- Moderate decrease
- Slight or no changes
- Moderate increase
- Major increase





Scale: 1:15,000,000
Projection: Albers Equal Area Conic
Central Meridian: 96° W
Latitude of Origin: 23° N
Datum: NAD83

0 125 250 500 750 1,000 Kilometers

Miles
0 125 250 500 750 1,000

Map Description

This map depicts the net change in forest density across the conterminous United States (CONUS) from 1873 to 2001. In this case, density is defined as the number of forested 40-acre blocks per square mile.

A scanned image of a 1873 map by William H. Brewer (Walker 1874) depicting six categories of density (in acres per square mile: 0-40; 40-120; 120-240; 240-360; 360-560; 560+) was georeferenced and digitized (Liknes et al. 2013). The same density categories were replicated for 2001 using data derived from MODIS satellite data and ground observations from the Forest Inventory and Analysis program (Blackard et al. 2008). The difference in forest density between the two time periods was then calculated using a geographic information system. The change class labels on the map are defined as follows: an increase or decrease of four or five density categories is a major change, a difference of two or three density categories is a moderate change, and a difference in zero or one category is slight or no change.

The pie charts on the inset map indicate the relative proportions of the change categories for the western and eastern United States. In the West, roughly half of the forested area has experienced slight or no net density change during the time interval, and increases and decreases are approximately equal. In the East, slight or no change has occurred on a little less than half of the forested area, and more areas have experienced increases than those that have experienced decreases.

The map is generally applicable at a national scale and does agree to some extent with what we know of the history of forests in the United States. It should be noted the change results are influenced by errors in both the 1873 and 2001 data sources. Net change does not capture all changes that may have occurred during intervening periods. The map provides a spatial portrayal of long-term forest change in the U.S. that has otherwise been depicted only with tabular statistics.

Data Sources

The map is a bitemporal change map derived from two sources. The time 1 data source is a scanned image of William H. Brewer's 1873 map of woodland density which was obtained from the U.S. Library of Congress. The time 2 map is derived from 2001 MODIS imagery and ground observations from the Forest Inventory and Analysis program. Political boundaries are from Environmental Systems Research Institute (ESRI) Data & Maps.

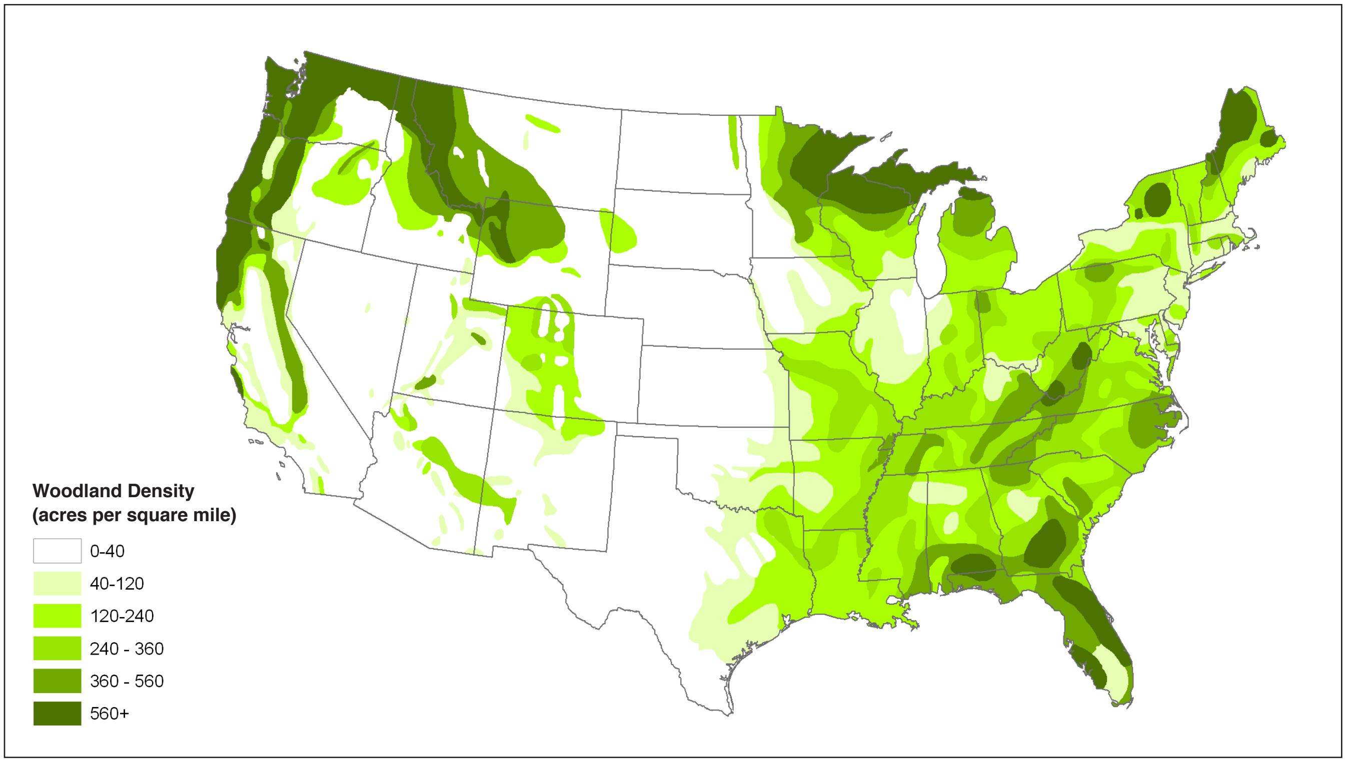


Figure 4.—Woodland density map derived from an 1873 William H. Brewer map via georeferencing and heads-up digitization. (Liknes et al. 2013). Please see footnote 1 on page 3.

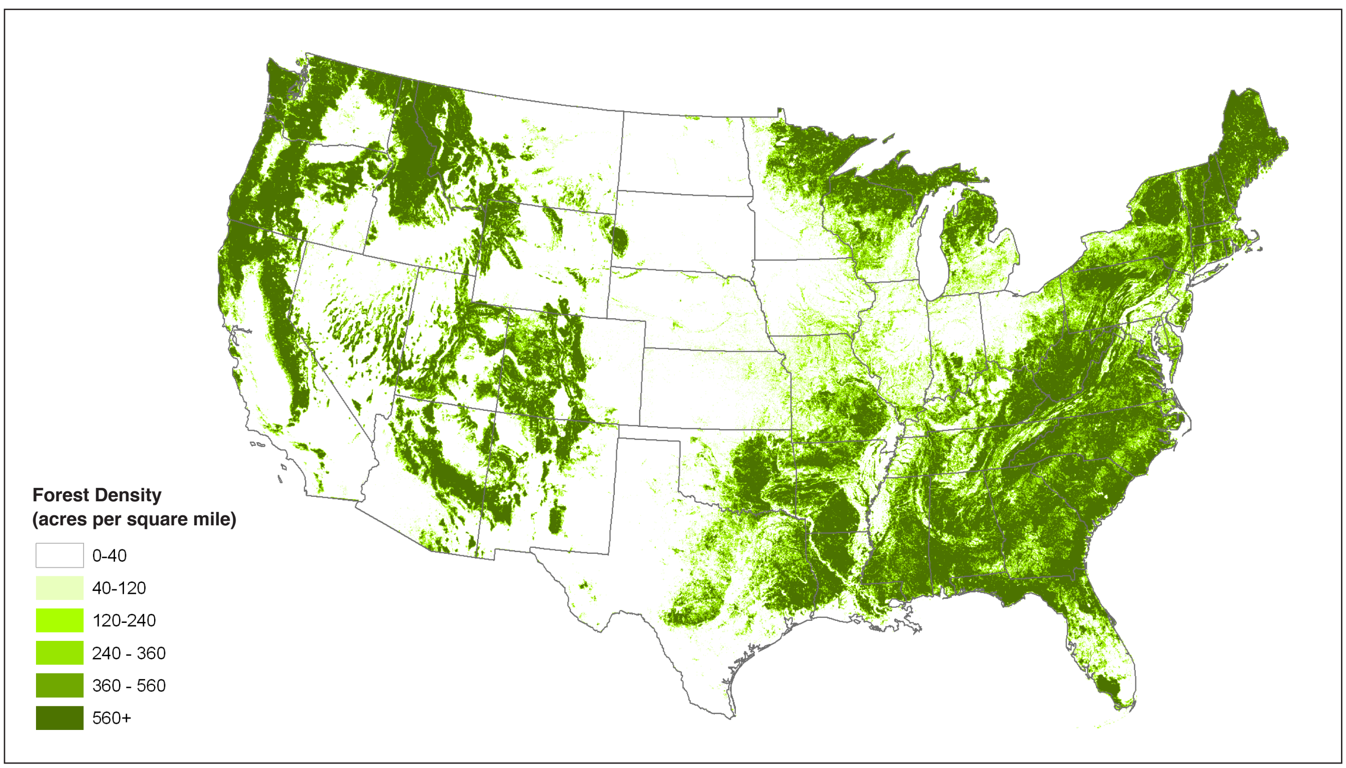


Figure 5.—Modern day forest density map derived from MODIS satellite imagery and ground based data from the U.S. Forest Service Forest Inventory and Analysis program (Blackard et al. 2008). Forest density refers to the number of 40 acre blocks per square mile that are forested.

NET CHANGE MAP

Once the final datasets from 1873 and the present were complete, a simple difference was calculated, and a map of net forest density change was produced (Fig. 6 and centerfold map). The results of the density difference calculation were aggregated but still depict different degrees of change. Areas increasing or decreasing by four or five density classes were labeled as major change, areas increasing or decreasing by two or three density classes were labeled as moderate change, and areas that remained in the same density class or changed by only one class were labeled as slight or no change. The map has been deliberately labeled as net change because the time interval is sufficient to mask widespread forest loss followed by recovery. Consider the predominance of slight or no change in the Lakes States (Minnesota, Wisconsin, and Michigan) and the Pacific Northwest. Heavy logging did not begin in these states until after 1873 (Williams 1989) and forests have since recovered to the point the areas show little net change.

Several regional patterns are apparent. The eastern United States is a very patchy mix of loss, gain, and no change with slightly more increase than decrease overall (see inset map, Fig. 6). Conversely in the western United States, areas of loss slightly exceed areas of density gain. Areas in the central United States, including portions of Ohio and Indiana, have experienced losses in density. As previously mentioned, much of the Pacific Northwest and the Lakes States have experienced no net change. In addition to regional patterns, a few subregional features are apparent, such as slight or no net change in Adirondack Park in northeastern New York, slight or no net change in the Yellowstone National Park area in northwestern Wyoming, and a major decrease in the Great Black Swamp in northwestern Ohio. Areas of major change appear to be concentrated in transition zones between forest and nonforest, such as in the eastern Rocky Mountains, along the prairie/forest boundary in central Minnesota, and south-central Florida.

MAP UNCERTAINTY

The map of net forest density change is the cumulative result of actual change (or stasis), thematic misclassification at time 1 and/or time 2, positional errors, and differences in thematic definitions between time 1 and time 2. Determining the total impact of these errors and the relative contributions of each component is always a challenge in change detection. We have attempted to match the density attribute from the 1873 map, and have noted the possible discrepancies in forest definition related to confusion between land cover and land use. Significant time was spent attempting to minimize locational errors in the 1873 map during the georeferencing process, yet error remains. However, because the map is intended for a broad-scale (regional to national) analysis, the importance of positional accuracy is somewhat reduced. Carmel (2004) reports a significant decrease in error in vegetation classification when pixels are aggregated to 3-10 times the size of locational error. Because a density class has been assigned to 640-acre blocks, some benefit of aggregation is realized in this case. While aggregation may lessen the impact of registration errors, we also acknowledge the drawbacks, such as reduced ability to represent local variance

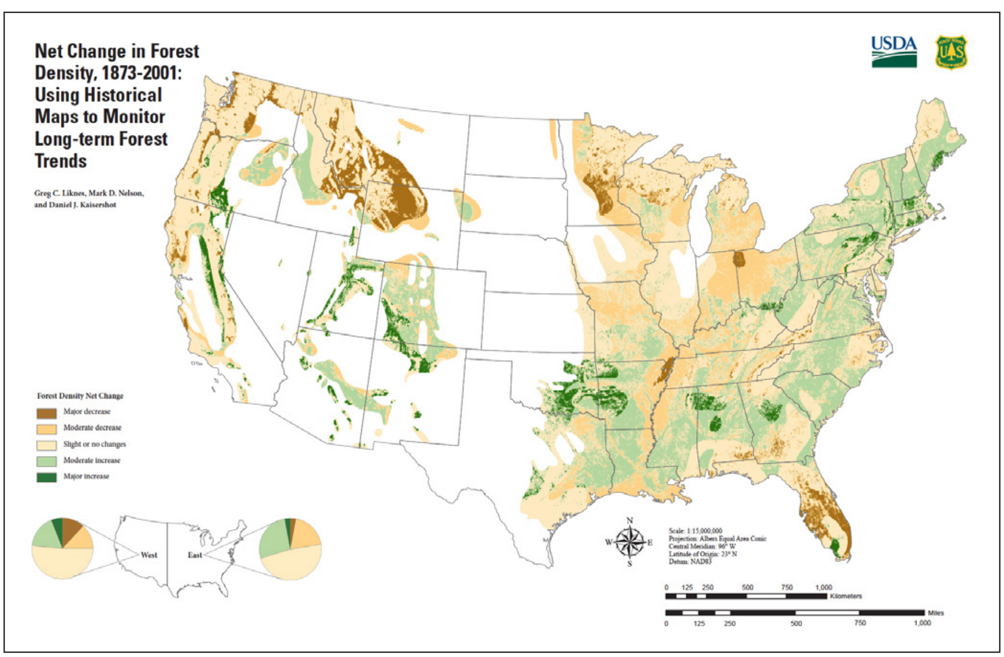


Figure 6.—Net change in forest density since 1873. Classes are based on density categories defined in an 1873 woodland density map by William H. Brewer. Change classes are labeled as follows: an increase or decrease of four or five density categories is a major change, a difference of two or three density categories is a moderate change, and a difference in zero or one category is slight or no change. The pie charts on the inset map indicate the relative proportions of the change categories for the western and eastern United States. For a larger version of this map, see pages 6-7.

(Goodchild 2001) and overrepresentation of land cover classes where cover is dense and underrepresentation where sparse (e.g., Nelson et al. 2009). Thus, it is difficult to separate offsetting positive and negative effects of the map scale, which can vary by density class.

Given the sources of uncertainty, we evaluated the validity of the net change dataset by asking the question, "Does the map make sense?" In some regions, the patterns agree with what we know of history. For example, there is evidence to suggest a large amount of unsuitable farmland reverted to forest in the eastern United States during the change interval. In fact, Brown et al. (2005) report a 22 percent decline in cropland area (much of which reverted to forest) east of the Mississippi River between 1950 and 2000. In the central United States, we noted areas of forest loss, and these correspond with the agricultural conversion of these lands in the late 19th century. Much of the West (including the Pacific Northwest) experienced no net change or has gained in density. This could be reflective of widespread conservation efforts that began early in the 20th century. However, the increases in density in the southeastern United States are difficult to corroborate. Estimates of forest land presented by Kellogg (1907) can be extrapolated backward in time using U.S. Census land-clearing records, resulting in a forest density in many areas that is substantially higher than the 1873 map (W. Brad Smith, U.S. Forest Service, personal communication). Thus, the 1873 map is questionable in the southeast, and the resulting net change may be suspect. The large area of major decrease in western Wyoming/Montana is also difficult to corroborate, and this could be the result of an overly generalized forest boundary line in the eastern Rocky Mountains on the 1873 map. We also noted the presence of smaller-scale features on the net change map; each has a plausible explanation. For example, it is reasonable to expect little change in Adirondack Park or Yellowstone National Park due to restrictions on logging. The Great Black Swamp in northwestern Ohio, which contained stands of oak, hickory, and sycamore trees, was drained for agriculture in the late 1800s (Mollenkopf 1999), resulting in a major decrease in forest density.

CONCLUSION

We examined whether historical maps provide meaningful baseline information for broad-scale monitoring of forest resources. In the process of converting an historical map to digital data, we found it valuable to use different georeferencing approaches for different geographic extents of a single map. Additionally, we took the approach of mimicking categories on the original map in the modern dataset to facilitate change detection. These findings may be helpful with similar data reconstructions. Though the map of forest density change is generally informative, challenges related to sparse metadata, incompatible definitional changes, thematic misclassifications, and positional accuracy resulted in a forest density change map that contains patterns inconsistent with other sources of information in some parts of the country. Additional research can be done to quantify real change indicated by the map as well as errors.

Brewer said this about the nature of mapping resources on such a broad scale:

> *"It is not possible to portray on one map all the characters of woodlands. The scale of this map is too small to show more than a very general distribution. Nor is it possible to convey the same idea to all persons by shades of density, especially not to persons whose observations have been restricted to limited areas widely separate, nor is it possible to convey by this means a correct idea of the character of the forests themselves. We cannot thus satisfactorily compare the grand forests of Puget Sound and Mendocino with the oak openings of Texas and the mesquite groves of Arizona; the hills clothed with a dense growth of small hardwood trees in New England, with the open forests of the pine barrens farther south; the fringe of willows and cottonwoods skirting a river of the plains, with the tangled growth of the coast ranges of the Pacific; or the scattered cedars on the ridges of Dakota, with the intricate forests of Florida. The map, therefore, is a compromise, on which I have tried to show as far as is possible what is known of our woodlands. As it is the first, it is to be hoped that the work will ultimately be more satisfactorily done from fuller data and in a series of maps…each to illustrate some separate character."*

Like Brewer, we, too, attempted to portray what is known of our forests and have arrived at a compromise in order to spatially portray changes over a large area and a long time interval. Over the course of many decades and at national or regional scales, cartographic products can provide useful information for sustainability reporting efforts, even with the inherent flaws and challenges, but should be corroborated with other data sources wherever possible.

ACKNOWLEDGMENTS

We thank Brad Quayle and Adrian Grell (U.S. Forest Service) for their ideas and assistance regarding georeferencing. We also thank W. Brad Smith (U.S. Forest Service) for his insights regarding changes to U.S. forests over time.

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European settlement of the United States and utilization of forests are inextricably linked. Forest products fueled development, providing the building blocks for railroads, bridges, ships, and homes. Perhaps because of the importance of its forests, the United States has a rich cartographic history documenting its resources. Long-term, broad-scale monitoring efforts for forests focus on relatively simple measures, such as forest area, change in forest area over time, and proportion of forest land. We demonstrate how historical cartographic products could be effectively used to produce information about the change of forests over time at regional or national scales. We georeferenced and digitized a map of U.S. woodland density circa 1873 produced for the first national atlas. Using a contemporary digital forest layer derived from MODIS satellite imagery, we developed density categories that matched the historical map and calculated changes since 1873. A process is presented for combining historical maps with modern data. We discuss challenges with georeferencing of scanned images, lack of metadata, thematic misclassification, and inconsistent definitions, all of which require that historical maps should be used with caution for the purpose of broad-scale monitoring of resources.

KEYWORDS: historical map, William H. Brewer, georeferencing, sustainability, forest resources

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