



Mapping pine plantations in the southeastern U.S. using structural, spectral, and temporal remote sensing data

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ABSTRACT

The southeastern U.S. produces the most industrial roundwood in the U.S. each year, largely from commercial pine plantations. The extent of plantation forests and management dynamics can be difficult to ascertain from periodic forest inventories, yet short-rotation tree plantations also present challenges for remote sensing. Here, we integrated spectral, temporal, and structural information from airborne and satellite platforms to distinguish pine plantations from natural forests and evaluate the contribution from planted forests to regional forest cover in the southeastern U.S. Within flight lines from NASA Goddard's Lidar, Hyperspectral, and Thermal (G-LiHT) Airborne Imager, lidar metrics of forest structure had the highest overall accuracy for pine plantations among single-source classifications (90%), but the combination of spectral and temporal metrics from Landsat generated comparable accuracy (91%). Combined structural, temporal, and spectral information from G-LiHT and Landsat had the highest accuracy for plantations (92%) and natural forests (88%). At a regional scale, classifications using Landsat spectral and temporal metrics had between 74 and 82% mean class accuracy for plantations. Regionally, plantations accounted for 28% of forest cover in the southeastern U.S., a result similar to plot-based estimates, albeit with greater spatial detail. Regional maps of plantation forests differed from existing map products, including the National Land Cover Database. Combining plantation extent in 2011 with Landsat-based forest change data identified strong regional gradients in plantation dynamics since 1985, with distinct spatial patterns of rotation age (east-west) and plantation expansion (interior). Our analysis demonstrates the potential to improve the characterization of dynamic land cover classes, including economically important timber plantations, by integrating diverse remote sensing datasets. Critically, multi-source remote sensing provides an approach to leverage periodic forest inventory data for annual monitoring of managed forest landscapes.

1. Introduction

Growing global demand for wood products, combined with efforts to conserve natural forests, have spurred a 65% increase in the global extent of planted forests since 1990 (FAO, 2015a). Approximately half of all industrial roundwood production in 2012 came from forests established artificially, through either planting or seeding (Payn et al., 2015). The United States is the largest producer of industrial roundwood, accounting for 17% of global production, with an estimated 41% of U.S. production from planted forests that account for only 9% of U.S. forest area (FAO, 2015a; Oswalt et al., 2014; Payn et al., 2015; Wear et al., 2016). The majority of U.S. planted forest area (~61%) and wood volume (~57%) is concentrated in industrial pine forest “plantations”

in the southeastern U.S. (FAO, 2015b; Oswalt et al., 2014). These intensively managed planted forests are predominantly monocultures of three native pine species (loblolly pine (*P. taeda*), shortleaf pine (*P. echinata*) and slash pine (*P. elliotii*); Oswalt et al., 2014).

Despite their importance for global wood production, pine plantations in the southeastern U.S. are not well characterized in terms of their total area, spatial arrangement, or management dynamics (Zhang and Polyakov, 2010). Recent studies suggest that pine plantations are expanding in the region and replacing both natural forests and non-forest habitats (Hanberry, 2013; Wear and Greis, 2013), with natural forest conversion to plantations estimated at 0.45% per year between 1989 and 1999 (Wear and Greis, 2002). Current estimates of plantation area are largely derived from U.S. Forest Inventory and Analysis (FIA)

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plots (Oswalt et al., 2014; Pan et al., 2011; Wear and Greis, 2013; Zhang and Polyakov, 2010). With uniform sampling methods since the year 2000, FIA data provide robust estimates of planted forests at large scales (county or state administrative units; O'Connell et al., 2015; Schroeder et al., 2014; Wear and Greis, 2002; Zhang and Polyakov, 2010). However, FIA plots sample a small proportion of the landscape (0.6 ha per 2428 ha; O'Connell et al., 2015), reducing their utility for characterizing fine scale (1–100 ha) land use patterns or lower frequency events such as forest disturbances, natural regeneration on abandoned lands, and plantation expansion (Boisvenue et al., 2016; Czaplowski, 2010; Schleeweis et al., 2013; Schroeder et al., 2014; Williams et al., 2014).

By contrast, satellite remote sensing data provide complete spatial coverage at spatial resolutions consistent with plantation forest management, yet dynamic plantation landscapes remain a challenge for traditional land cover classification or forest change products. National and regional land cover maps do not isolate tree plantations as a map class (Hansen et al., 2013; Masek et al., 2013; Ruefenacht et al., 2008; Xian et al., 2009; Yeo and Huang, 2013, but see Drummond et al., 2015). Previous remote sensing studies in the southeastern U.S. have characterized forest change without attribution to planted or natural forest types (Hansen et al., 2013; Jin et al., 2013; Masek et al., 2013). In addition to timber harvests, management of pine plantations through thinning, burning, or herbicidal treatments may be detected as forest change at Landsat resolution (Cohen et al., 2016; Harris et al., 2016; Masek et al., 2013; Schleeweis et al., 2013). A number of studies have used optical or lidar remote sensing to characterize pine plantations across small areas (Banskota et al., 2011; Blinn et al., 2012; Petersen et al., 2016; Popescu et al., 2004; Shamsoddini et al., 2013; Van Aardt and Wynne, 2007). However, relying on a single type of remotely-sensed data can limit the ability to isolate tree plantations, especially for native tree species that are spectrally and structurally similar to natural vegetation (Drummond et al., 2015; Fagan et al., 2015; Puyravaud et al., 2010). The potential to overcome these limitations by integrating different data types has not been extensively explored for mapping tree plantations. Classifications of “tree crops” (tree plantations for crop production) such as rubber and oil palm have benefitted from optical-SAR fusion (Chen et al., 2016; Dong et al., 2013; Gutiérrez-Vélez and DeFries, 2013; Joshi et al., 2016; Qin et al., 2016; Torbick et al., 2016), but timber plantations often have greater structural resemblance to natural forests than tree crop plantations (Brockhoff et al., 2008).

Tree plantations have several distinct spectral, structural, and temporal characteristics that may increase the likelihood of detection using a diversity of remote sensing data types. First, most plantations established for wood production are single-species monocultures, which leads to spectral homogeneity at spatial scales consistent with moderate resolution (30 m) multispectral and hyperspectral imagery (Danson and Curran, 1993; van Aardt and Norris-Rogers, 2008). Second, even-aged monoculture stands tend to have homogenous canopy structure, which could be detected using very high resolution imagery (Shamsoddini et al., 2013), lidar, or radar (e.g., Dong et al., 2013; Donoghue et al., 2007). Finally, the temporal signal of regular stand harvesting and replanting may be discernable using long time series of passive or active remote sensing data (le Maire et al., 2014). Algorithms to detect annual or subannual forest disturbance and regrowth in moderate-resolution optical data (e.g., Cohen et al., 2017) provide estimates of forest cover change since 1984 using Landsat data. In the southeastern U.S., timber harvests are common in both natural forests and pine plantations, but intensive management in pine plantations typically results in shorter harvest rotations than natural pine and mixed deciduous forests (Smith et al., 2006; Wear and Greis, 2002; Zhou et al., 2013).

In this study, we quantified the extent of plantations in the southeastern U.S. using structural, spectral, and temporal data from airborne and satellite remote sensing platforms. Specifically, we evaluated the ability of three main types of remote sensing data, alone and in

combination, to distinguish pine plantations from natural forests of mixed pine and deciduous species. Along flight lines of NASA Goddard's Lidar, Hyperspectral, and Thermal (G-LiHT) Airborne Imager, we first assessed (1) structural data from small footprint lidar, (2) spectral data from Landsat NDVI, lidar apparent reflectance, and national land-cover classifications derived from Landsat imagery, and (3) temporal data on forest disturbance derived from Landsat time series. We hypothesized that structural or temporal data alone would each be more effective than spectral data for distinguishing pine plantations, given variability within and among plantations based on the diversity of age classes, management impacts (e.g., thinning), and species composition (Wear and Greis, 2002). Second, after evaluating methods for mapping plantation forests using only spectral and temporal metrics from Landsat, we estimated the regional extent of plantation forests and harvest dynamics. Regional maps of plantation forests are critical for quantifying spatiotemporal differences in forest management and the impacts of plantation forests on habitat connectivity, landscape fragmentation, and the contribution from forest management to U.S. forest carbon sources and sinks (Coulston et al., 2015; Wear and Greis, 2013; Zhou et al., 2013).

2. Methods

2.1. Study area and system

The study region encompassed two large ecoregions (Olson et al., 2001), the southeastern mixed forests and the middle Atlantic coastal forests (Fig. 1), and covered most of the coastal plains and piedmont of the southeastern U.S. where industrial pine forests are common. Pine plantation monocultures in the study region originate either through direct planting, direct seeding, or natural regeneration followed by herbicidal removal of competing deciduous species. Thinning of timber stands is common, either through selective felling or direct removal of young trees in rows. Upland natural habitat in this landscape is dominated by mixed conifer-deciduous forests, with occasional stands of longleaf pine on sandy soil, and riparian habitats are dominated by deciduous bottomland forests.

2.2. Data sources

2.2.1. Structural data

Lidar data were collected in June–August of 2011 by NASA's G-LiHT Airborne Imager (Nelson et al., 2017). The G-LiHT lidar uses a 1550 nm wavelength, with 5–10 pulses/m² and a maximum of 4 returns per pulse (Cook et al., 2013). Lidar data were restricted to the central 30° field of view. A total of twelve flight lines fall within the study region (Fig. 1), totaling ~81,000 ha (2700 km × 0.3 km; Nelson et al., 2017). G-LiHT data are available online at <https://gliht.gsfc.nasa.gov/>.

G-LiHT lidar data were used to characterize vegetation structure in tree plantations, natural forests, and open habitats along the flight lines. We calculated standard lidar metrics at 15-m resolution to be consistent with both the 7.3 m radius of FIA sub-plots and 30 m Landsat data. Three novel metrics that characterized spatial variability in the vertical profile of lidar returns are described in more detail in the Supplementary materials. A total of 24 metrics (Table S1) were used to capture structural attributes of plantation forests and other vegetation after eliminating highly correlated metrics ($r > 0.9$).

2.2.2. Spectral data

We used three main sources of spectral data to discriminate plantation forests, natural forests, and non-forest land cover classes. First, to characterize the phenology of evergreen and deciduous vegetation, we calculated seasonal NDVI metrics from Landsat 5 composites in Google Earth Engine. Cloud- and snow-free spectral composites for 2011 were created using median pixel values of all available imagery for summer (June–August) and winter (November–February). Seasonal metrics

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