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# Spatial and temporal patterns of plantation forests in the United States since the 1930s: An annual and gridded data set for regional Earth system modeling

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**Abstract.** Plantation forest area in the conterminous United States (CONUS) ranked second among the world's nations in the land area apportioned to forest plantation management. As compared to the naturally-regenerated forests, plantation forests demonstrate significant differences in biophysical characteristics, and biogeochemical and hydrological cycles as a result of more intensive management practices. Inventory data have been reported for multiple time periods at plot, state and regional scales across the CONUS, but there lacks the requisite annual and spatially-explicit plantation data set over a long-term period for analysis of the role of plantation management at regional or national scale. Through synthesizing multiple inventory data sources, this study developed methods to spatialize the time series plantation forest and tree species distribution data for the CONUS over the 1928-2012 time period. According to this new data set, plantation forest area increased from near zero in the 1930s to 268.27 thousand km$^2$ by 2012, accounting for 8.65% of the total forest land area in the CONUS. Regionally, the South contained the highest proportion of plantation forests, accounting for about 19.34% of total forest land area in 2012. This time series and gridded data set developed here can be readily applied in regional Earth system modeling frameworks for assessing the impacts of plantation management practices on forest productivity, carbon and nitrogen stocks, and greenhouse gas (e.g., $CO_2$, $CH_4$ and $N_2O$) and water fluxes at regional or national scales. The gridded plantation distribution and tree species maps, the state-level tree planting area and plantation distribution area during 1928-2012 are available from https://doi.pangaea.de/10.1594/PANGAEA.873558.

## 1 Introduction

A forest plantation is defined as an area of introduced or native tree species established through planting or seeding for wood/non-wood forest products (i.e., industrial forests) or the provision of other ecosystem services (i.e., protective forests; FAO, 2005). In the conterminous United States (CONUS), all of the plantation forests are used for forest products (FAO, 2005, 2015). The United States is ranked as the second largest country in the world for plantation forest with a total area of about 263 thousand km$^2$ in 2012, which accounts for about 8.5% the total national forestland area (or 12.72% of forest area classified as “timberland”) (Oswalt et al., 2014; FAO, 2015). Plantation forests in the CONUS are generally intensively managed, including practices such as the use of genetically improved seedlings, site preparation, nitrogen (N) and phosphorus (P) fertilization, and pre-commercial thinning. These plantation forests could significantly reduce the pressure on natural forests to meet fiber and other wood products demands (Sedjo, 2001). Upper-estimates suggest that world demand for wood could be met by harvesting 10% of the global forest area under intensive management (Oliver, 1999). In the CONUS, dependence on forest plantations to supply wood and non-wood products is increasing (Stanturf and Zhang, 2003). Plantation forests play a major role in current and anticipated future supplies of timber because of their high growth rates, easy operability, and intensive management (USDA Forest Service, 2011).

Due to intensive interventions of human activities, plantation forests are distinct from naturally-regenerated forests. Plantation forests have more uniform stand structure characterized by even-aged stands, single or low diversity of tree species, and less understory vegetation. The simple stand structure is also often characterized by fixed spaces among planted trees, which could significantly reduce the competition for resources by more even allocation of nutrients, water, and light among dominant trees. At present, most of the planted tree seedlings in the CONUS are genetically improved through either best seed sources selection or seed orchard breeding (Fox et al., 2007). Site preparation (e.g., root excavation, soil disking and bedding, slash burning, herbicide and insecticide application, fertilizer use, etc.) is commonly used before and during plantation forest establishment (Fox et al., 2004; Jokela et al., 2010; Allen et al., 2005). During tree growth, forest plantations are generally managed with fertilization, mid-rotation thinning, and weed control. In addition, plantation forests are more frequently harvested at a younger stand age as compared to naturally-regenerated forests. These contrasting management practices relative to naturally-regenerated forests significantly alter biogeochemical and hydrological cycles in plantation forests (Gyawali and Burkhart, 2014; Jokela et al., 2010; Achat et al., 2015a; Allen et al., 2005; Sun et al., 2006).

It is still a challenge to study the feedbacks between human and natural systems due to the complexity of both systems (Chen et al., 2012; Tian et al., 2014). With increasing human interventions and the uniform ecosystem structure, plantation forests are an ideal managed ecosystem to characterize the coupling effects of human activities and natural environmental factors on biogeochemical and hydrological cycling at large scale. Previous studies have reported the distinct, local-scale carbon, nitrogen and water cycles in plantation forests as compared to naturally-regenerated forests (e.g., Fox et al., 2007; Albaugh et al., 2012, 2015; Sun and Vose, 2016; Gyawali and Burkhart, 2015; Vose et al., 2012; Hoover et al., 2014). Although the importance of plantation forests has been recognized, there still lacks a representation of plantation management practices in current Earth system models (e.g., Hayes et al., 2012; Tian et al., 2014; Pan et al., 2015), mainly due to few established relationships between management practices and ecosystem biogeochemical and hydrological cycling, as well as no available long-term and high spatial resolution gridded plantation maps at regional/national scales (Escalante Fernandez et al., 2002). In the CONUS, the effects of tree planting and management practices on forest productivity, carbon sequestration and greenhouse gas emissions are monitored through various ongoing field experiments and measurement programs, including the USDA Forest Service Forest Inventory and Analysis (FIA) program, Forest Productivity Cooperative (FPC; http://forestproductivitycoop.net/), Plantation Management Research Cooperative (PMRC; http://pmrc.uga.edu/), Forest Modeling Research Cooperative (FMRC; http://www.fmrc.frec.vt.edu/), Forest Biology Research Cooperative (FBRC; http://www.sfrc.ufl.edu/fbrc/) and the PINEMAP observation network (http://pinemap.org/). These field observations build a solid basis for extending field or local level studies to regional or national scales through remote sensing, modeling or statistical extrapolation methods.  Such scaling-up studies rely on a series of spatially-explicit and long-term regional datasets including various management practices, plantation distribution maps, and information on environmental conditions. The critical first step is to generate long-term and spatially-explicit plantation distribution maps. Therefore, in this study, we aim to develop a long-term (1928-2012) forest plantation area and spatial distribution data for the CONUS, through a synthesis of various inventory data sets across multiple scales. This dataset can be used for ecosystem modeling and statistical extrapolations of productivity, carbon storage, greenhouse gas fluxes, and hydrological cycling in plantation forests, which will improve the estimation accuracy of greenhouse gas balance in the CONUS as well as advance our understanding of how intensive land management modulates climate-ecosystem feedbacks.

## 2 Data and Methods

### 2.1 The workflow

Fig. 1 showed the datasets collected in this study and the workflow for overall processes. At first, the initial collections of various inventory data (in gray color boxes; Fig. 1) at plot-, state-, subregion- and region-scales were used to develop the middle products (in black boxes) including gridded plantation forest fraction map, and the state-level annual plantation area data. Then, these inventory data and middle products were integrated into the mechanistic program (in the circle; Section 2.7) to determine spatial distributions of plantation forest area and tree species (our final products) during 1928-2012.

### 2.2 Divisions of study area

In this study, we collected and synthesized various data from different scales organized by division of the study area into several spatial units, as described here. The FIA reports (e.g., Smith et al., 2009) commonly divide the CONUS into 8 ecological subregions (Fig. 2), and further grouped into 3 regions (South, West and North). The South Central subregion includes states OK, AR, TX, LA, MS, AL, TN and KY. The Southeast includes states GA, FL, SC, NC, and VA. The Northeast includes states ME, NY, VT, NH, NJ, PA, MD, DE, CT, MA, and WV. The North Central includes the states MN, MI, WI, IA, IL, MO, IN, and OH. The Great Plains includes states ND, SD, NE, and KS. The Intermountain includes states MT, ID, WY, NV, CO, UT, AZ, and NM. The Pacific Northwest includes states WA and OR, while the Pacific Southwest includes CA.

### 2.3 FIA plot scale data and processing

Due to the difficulty in distinguishing the optical reflectance of plantation forests from naturally-regenerated forests, remote sensing products are not currently available to directly identify spatial locations of plantation forests across landscape scales. However, owing to thousands of FIA plots and the plantation forest records, here we are able to roughly determine the spatial locations, despite of some inaccuracy due to assumptions and extrapolations.

We collected the USDA Forest Service FIA plot-level stand origin data (the variable is STDORGCD in the stand condition table of FIA data; https://www.fia.fs.fed.us/) for generating the spatial locations of plantation forests. The earliest available FIA plot data were collected in the mid-1980s. However, due to the inconsistent inventory time periods and missing observations of forest origin for some states, we chose only plot-level inventory data for the 5 years (2000-2004) when most of the states have records for forest origin. We used these data to represent the distribution of plantation forests in 2001, consisting of 16,677 plots in total with plantation forests records (Fig. 3). According to FIA privacy policy, the geographic coordinates (i.e., latitude and longitude) of plots are "swapped" with near-by (within 675m x 675m), ecologically similar plots and thus do not represent the exact locations at the fixed latitude and longitude (https://www.fs.fed.us/ne/rsb/plotlocl.html#need). Our spatial units for grid cells in this study are either 1 km or 8 km, so these deviations in spatial locations may not significantly influence our accuracy for assigned grid-cell locations of plantation forests.

Based on the collected plots for plantation forests, we calculated the gridded fraction data using the method:

$$F_{mn} = N_{mn} \times A/B + \mathcal{E}_{mn} \tag{1}$$

Where, $F_{mn}$ is the fraction of the plots that plantation forests within each grid cell; $N_{mn}$ is the plot numbers with plantation forest in each grid cell; $A$ is the represented area (675 m × 675 m) of each plot; $B$ is the grid cell area (8 km × 8 km); $\mathcal{E}_{mn}$ is a residue, which is used to add a small fraction (at the 0.01% scale) to the grid cells with the same plot numbers ($N_{mn}$) and calculated based on the percentage of forest (percentage% × 0.0001) from NLCD2001 land cover data (http://www.mrlc.gov/nlcd01_data.php). The calculated $F_{mn}$ of each grid cell will be a unique value, which is shown in Fig. 4.

## 2.4 County-, state- and region- scale inventory data

The inventory-based plantation forest area data at three spatial scales were collected to generate the gridded dataset. First, county-level data from 2007 were collected to evaluate the performance of the generated grid-scale plantation forest area for counties.

Second, state-level inventory data of plantation forest area for 8 time periods (i.e., 1952, 1962, 1970, 1982, 1989, 1999, 2007, and 2012) for the states in the South Central and Southeast were collected from the southern forest resource assessment report (Wear and Greis, 2002). Due to a lack of available historical data, our data set includes only years 2007 and 2012 for other states in the CONUS, as collected from USDA Forest Service reports (Smith et al., 2009; Oswalt et al., 2014). Third, the subregional (Fig. 1) annual forest planted area data from 1928 to 2011 were collected from Oswalt et al. (2014), in which the data from 2003-2011 were not available for all subregions except for the Southeast and South Central (Fig. 6). Annual tree planting area in the Southeast and South Central exhibited two quick increasing periods during 1945-1960 and 1966-1989 and no obvious tendency after 1990.

## 2.5 Forest species data

We collected forest cover type data at spatial scale of 250 m generated by the USDA Forest Service Forest Inventory and Analysis Program and Remote Sensing Applications Center (https://www.fia.fs.fed.us/library/maps/). In total, 113 major tree species are divided in this dataset. According to the plantation forest species area data for the three regions (i.e., South, North and West) in Oswalt et al. (2014), we identified the major plantation forest species in the CONUS and further regrouped into 11 major tree species groups, i.e., loblolly-shortleaf pine, longleaf-slash pine, Douglas fir, white-red-jack pine, ponderosa pine, spruce-fir-large-hemlock, oak-hickory-gum-cypress, elm-ash-cottonwood, maple-beech-birch-aspen, other hardwoods (including juniper, palm, mangrove and others), and other pine species (including redwood, sand pine, western white pine, lodgepole pine, and others). Using the aggregation method in ArcGIS, the 250 m forest type data were then aggregated to continuous values representing the fraction of each species group per 8 km grid cell. Based on the same methods in section 2.7, we generated a map with the Boolean (0, 1) data for each forest type group, with 1 representing the grid cells occupied by this forest type. The forest type data were then overlaid with our generated plantation maps (section 2.7) to obtain the 8 km resolution plantation forest type information. In the report of Oswalt et al. (2014), there is a plantation group of non-stocked forest type (3.88 thousand km$^2$ in total), which mainly includes young plantation stands and seedling orchards that have yet to reach a crown density of 10% (https://www.fs.fed.us/ne/fia/methodology/def_ip.htm). We were unable to directly assign it to the regrouped 11 plantation types; instead, we compared the fractions of all 11 plantation types in the grid cells with “nonstocked”, and assigned the plantation types with the highest fractions within these grid cells.

The USDA forest type map was also generated based on the FIA plot data. Furthermore, the majority of the trees in plantation forests of the CONUS are native species (Escalante Fernandez et al., 2002; FAO, 2005), which can help reduce the pixel contamination due to the neighboring grid cells. Therefore, the forest type map matches well with our generated plantation distribution data. Fig. 7 illustrated the generation of plantation tree species groups based on the fractional data and regional inventory area of each tree species group.

### 2.6 Generation methods for state-level annual plantation area

We have collected state-level plantation area data for 8 periods: 1952, 1962, 1970, 1982, 1989, 1999, 2007, and 2012, but we lack data to capture interannual patterns within these periods. To make the state-level data consistent among all periods, we post-processed these inventory data. In this study, we assumed that the plantation forest area did not decrease with time for each state, so if the data at the previous period (e.g., 2007) was less than the data at present period (e.g., 2012), the data at the present period (e.g., 2012) was then replaced by the previous one (e.g., 2007). We assumed the data in 2007 is the actual plantation area (i.e., assume the inventory data in this year are accurate) to control the post-processing, and therefore, the plantation area in other periods could not be exactly the same with the collected inventory data. The annual tree planting area in 1928 was used as the control of initial plantation area ($A_0$), and the other 8 time periods for the South and Southeast were assigned as $A_1$ to $A_8$. The other states had data only for two periods (2007 and 2012) were assigned as $A_1$ and $A_2$. We integrated the annual plantation forest area data for 8 subregions and state-level plantation area data to linearly interpolate annual distribution pattern for each state. The interpolation method is as follows:

$$C_{sum} = \sum_{j=1}^{N} C_j \tag{2}$$

$$TA_i = A_p + (A_{p+1} - A_p) \times {C_j}/{C_{sum}} \tag{3}$$

Where, $i$ is the year (1928-2012); $TA_i$ is the generated targeted plantation area in year $i$; $p$ is the time periods (0-8 for the South and Southeast states, while 0-2 for other states); $A_i$ is the inventory plantation area at year $i$; $A_{p+1}$ is the inventory plantation area at time period $p+1$; $j$ is the year between two periods ($A_p$ and $A_{p+1}$); $C_{sum}$ is the total planted area during period $p$ to $p+1$; $C_j$ is the planted area at time $j$ during period $p$ to $p+1$.

## 2.7 Methods for spatialization of gridded plantation area and tree species data

Boolean (0, 1) plantation data were developed at 8 km × 8 km spatial resolution (125,718 grid cells), with 0 denoting naturally-regenerated and 1 denoting plantation forest. Since plantation forests are generally pure forests and similarly managed at a large scale in the CONUS, the Boolean data at a moderate (8 km) spatial resolution might be adequately to apply in future modeling or statistical studies. During data generation, we assume that the plantation forests will not be converted back to naturally-regenerated forests, i.e., if this grid cell is identified as plantation in 1928, it will always be plantations since then.

Fig. 7 describes the procedure to produce the spatial distribution maps of plantation forests. The state-level annual plantation forest area dataset ($TA_i$) generated in section 2.3 is the targeted plantation area for this specific state *i*. To determine if a grid cell is plantation forest, the fraction data set ($F_{ij}$) generated in section 2.2 is used. The principle is to progressively narrow down the fraction threshold ranges ($T_{i,min}$ and $T_{i,max}$) to a fixed threshold value ($T_i$), and based on this determined threshold, we ultimately reach the targeted plantation area for state *i*. At the first-round run of the program, a minimum threshold 0 and maximum threshold 1 are assigned. The $T_i$ is calculated as the average of $T_{i,max}$ and $T_{i,min}$. Based on this $T_i$ value, we run the a program to check if the fraction data ($F_{ij}$) is higher than $T_i$ for each grid cell within the specific state, if "yes", then this grid cell is assigned as a value of Boolean 1 ($B_{ij} = 1$); otherwise, it is assigned as 0 ($B_{ij} = 0$). The $B_{ij}$ values for all grid cells within this state are added to calculate the total plantation area ($A_i$). If the total area is smaller than $TA_i$, the program will assign $T_{i,max} = T_i$; if the total area is larger than $TA_i$, the program will assign $T_{i,min} = T_i$. Based on the new $T_{i,max}$ and $T_{i,min}$, the program will go to the second round run and repeat all above processes. After the second round run, if the Ai is still not equal to $TA_i \pm 1$ km$^2$, the program will run more rounds until $A_i = TA_i \pm 1$ km$^2$. Under this condition, the generated state-level plantation area is very close to targeted plantation area at the end. Finally, the $B_{ij}$ maps (0 and 1 Boolean values) represent the spatial distributions of plantation forests in this specific state $i$. This program was run for all the CONUS states, and eventually resulted in the spatially-explicit plantation forest distribution maps from 1928-2012.

Based on the regional inventory data and gridded fractional data for individual plantation tree species groups (see section 2.5), we also applied above methods to generate the annual plantation tree species groups maps during 1928-2012.

## 3 Results and Discussion

### 3.1 Plantation forest area and temporal variations

plantation forest area in the CONUS showed a continuous increase from 1928 to 2012, with the largest increasing rates during the 1950s (176% per decade) and during the1960s (86% per decade), and the least during the 1970s (Fig. 8). Plantation forest area was 268.27 thousand km$^2$ in 2012, accounting for 8.65% of CONUS forest land area and 2.93% of the total land area. The global plantation area was reported to account for about 6.95% of the total forest land area (FAO, 2015), which is lower than the fraction in the CONUS. The increasing rate showed a slight leveling-off trend during the recent decades; however, the total plantation area still increased by 36.81% from 2000 to 2012, with this time period having the largest absolute increase (+72.16 thousand km$^2$) in plantation area. The West region had the largest forest area (1.40 million km$^2$; Oswalt et al., 2014) as compared to the North (0.71 million km$^2$) and South (0.99 million km$^2$); however, the South had the highest plantation forest area since 1950, followed by the

West since 1976. In 2012, the plantation forest area in the South, North and West were 191.78, 25.90 and 50.55 thousand km$^2$, respectively. The plantation forest area accounted for 19.34% of the total forest area in the South, while only about 3.62% in both the North and West. Over the earlier time periods (1928-1950), the North had the highest planted forest area. The West had the smallest plantation forest area before 1976, but it increased faster than the North and overpassed its area after 1976. The plantation area in the South increased the fastest since 1950 as compared to the other two regions. The plantation area in the South and North maintained increasing rates in recent decades while the rate of increase in the West was slowing down.

The smaller proportion of plantation forests in the West does not imply a greater potential to increase plantation forest area in this region in the future, because the mountainous terrains and relative dry climate (the southern and central portions) are not suitable for tree planting and management. In addition, most of the forest area in the West belongs to public land (USDA Forest Service, 2014), which is managed for multiple uses and generally not managed as intensively for forest product yields as privately-owned, profit-oriented forest properties. The North region has a far smaller fraction of public forest than the West; however, the cooler climate may result in less productivity and thus restrain its potential in wide spread of plantation forest area in the future. In contrast, although the South has a very high fraction of plantation forest and provided most of the wood/non-wood forest products for the CONUS, it still has a large potential to increase plantation forest area, which was also predicted by Smith et al. (2012). The demands for wood products in the US and global markets, as well as food and bioenergy price and demands, are likely to significantly influence plantation forest area in the South in future.

By adding the annual planted forest area together (Fig. 5), we found that the Southeast and South Central have in total planted 180.17 and 179.24 thousand km$^2$, respectively during 1928-2011. The total area of plantation forest in these two regions in 2012 was 101.13 and 90.69 thousand km$^2$, respectively. Total planted area was 54.03 and 87.41 thousand km$^2$ in the North and West, respectively during 1928-2003 (no annual planted area data since 2004), while the plantation area in 2004 was 23.46 and 46.58 thousand km$^2$, respectively. Comparing the total planted area over the historical period with the existing plantation area in 2004/2012, we can conclude that the plantation forests in the CONUS have been harvested and replanted many times during the study period.

## 3.2 Spatial distribution patterns

Before the 1950s, there was only a small plantation forest area (230 grid cells), mainly scattered among the South, Northeast, Pacific Northwest and North Central (Fig. 9). The late1950s was essentially marked as the beginning of extensive pine plantation establishment in the South (Frederick and Sedjo, 1991). The time period 1950-1970 had the fastest increasing rate of plantation forests; therefore, the plantation forests were widely spread across the South, the Northeast and the Pacific Northwest. The spatial distribution patterns of planation forests were quite similar among the time periods after 1980 and the area expansions occurred within these three regions. Further analyses indicated that the 20 states with the largest plantation area accounted for about 96.32% of the total CONUS plantation area in 2012, and the top 10 states accounted for about 76.62% of the total (Fig. 9). Among the 20 states, GA had the highest plantation area, followed by AL, OR and MS, while OK and TN had the smallest area. The plantation forest area accounted for 31.2%, 30.6%, 30.4%, 29.3%, and 28.4% of total forest land area in GA, LA, AL, MS and FL, respectively. Although LA has lower total forest land area (about 59% of GA) as compared to the other 4 states, it had the second largest plantation proportion. Plantation area in these southern states was projected to continue increasing from present to 2060 (Wear and Greis, 2012). Notably, the Pacific Northwest states of OR and WA had relatively high proportions of plantation forests (20.1% and 19.9%, respectively), with OR ranked as the third largest state of forest land area in the CONUS, and might have a greater potential for a continuing increase in planation area in the future.

During 1990-2012, AL had the largest increase (238.0%) in plantation area, followed by MS (236.8%) and LA (191.2%; Fig. 10). These states had small increasing rates of 13.2%, 5.49% and 5.77%, respectively during 1950-1990. In contrast, plantation area in GA, FL and OR showed continuous and stable increasing trends during 1950-2012. Among the top 20 states, the absolute plantation area was the smallest in OK; however, this state showed a large increasing rate (137.9%) during this period. In addition, the states of TX and AR also displayed a relatively high increasing rate. These two states might become the major contributors to the increasing plantation area in the CONUS in the future since their forest land area is relatively large and could sustain more conversions of plantations from naturally-regenerated forest land. On the other hand, several Northeast states (e.g., WI, MI, NY, and PA) and Southeast state FL showed the smallest rates of increase.

### 3.3 Plantation tree species

Tree species is key information to estimate both endogenous growth rates as well as the responses of exogenous growth to environmental changes and management practices. To identify the tree species in the plantation forests during 1928-2012, the plantation maps were overlaid with the tree species distribution map in 2012 (Fig. 11). In the CONUS, almost all planted tree species are native species and planted for productive purpose (Escalante Fernandez et al., 2002; FAO, 2005). In the South, over 69.2% of the planted tree species were loblolly-shortleaf pine, followed by longleaf-slash pine (15.6%), oak-pine (7.5%) and oak-hickory (Oswalt et al., 2014). The slash pine forests have less productivity than loblolly pine, but generally produce higher quality wood (Escalante Fernandez et al., 2002). Therefore, this species was widely planted in the southern AL, GA and the northern FL. In the North, about 48.8% of the planted tree species were white-red-jack pine, followed by spruce-fir (11.3%). The white-red-jack pine types are scattered across the North Central states, while spruce-fir occurs mainly in ME and MN. In the West (primarily Pacific Northwest), Douglas-fir accounted for 60.3% of the planted tree species, followed by the Oak-hickory-gum-cypress (11.9%) and Ponderosa pine (9.4%). Douglas fir is primarily located along the coastline in WA and OR. At national scale, loblolly-shortleaf pine accounted for most (49.45%) of the plantation forest area, followed by longleaf-slash pine (11.04%) and Douglas fir (11.17%).

### 3.4 Plantation management practices and their impacts

The plantation forests in the CONUS are mostly privately owned and about two thirds of the plantations are timberland (Escalante Fernandez et al., 2002). Therefore, intensive management practices were widely applied to promote productivity, especially after 1990

(Fox et al., 2004, 2007; Stanturf et al., 2003). Plantation management intensity is primarily determined by ownership, region, and tree species. Generally, management intensity among regions is greatest in the South and lowest in the Northeast (Escalante Fernandez et al., 2002). Commercial forest industry manages the most intensively; other corporations and large non-industrial private owners manage less intensively; while the small non-industrial private owners manage the least intensively for traditional wood products. The major plantation management practices include site preparation (e.g., soil disking, bedding, litter raking, and herbicide use), genetic improvement (e.g., breeding and seed tree selection), fertilization, thinning, prescribed fire, and harvesting. Vance et al. (2010) and Fox et al. (2004) summarized the major management practices and their impacts on productivity and yields in the CONUS.  The late1950s was thought to be the beginning of extensive pine plantations in the CONUS (Frederick and Sedjo, 1991; Vance et al., 2010). During the recent two decades (1990-2009), pine plantations were harvested (including partial and clearcut harvest) about 3.15 thousand km$^2$ per year in the CONUS (Smith et al., 2009). Thinning, site preparation, and slash burning area per year were 1.25, 2.87, and 2.70 thousand km$^2$, respectively. About 6.47 thousand km$^2$ of pine plantations were fertilized in 1999 alone, while about 40.47 thousand km$^2$ in total have been fertilized in the South since 1969 (Fox et al. 2007).

Vance et al. (2010) synthesized the extent and benefits of multiple intensive management practices and the factors influencing productivity in the different subregions of CONUS. The different management practices were reported to significantly increase tree productivity, carbon stocks and mean/periodic annual increment (MAI/PAI). Fox et al. (2004) even indicated that multiple management practices would increase pine volume at harvest by over four times in the South. Besides carbon dynamics, the intensive management practices were reported to significantly change the ecosystem hydrological and nitrogen cycles based on numerous field experiments and observations from various observational networks (e.g., FPC, FIA, FMRC, PMRC, FBRC, PINEMAP, AmeriFlux, and LTER networks). These studies have addressed the ecological impacts of plantation forestry in terms of tree species and environmental conditions, as well as management regime, intensity and frequency. Continued observational and experimental evidence of plantation forest function is critical to assess or predict the relationships between environmental changes, plantation management practices and managed forest carbon, nitrogen and water cycles. At present, it is highly likely for researchers to scale up the field or local experiments/observations to regional or national scales through remote sensing, modeling or statistical extrapolation methods.

## 4 Data Availability

The gridded (8 km × 8 km) plantation distribution and tree species maps, and state-level tree planting area and plantation forest area during 1928-2012 are available from https://doi.pangaea.de/10.1594/PANGAEA.873558. There are two data formats for gridded data: text/ASCII and ArcGIS GRID formats; excel format table is used to contain the annual tree planting area and total plantation area data for the 48 states in the conterminous US during 1928-2012. A supplemental file is added to show the plantation distribution maps in 1952, 1962, 1970, 1982, 1989, 1999, 2007, and 2012.

## 5 Conclusions and Outlooks

This study developed an annual and spatially-explicit dataset for plantation forests in the CONUS during 1928-2012. The dataset showed that the plantation forests increased rapidly since the 1960s. While these increasing rates have stabilized during recent decade, there was still great potential to increase plantation area in terms of the small fraction of plantation forests (8.65%) currently existing in the CONUS. With suitable climate and geophysical environmental conditions, the southern US is the major plantation forest base, with plantation forests accounting for 19.34% of total forest land.

Many short- and long-term field experiments in the CONUS, especially in the South, are ongoing to monitor intensive management practices effects on plantation forests. The large amount of available observational data has greatly improved our understanding of the impacts of forest planting and management practices on ecological and socioeconomic services. Scaling-up these studies from local-scale observations to regional understanding requires a series of spatially-explicit and long-term regional/national datasets that include information on various management practices, plantation distribution, environmental conditions, and vegetation maps. The first and critical step is to generate the long-term plantation distribution maps. Recognizing this, we synthesized various inventory data to generate the gridded plantation distribution and species maps during 1928-2012. There are some aspects of uncertainty in our methods where the datasets might be unable to track the exact plantation locations; however, our datasets had a relatively high spatial resolution (8 km) as required for terrestrial ecosystem modeling or statistical extrapolations at regional or national scales. The detailed spatio-temporal data for plantation tree species enables future research in simulating and extrapolating the regional/national-scale carbon, nitrogen, and water dynamics in plantation forests based on species-specific parameters, which could further improve the mechanisms and estimation accuracy of regional Earth system models.

The future plantation area and distribution will be determined by many factors, including wood product markets, bioenergy technology and biofuel prices, food supply and demand, environmental policies, and other socioeconomic factors (Wear and Greis, 2012). The plantation forest area in the South is projected to increase to 26% (high scenario; Wear and Greis, 2012) of total forest land. From socioeconomic perspective, present plantation forests in the CONUS are generating positive economic profits along with providing good environmental services. From a carbon credit perspective, the plantation forests in the South are regarded as a major contributor to carbon sink in the CONUS and North America (Hayes et al., 2012; King et al., 2012; Tian et al., 2012, 2014); however, recent studies (Achat et al. 2015a,b; Nave et al., 2010) suggested that the shorter rotation age and some intensive management practices (e.g., site preparation for soil bedding, slash burning and harvest residue raking) might reduce soil carbon stocks in plantation forests, implying plantation forests could be a carbon source. From the hydrological perspective, plantation forests may increase water use and alter the water cycle due to higher productivity and management practices (e.g., short rotation, mechanic site preparation and drainage), especially in the regions with strong precipitation limitation (Vose et al., 2012). From the perspective of nutrient cycling, plantation management practices could change soil available/total nitrogen, soil nitrous oxide emission, vegetation nitrogen, and nitrogen contents in nearby water bodies. Many past assessments have been conducted at the scale of the individual perspective; however, there is still lack of a comprehensive assessment of plantation forests' function in mitigating future climate change by considering carbon, nitrogen and water fluxes across broader regions. Such a comprehensive assessment is critical for determining whether the policy-makers or land managers are going to plant more trees and how to best manage the forests in the CONUS (Sun and Vose, 2016).

## 6 Author Contribution

GSC involved in collecting and compiling the inventory data, developing spatialization methods and leading the writing. SFP, DJH, and HQT participated in developing methods and manuscript writing.

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**8 Competing interests**. The authors declare no conflict of interest.

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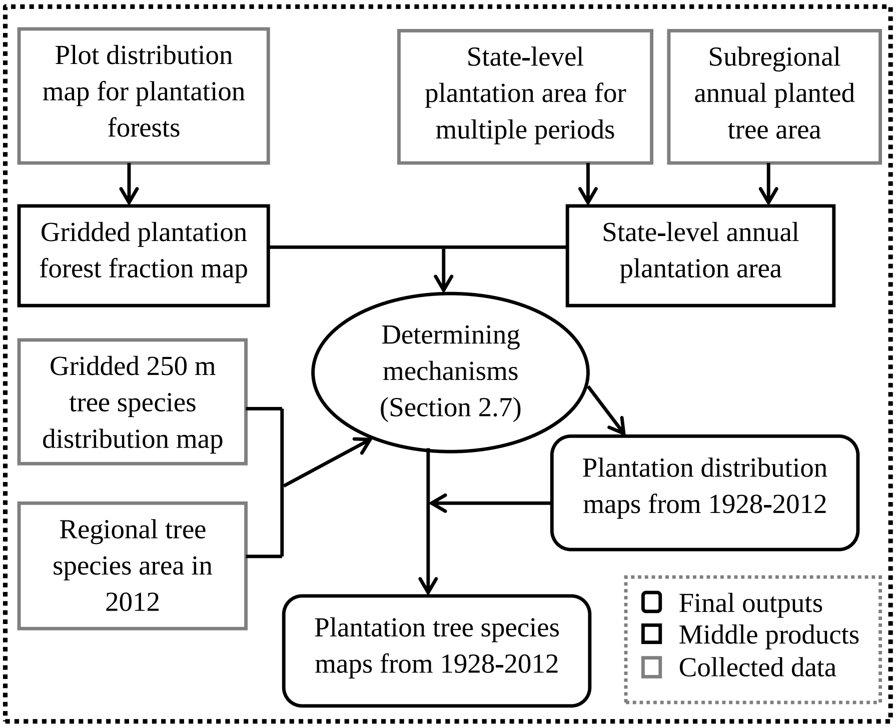

**Figure 1.** The workflow of overall processes in the generation of gridded (8 km × 8 km) plantation distribution and tree species maps from 1928-2012.

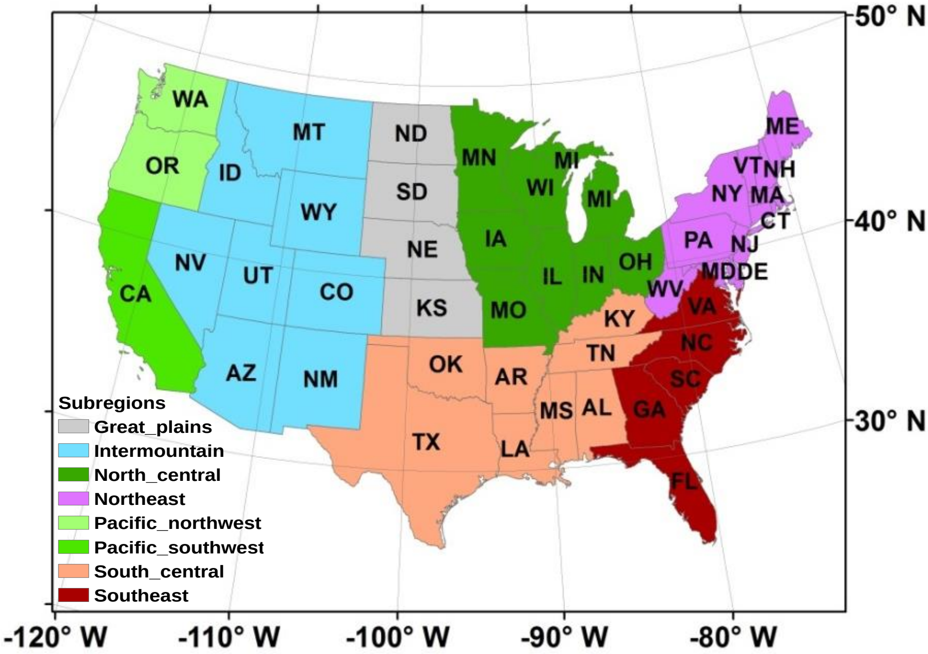

**Figure 2.** The division of the CONUS into 8 subregions for data synthesis and analysis in this study. Note: 3 regions are further grouped in some reports, i.e., South (South Central and Southeast), North (Northeast and North Central), and West (Great Plains, Intermountain, Pacific Northwest and Pacific Southwest). Data source: Smith et al., 2009.

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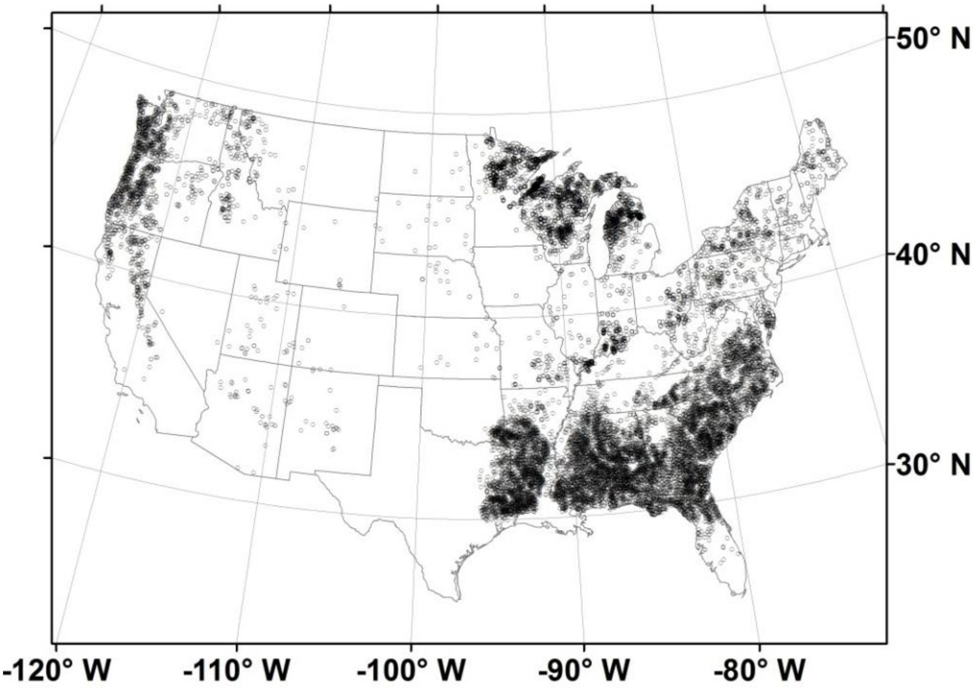

**Figure 3.** FIA plot distributions (16,677 plots in total) with plantation forest in the conterminous US during 2000-2004.

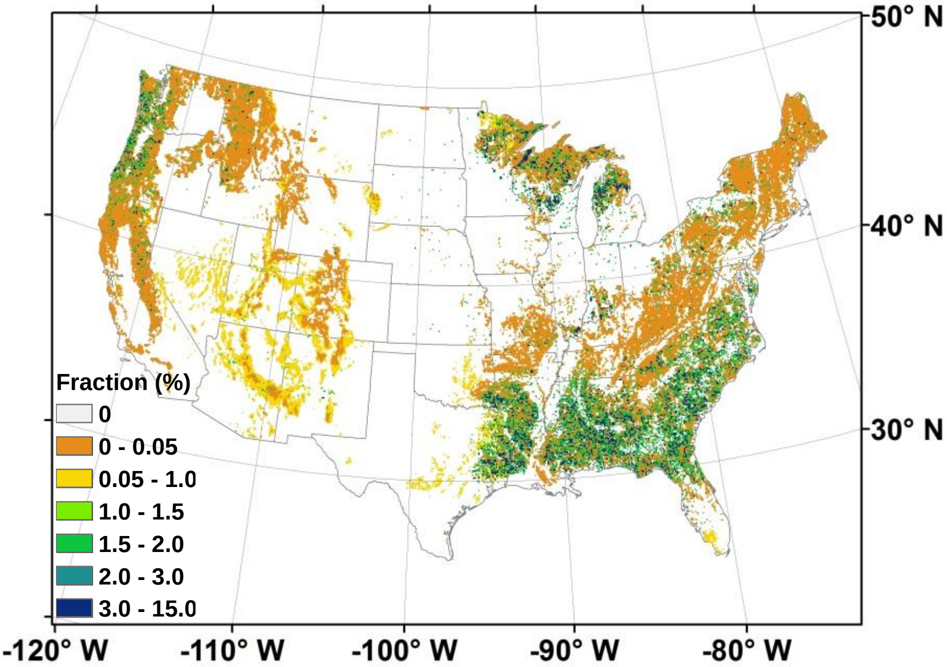

**Figure 4.** Fraction of the plots with plantation forests in each 8 km × 8 km grid cell.

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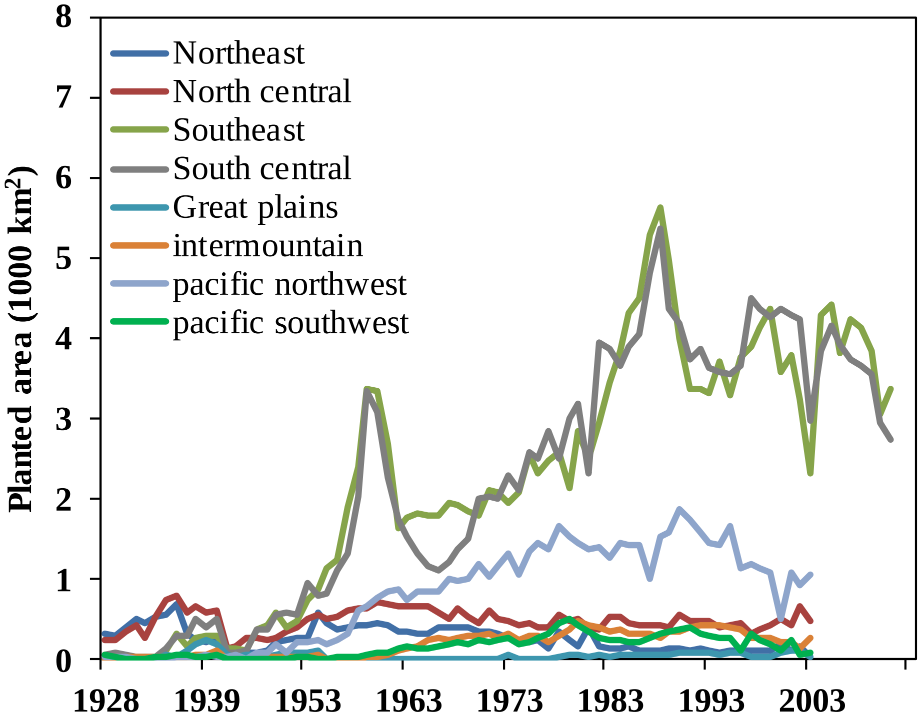

**Figure 5.** Annual planted forest area (1000 km$^2$/yr) for 8 subregions in the CONUS during 1928-2011 (data source: Oswalt et al., 2014). Note: the data for the Southeast and South Central are extended to 2011, while the continuous inventory data end at 2003 and resume at 2011 for other subregions.

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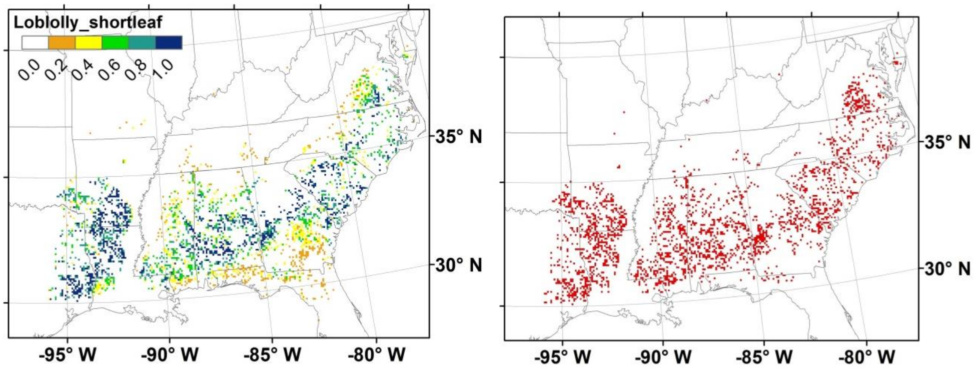

**Figure 6.** Illustration of the generation of spatial distribution maps for tree species groups in terms of fractional data and regional inventory area data using loblolly-shortleaf pine as an example. Left panel: fraction of loblolly-shortleaf pine species group in each grid cell; Right: identified final grid cells with loblolly-shortleaf pine.

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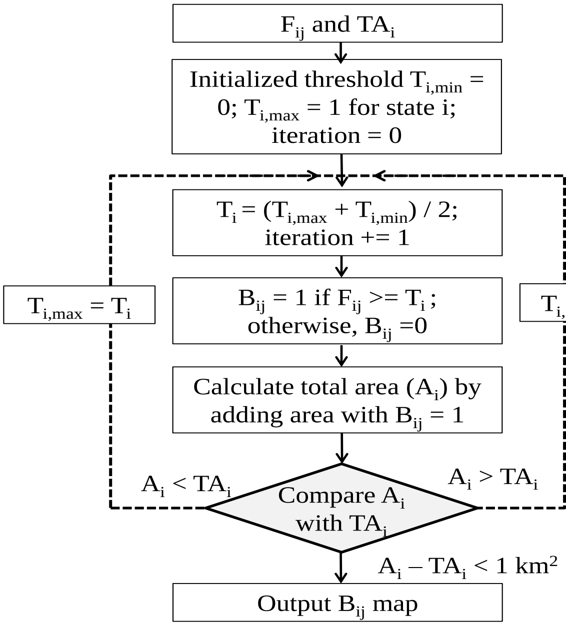

**Figure 7.** The procedure to identify the spatial distribution maps of plantation forests for each state based on grid-cell fractional data and state-level inventory data. Where, *i*: state; *j*: grid cell ID; $F_{ij}$: fraction of plantation forest for grid cell *j* in state *i*; $T_i$: calculated threshold fraction for state *i*; $T_{i,max}$: identified maximum fraction threshold; $T_{i,min}$: identified minimum threshold; $B_{ij}$: plantation distribution represented by Boolean values (0, 1) for grid cell *j* in state *i*; $A_i$: calculated plantation area in state *i*; $TA_i$: targeted plantation area in state *i*.

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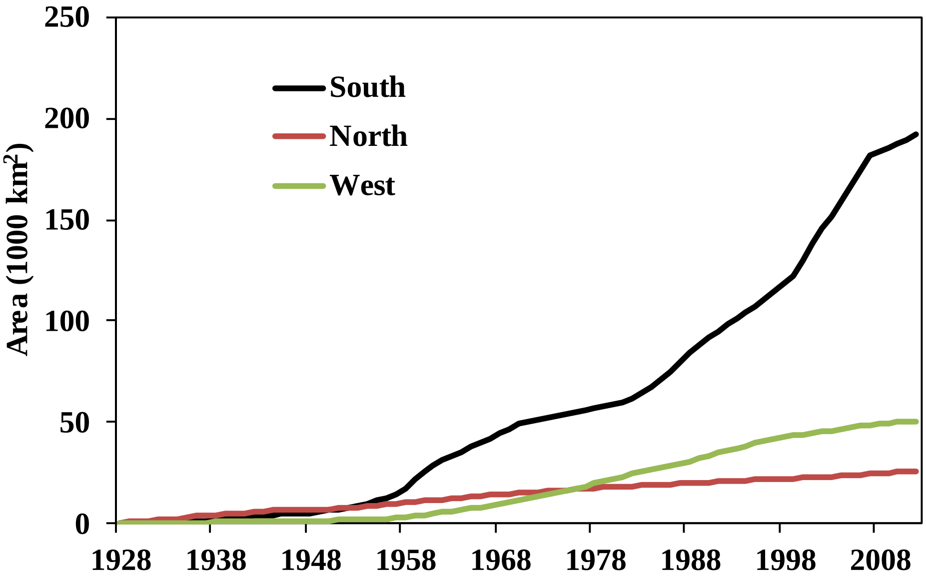

**Figure 8.** Area (1000 km$^2$) of the annual planted forests for different regions in the CONUS during 1928-2012.

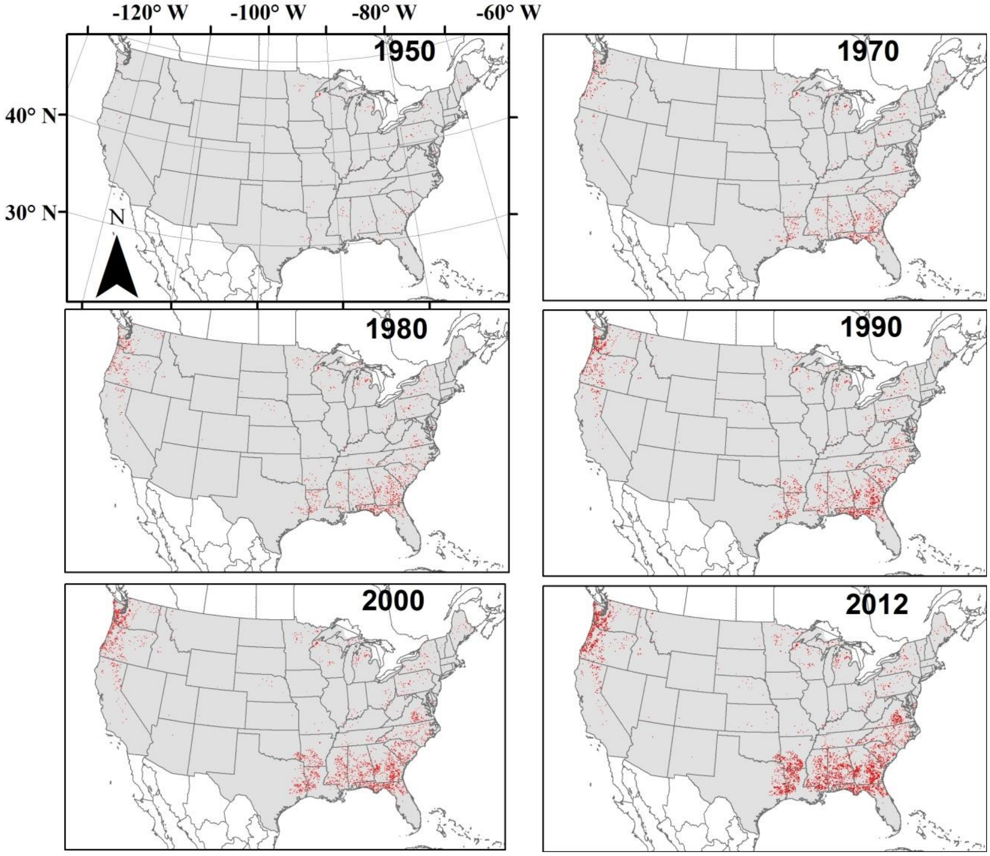

**Figure 9.** Spatial distributions for plantation forests during 1950, 1970, 1980, 1990, 2000 and 2012 at a spatial resolution of 8 km for the CONUS.

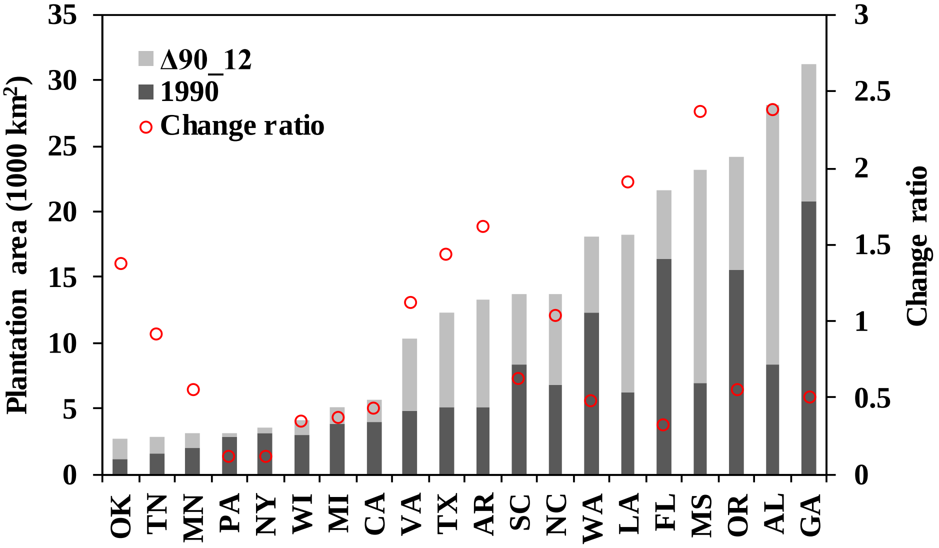

**Figure 10.** Plantation area in 1990 (dark gray), area change from 1990 to 2012 (light gray), and change ratio (Δ90_12 / 1990; red circle) for the selected top 20 states with the largest plantation area in the CONUS.

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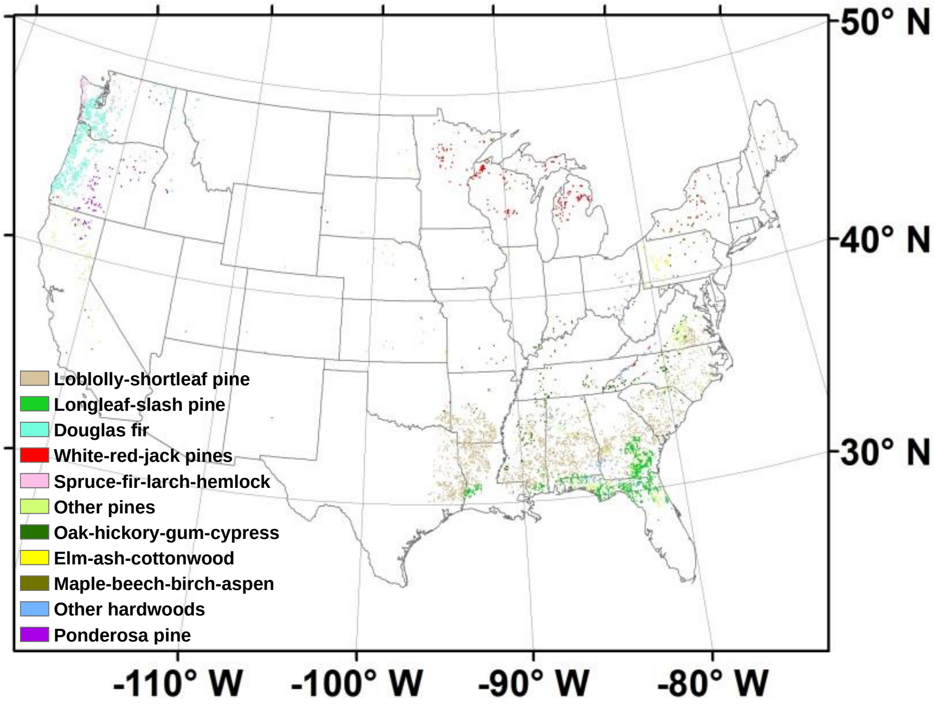

**Figure 11.** Spatial distribution of plantation tree species in the CONUS in 2012.