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ORIGINAL ARTICLE

Planted forests and natural regeneration in forest transitions: patterns and implications from the U.S. South

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Abstract
Forest transitions—shifts from deforestation to reforestation—are of increasing interest to scientists and policy-makers due to the importance of forest-related environmental benefits. Forest transitions occur through several pathways, including forest scarcity and economic development, each with different drivers and environmental outcomes. The relative roles of planted forests and natural regeneration in forest transitions are critical but rarely examined. We examined an ongoing forest transition in the USA using county-level data from 1968 to 2017 for 13 southeastern states to analyze the distribution and drivers of forest changes cover for both forest cover types. A forest scarcity pathway predominates in the region, occurring as planted forests have increased in a belt across the Deep South due to government tree planting incentives, urban influence, and demand for wood products. An economic development pathway is characteristic of other areas, where naturally regenerated forests have increased in association with lack of prime agricultural land and little demand for wood products. Where planted forest increased, it replaced both agricultural land and natural forest. We suggest that future forest transitions are more likely to be driven by government incentives and tree planting, and our results provide insight into the forest cover types and patterns we might expect to occur.

Keywords Forest transitions · U.S. South · Planted forests · Natural regeneration · Multivariate analyses of forest cover change

Introduction

Forests provide important environmental and societal benefits, and restoring global forest cover is attracting new attention. At the broadest level, a growing international movement for forest landscape restoration seeks to mitigate climate change, conserve biodiversity, provide socioeconomic benefits, promote food security, and improve ecosystems services (Chazdon and Brancalion 2019). At a more specific level, restoring forests is seen as a "natural climate solution" that can capture carbon and mitigate global climate change (Bastin et al. 2019; Griscom et al. 2017). But the potential benefits of increased forest cover depend on the specific attributes of new forests (Wilson et al. 2017), in particular whether they originate through natural regeneration or planted trees (Chazdon and Brancalion 2019; Grainger et al. 2019; Heilmayr et al. 2016; Pirard et al. 2016; Sloan et al. 2019).

A forest transition is defined as a change from shrinking to expanding forest cover (Mather and Needle 1998). The concept of a forest transition began as a historical generalization of European forest cover change after 1800, but forest transitions are now considered to be global in extent (Lambin and Meyfroidt 2010; Mather and Needle 1998; Rudel et al. 2020). Interest in forest transitions as a theoretical framework has surged in recent years with increased attention to forest landscape restoration as a means for mitigating climate change (Bastin et al. 2019; Chazdon and Brancalion 2019; Lamb et al. 2012). Forest transitions are the result of particular conjunctures of conditions in place and time, but general pathways have been identified (Lambin and Meyfroidt 2010; Rudel et al. 2020). In the *economic development pathway*, forest transitions occur with limited human intervention when forests regrow after abandonment of marginal agricultural fields due to agricultural intensification, industrialization,

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and urbanization (Meyfroidt et al. 2018; Rudel et al. 2020; Wilson et al. 2017). In the *forest scarcity pathway*, scarcity of forest products, crisis narratives, and changing environmental values lead to tree planting efforts by landowners, states, and NGOs to prevent flooding, protect watersheds, provide timber and fuelwood, and sequester carbon to mitigate climate change (Lambin and Meyfroidt 2010; Meyfroidt et al. 2018; Rudel et al. 2020; Wilson et al. 2017). Rudel et al. (2020) suggest that the nature of forest transitions has changed over time; early forest transitions were more passive, as farmland declined due to rural to urban migration and trees regenerated on the abandoned fields, while more recent forest transitions are more likely to include trees planted with government support to provide timber, protect watersheds, restore degraded lands, and mitigate climate change. In this paper, we examine the differences in drivers and resulting patterns of planted and naturally regenerated forests in the U.S. South over a 48-year period spanning the late twentieth and early twenty-first centuries.

Reforestation through tree planting and natural regeneration

Planted and naturally regenerated forests have different drivers and different environmental outcomes (Chazdon et al. 2016; Heilmayr et al. 2016; Sloan et al. 2019). Land abandonment leading to natural regeneration of forests is most likely to occur when prolonged urbanization leads to outmigration from rural areas and associated labor scarcities on farms (Mather and Needle 1998). Natural regeneration also occurs in response to catastrophic events such as natural disasters and war or civil conflict, as well as in association with green globalization (ecotourism, green markets, and changing environmental values) and with intensification of agriculture on more productive lands (Hecht 2014). Naturally regenerated forests may provide more environmental benefits than planted forests, while at the same time often being less economically productive (Baral et al. 2016; Chazdon et al. 2016).

Planted forests have increased in proportion over time in many parts of the world as landowners have responded to demand for forest products, and governments and NGOs have made efforts to restore forest cover (Chazdon et al. 2016; Pirard et al. 2016; Rudel et al. 2016, 2020). It has long been known that providing returns and benefits to landowners over short to moderate time periods, generally through planted forests, is often critical to increasing forest cover (Schelhas et al. 1997). There is variation among planted forests in terms of species (native versus non-native species, single versus multiple species) and stand structure (even-aged versus more complex structures, degree of understory management) (Lugo 1997; Heilmayr et al. 2016). The rate of turnover in tree cover may also differ across planted forests (e.g., when even-aged planted stands are clear-cut) (Rudel et al. 2016; Sloan et al. 2019). Planted forests, generally even-aged stands, often show rapid cycles of clearing and reforestation (Rudel et al. 2016; Sloan et al. 2019). Planted forests can play a disproportionately large role in wood supplies at the local, national, and international levels, but generally contain less biodiversity (Heilmayr et al. 2016; Paillet et al. 2010). Studies at local and regional levels around the world show various combinations of government reforestation policies, wood markets, and agricultural intensification (increasing production on existing agricultural land through applications of labor and technology) leading to different types of planted forest transitions in countries (He et al. 2014; Heilmayr et al. 2016; Meyfroidt and Lambin 2008).

As noted above, the drivers of forest expansion should differ fundamentally depending on whether or not expansion occurs through the planting of trees or through the natural regeneration of trees on abandoned land. Landowners in search of economic returns have driven the spread of tree plantations throughout the world. In contrast, the spread of naturally regenerated forests occurs largely through land abandonment by farmers. An associated logic about the quality of agriculture lands would imply little natural regeneration of forests in places with high-quality agricultural lands. Agriculture on these lands is simply too lucrative a land use to give up, so farmers rarely abandon these lands. For this reason, we might expect little natural regeneration in places with an abundance of high-quality agricultural lands.

Differences in the frequency of wood product harvests across the two types of secondary forests would also contribute to differences in extent of the two types of forest expansion. Planted forests would be subjected to a treadmill of production in which harvesting occurs when economically profitable. Conversely, in naturally regenerated forests, thinning and harvest are much less frequent than in planation forests, and clearing of forests will only occur when a change in contextual conditions, like a large rise in the price of agricultural products, makes it profitable to convert the secondary forest into fields for a farm. Given these two dynamics, we would expect much higher wood product removals from planted forests than from naturally regenerated forests. We would also expect that wood product removals would spur reforestation through tree planting because these removals represent profitmaking opportunities. In contrast, an absence of tree removals from a locale might be associated with natural regeneration because landowners would not want to spend money to plant trees in these locales. Conversely, locations close to urban areas might be associated with forest expansion through tree planting. These settings imply close proximity to urban areas that process and consume tremendous amounts of wood in construction and industrial activities. This proximity to urban areas would, for this reason, encourage tree planting.

Finally, we might expect conservation initiatives like the Conservation Reserve Program (CRP) to induce forest expansion in both planted and naturally regenerated forests. The Food Security Act of 1985 created the CRP, which has provided subsidies for tree planting that removes agricultural land from production and is the largest reforestation program in the USA in recent decades (Helms 2006). Natural regeneration has been occasionally incentivized under the CRP and several smaller conservation programs for wildlife and timber (Wear and Greis 2002). For this reason, acreage in the CRP should be positively associated with growth in the size of planted and naturally regenerated secondary forests.

We put these expectations about the different types of forces driving the expansion of forests to a test using data on fluctuations in forest cover in the southern region of the United States.

Methods

The analyses presented here rely on historical data about forest cover, wood product flows, forest policy participation, and human population concentrations that have been aggregated to the county level for 13 states in the U.S. South (Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia). Both forest-wood product data and human policy-settlement data are available for counties, and the coincidence of both types of data at this level allows us to investigate how fluctuations in human variables like urbanization and wood product flows affect reforestation dynamics across the counties.

We work with panel data from forest inventories that measure the extent of forests in counties at several points in time, one in the 1970s or the 1980s (T1) and another in the 2013–2016 period (T2) (see Table 1). We focus on three types of changes in forest between the two years: changes in overall amounts of forest cover, changes in amounts of planted forest cover, and changes in amounts of naturally regenerated forest cover. We are interested in describing and explaining these changes in forests.

We use an ordinary least squares (OLS), panel regression approach to fitting these data. We have chosen a panel regression approach rather than a time series approach because, by making forest change the dependent variable in the multivariate analysis, the variation that we seek to explain is intuitively obvious, even to readers who may not be familiar with quantitative methods. In a pooled time series, another common approach to this kind of analysis, the reader's focus ends up being on cross-sectional differences associated with the different dates of data collection and not on the different amounts of forest change. In a word, the OLS panel regression approach used here seems more legible.

This approach begins with a mathematical formulation in Eq. 1 of the arguments outlined in verbal form in the first few pages of this article. Our intent is to create causal models for the changes in the extent of southern forests. The independent variables in these models take two forms: control variables and explanatory variables. Together, they minimize the sum of the squares of the residuals in the equation. The equation that predicts the changes over time in the extent of southern forests takes the following form.

$$Y = a + \beta_{1\mathrm{i}} X_{\mathrm{i}} + \beta_{2\mathrm{k}} X_{\mathrm{k}} + \mu_{\mathrm{i}} \tag{1}$$

In Eq. (1), Y, the dependent variable, equals the change in forest extent between T1 and T2. It varies slightly from equation to equation in the regression analyses reported in Tables 3, 4, and 5. Y is the change in overall extent of forests in Table 3. It is the change in the extent of planted forests in Table 4, and it is the change in the extent of naturally regenerated forests in Table 5. X_{i} represents the control variables, X_{k} represents the explanatory variables, and μ_{i} is the error term in the equation. The details associated with the measurement of each of these variables are outlined below.

Dependent variable—forest cover changes

Forests in the U.S. South have been regularly inventoried since the late 1960s by the Forest Inventory and Analysis (FIA) program. Forest inventories were implemented periodically at 10-year intervals until the late 1990s when an annualized system was put in place. The FIA program defines forest land as having a minimum of 10% tree cover and not being subject to non-forest use(s) that prevent normal tree regeneration. The FIA program systematically installed permanent forest inventory plots on forest land across the region where forest resource status and trends are then assessed.

The earlier periodic forest inventories only surveyed timberland. Timberland is a subset of forest land with two exclusions. First, the forest land cannot be reserved from harvesting due to law or statute, such as being within the boundaries of a national park. Second, the site must be capable of producing at least 1.4 m^3 of wood volume per hectare (20 ft^3 per acre) per year. This restriction excludes areas of semi-arid scrub growth from identification as "forest" and is less than 1% of the total forest land in all southern states except for Florida (3.7%), Oklahoma (42.6%), and Texas (77.7%). While a forested land's designation as timberland can change over time, for example, if an area is designated a park and reserved, these changes were minimal during the study period. Because the time intervals between the forest inventories varied from state to state, the amount of time in years between the first and last inventories in states varied from one another in small ways. To achieve comparability in these measures of change in forest cover across the states, we adjusted the forest change scores by the interval of time between the first and last inventories in each state.

Details on these and other FIA methods and definitions can be found in the southern regional version of the FIA National Core Field Guide and FIA Database documentation (USDA Forest Service 2018a, b). We limited our use of FIA data to timberland to maintain comparability across the entire time period of the study, from the late 1960s to 2017. The years that data were collected in individual states varied because from the late 1960s to the late 1990s, the forest inventories were conducted periodically. An entire state was finished in 1 year; then, field crews worked on the next state for a year, moving from state to state in a cycle. Therefore, we do not have timberland data for every state for every year. The forest inventory data includes whether the forest stands originated from natural regeneration or artificial means (tree plantations) and the forest type. The inventory also captures when these stands are harvested or removed due to land use change.

These data are stored in the publicly accessible FIA database which we queried for forest acreage in the southern region from 1968 to 2017 (see the FIA program Data and Tools website at https://www.fia.fs.fed.us/tools-data/index.php). Specifically, we queried the data to produce estimates by state and county of trends over time in total, naturally regenerated and artificially regenerated timberland, how much volume was removed by harvesting (excluding volume removed due to land use change), by "hardwood" and "softwood" forest–type groups. Forest typing in FIA is done by a combination of field assessment and a complex forest typing algorithm, but basically "hardwood" forest types are those where the basal area is predominately in broadleaf, mostly deciduous tree species while "softwoods" are forests where coniferous species predominate. We differentiate between these different types of regeneration and broad species composition categories because they are subject to very different silvicultural practices, management intensities, harvest regimes, and economic pressures across the South. Spatial distributions differ, also, with hardwood-dominated forest types predominating in the more northerly states of Tennessee and Kentucky and higher elevation portions of other states, while pine-dominated forests are found more to the south and particularly along the coastal plains. The FIA data includes the Federal Information Processing Standard (FIPS) codes for state and county, allowing them to be merged with U.S. Census Bureau county boundary files in ArcGIS (data source: FIA, Forest Service (USDA Forest Service n.d.-a)).

Independent variables

Control variables

Two of the independent variables are control variables that covary with the forest cover change variables. They are *county area* and *forest cover area, the 1970s*. These associations do not represent theoretically meaningful findings. Large amounts of forest expansion can only occur in counties with large land areas. Similarly, forest expansion can only occur in places that did not have forest at the beginning of the period under study. We include these variables in the regression analyses to prevent the other, theoretically meaningful variables from explaining more variation in forest cover change than is due to them (Blalock 1972:433).

County area (acres): square miles. Data source: U.S. Census Bureau (2011)

Forest cover (acres), the 1970s: Forest Inventory and Analysis (FIA) data on the extent of all forests in a county at T1, usually during the 1970s (data source: USDA Forest Service n.d.-a)

Explanatory variables

CRP acreage This legislation continued a land preservation effort that began during the 1930s as an effort to limit agricultural land use to those lands capable of sustaining agriculture over the long term. Through this legislation, the government encouraged landowners to either retire lands from cultivation or undertake a set of conservation practices designed to reduce soil erosion. The encouragement came in the form of financial payments for each participating acre of land. The measure is the acres in a county enrolled as trees in the Conservation Reserve in 1989 (data source: USDA FSA 2020).

Land capability During the 1930s, amidst devastating dust storms, drought, and economic depression, New Deal officials expressed concern over the poverty of rural families who cultivated agriculturally marginal lands. The accentuated slope, excessive deposits of rocks, inadequate soil moisture, and minimal organic matter contributed to low yields from these lands. To discourage the cultivation of these lands, USDA classified all rural lands in the USA according to their agricultural potential. The first two classes of land exhibit no impediments to agricultural use. The remaining seven categories of land impose substantial limits on agricultural activities (Barnes and Marschner 1933). The proportion of county lands that fall into the first two categories of land capability provides a measure of the agricultural potential of lands in a county (data source: USDA NRCS n.d.).

Volume of wood drawn, 1986 (ft^3) We also extracted data from the USDA Forest Service's Timber Product Output (TPO) database. The TPO program surveys the wood products industry, but not fuelwood. In the U.S. South, survey forms are sent to pulp and paper mills annually and to sawmills and other primary wood product producers biennially, requesting information on their intake of roundwood and

Table 1 Net changes in natural and planted forests in the US southern states, 1968–2017 (in thousands of acres)

	Change in natural forests	Change in planted forests	Change in overall extent of forests
Alabama (1972–2016)	− 62.5	86.3	23.8
Arkansas (1978–2017)	− 6.0	34.5	28.5
Florida (1970–2013)	2.0	28.7	30.7
Georgia (1972–2014)	− 26.8	27.9	1.1
Kentucky (1988–2014)	− 1.3	− .9	− 2.2
Louisiana (1974–2015)	− 45.0	50.7	5.8
Mississippi (1977–2015)	− 22.3	49.0	32.7
North Carolina (1974–2015)	− 26.3	22.1	− 4.2
Oklahoma (1976–2014)	37.2	35.3	72.5
South Carolina (1968–2016)	− 28.4	45.5	17.1
Tennessee (1980–2013)	7.8	2.3	10.1
Texas (1975–2013)	− 49.1	56.2	7.1
Virginia (1977–2016)	− 15.5	18.1	2.7

Years of the FIA surveys utilized for each state are in parentheses. The amount of time between T1 (the first FIA in a state) and T2 (the last FIA in a state) varies by state . Because the times between T1 and T2 vary by state, we created another variable which is the mean of the amount of time between T1 and T2 for all states divided by the amount of time in that state between T1 and T2. This number ranges from .67 for states with a long time period between T1 and T2 and 1.32 for states with a short time period between T1 and T2. We then multiply this number by the forest cover change for that particular state to adjust the forest cover change figure for the different lengths of time between T1 and T2 for the different states for the regression. With this kind of normalization, we then ran regressions on the forest cover change variable without worrying about the differences in the amount of time between the first FIA and the last FIA. Source: FIA, U.S. Forest Service, USDA

output of products. These data are added to the publicly available TPO database. Details on the TPO program's methods and data can be found in Johnson et al. (2011). We queried the TPO data for survey years 1971 to 2011, the earliest and latest dates available at the time of this study. Specifically, we extracted estimates of the volume of wood drawn from counties, by product type and survey year. The product types were saw timber, veneer, panels, and pulpwood, by hardwood and softwood species groups (data source: USDA Forest Service n.d.-b).

Urban influence, 1993 This rank order variable measures the prevalence of urban land uses in a county, with 1 indicating a large population and a very urban ensemble of land uses and 12 indicating a very small population and rural ensemble of land uses. The proximity of a county to large urban centers also figures in this rural to urban score. Counties adjacent to large urban centers have lower (more urban) scores (data source: USDA ERS 2013).

To prevent confusion over the direction of causation in multivariate analyses, sometimes referred to as simultaneity bias (Greenwood 1975), the explanatory variables have been chosen from early during the 1968 to 2017 period and used to predict the values of forest cover change later, during the subsequent four decades. The equations presented in Tables 1, 3, and 4 are free of the major problems that usually afflict multivariate analyses. The residuals are normally distributed. There is no heteroscedasticity visible in the plot data. The levels of multicollinearity are modest. The highest condition index is under 10. We did drop one county (Collier County in Florida) from the analysis because the amount of the reported forest increase between 1970 and 2013 seemed inconceivable.

Table 2 Changes over time in forest types, Southern U.S., the late 1970s to 2010s (thousands of acres). Data source: USDA Forest Service FIA (USDA nd-3)

	T1 (mean—1997)	T2 (mean—2015)
Natural forest area	178,390 91.5%	159,590 77.0%
Planted forest area	16,525 8.5%	47,579 23.0%
Total forest area	194,916 100%	207,169 100.0%

Results

A clear picture of forest cover change in the thirteen states included in the study emerges for the 1968 to 2017 period. Forests in the region increased during this period by 12.253 million acres. Natural forests (consisting of a combination of hardwood, softwood, and mixed forest types) over the same period declined by 18.80 million acres. The increases in forests came almost entirely from increases in planted forests, which were almost entirely softwoods, that is, stands of planted native pine species, predominately loblolly pine

(*Pinus taeda* L.). Between the 1970s and 2010s, planted forests in the South increased by 31.05 million acres. Across the entire region, forests area increased by 6.3% over a four-decade period, with natural forest cover declining by 10.5% and planted forest cover increasing by 187.9% (Table 2).

Table 1 describes the changes across the thirteen states. As expected, given the patterns in Tables 1 and 2, natural forests declined across much of the region, with the notable exception of Southeastern Oklahoma where natural forests regenerated across the rugged terrain that predominates in that region. Most of the increases in planted forests occurred in a climatically defined belt of land that extends from eastern Texas to South Carolina, an area with climate and soils favorable to pine forest silviculture.

Maps of these changes provide additional information. Change in total timberland (Fig. 1) shows that forest lost is mostly concentrated along the rapidly urbanizing Interstate Highway 85 corridor through the Piedmont that stretches from Eastern Virginia to Montgomery Alabama, as well as developing coastal areas along the Atlantic Ocean and Gulf of Mexico. Planted softwood forests (Fig. 2) are increasing across the South with the exception of a few areas along the Mississippi River and peninsular Florida, clearly at the expense of both natural hardwood and softwood forests (Fig. 3). The expansion of planted forests is largely on the flatter terrain of the coastal plain where more mechanized harvesting is feasible and mills are located, rather than more rugged slopes of the southern Appalachian Mountains. Given these locational considerations, the planted forests occur primarily on accessible land near markets.

Tables 3, 4, and 5 investigate, by means of multivariate analyses, the political and economic forces that have driven these shifts in forests. Table 3 outlines these dynamics for overall forest cover, in other words for planted as well as spontaneously restored forests. Consistent with the idea that governments frequently promote the restoration of forests, active conservation programs in a county predict the expansion of forests in the county. The more acreage enrolled in the Conservation Reserve Program, the more forests expanded in a county. Consistent with classic forest transition theory (Mather and Needle 1998), forests did not expand in counties with extensive tracts of arable agricultural land. Finally, counties with more urban settlements or more proximity to urban settlements experienced more forest expansion than did counties far from urban settlements.

Tables 4 and 5 explore more specific forest dynamics. Table 4 examines the dynamics of planted forest expansion. As with overall forest expansion in Table 3, this analysis indicates that acreage in Conservation Reserve programs as well as proximity to urban areas predicts the expansion of forests. Interestingly, the volume of trees removed from the forests of a county associated positively with forest expansion during the subsequent decades. If forest expansion proceeds via the planting of trees, it presages relatively rapid exploitation of the newly planted forests, so we get an association between the spread of tree plantations and an increase in tree removals across the counties. Table 5 examines the drivers of natural forest expansion in the South. Here, the presence of prime agricultural lands in a county makes it less likely that significant natural forest expansion will occur in a county. Similarly, a low level of tree removals from lands in a county, perhaps signaling a moribund local timber economy, makes it more likely that natural forests rather than tree plantations will expand in a county. More acreage in the Conservation Reserve Program did promote more natural regeneration of natural forests.

Discussion

Forest cover change in the U.S. South during the study period shows an overall increase in forest cover. Forest cover change is uneven across the region at the state and county levels, both in amount of overall forest cover and in the distribution among planted and naturally regenerated forests. There has been a shift toward more planted forest in a belt across the Deep South, where planted forests have both increased on former agricultural land and replaced naturally regenerated forests. In other places, natural forest cover has increased or remained mostly stable.

Analyses found that increases in overall forest cover were driven by government incentives through the Conservation Reserve Program as well as by urban influence, while being negatively associated with prime agricultural land. However, examining planted and natural forest separately produced more nuanced results. Planted forest increases were driven by government reforestation incentives and urban influence but were also associated with the value of earlier tree removals. This suggests that markets for wood products

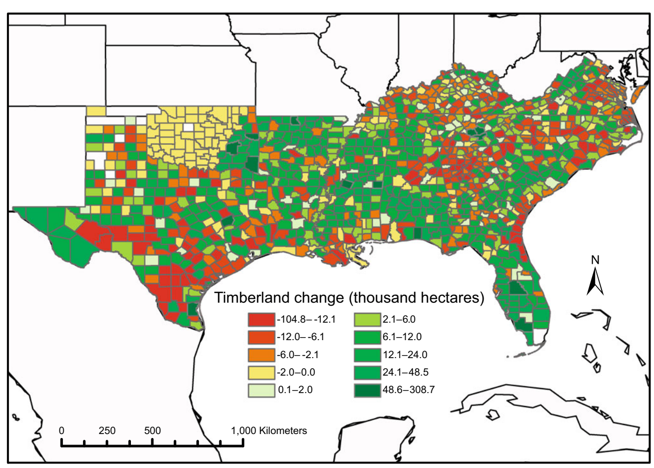

Fig. 1 County-level change in total timberland by natural and artificial regeneration in the southern United States, 1968 to 2016

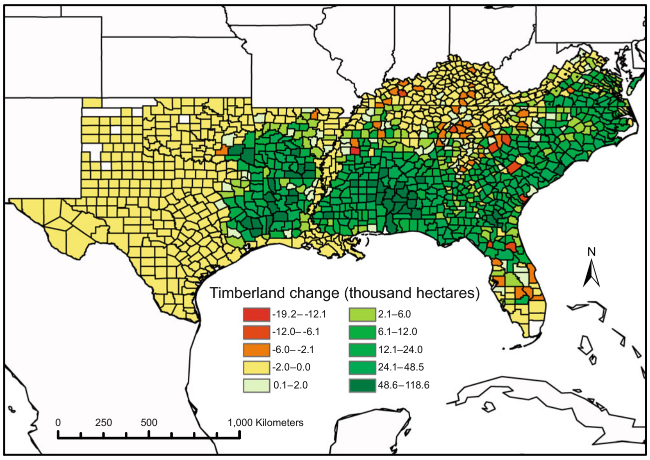

Fig. 2 County level change in planted softwood timberland in the southern United States, 1968 to 2016

encourage tree planting and is consistent with a demand-driven forest transition amplified by government policies. On the other hand, natural forest expansion was more likely to occur in places with little prime agricultural land and few tree removals. In these areas, forest cover increases as land is removed from productive use, but there is little investment in these forests.

These results suggest that the U.S. South's recent forest transition is complex, with the overall pattern being a mix between two different pathways. The natural regeneration forest increase is mostly like the economic development pathway, where forests regenerate as wage labor employment and urban development draw labor out of rural areas and farming on marginal lands is abandoned (Meyfroidt et al. 2018). The planted forest increase is similar to a forest scarcity

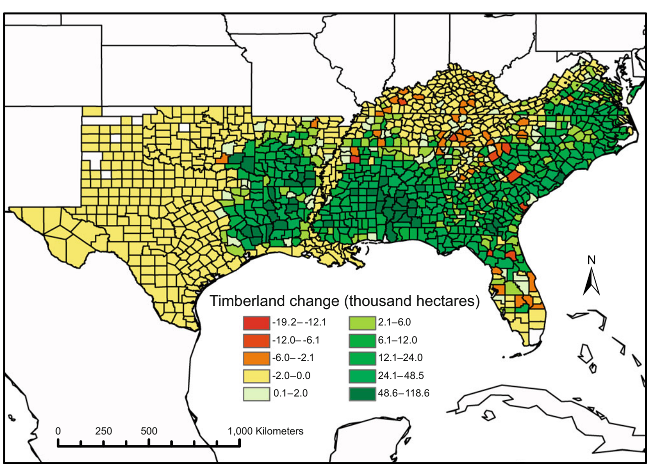

Fig. 3 County level change in naturally regenerated timberland in the southern United States, 1968 to 2016

Table 3 Changes in overall forest cover, southern counties, the 1970s–2010s

Control variable	
Land area	.056*** (.005)
Total forest area, the 1970s	− .078*** (.012)
Drivers of change	
Acreage in Conservation Reserve Program, 1989	.012*** (.002)
Proportion of land in prime agricultural categories	− 22.672** (8.346)
Size of urban communities in county	2.353*** (.511)
R^2 (Adj.)	.174
N of counties	1021

***$p < .001$, **$p < .01$, *$p < .05$

pathway, where a perceived decline in forest products and services drives efforts by institutional actors to encourage and incentivize tree planting by landowners (Meyfroidt et al. 2018). Notably, however, this is also driven by strong markets for forest products through well-developed institutions supporting a regional forest industry, much like in Chile (Heilmayr et al. 2016). Planted forest increase is also concentrated on lands that are climatically and topographically amenable to intensive silviculture with native pines, which is mostly the expansive coastal plains along the Atlantic Ocean and Gulf of Mexico (Wear and Greis 2002). The role of proximity to urban areas in plantation establishment may be the result of an overall tension across the South between development and forest product markets around urban areas. Greater proximity to urban areas will inhibit forest area increase due to competition with developed land uses, while increased infrastructure and reduced transportation costs to mills may promote the more intensive forestry associated with tree planting (Meyfroidt and Lambin 2010). The increased forest cover with planted pines associated with urban areas appears to take place in a sweet spot at the intersection of processes of economic development (both infrastructure and industrial development), government incentives that support tree planting and forest markets, and landowner decision-making.

Table 4 Patterns of change in planted tree cover between the 1970s and 2010s

Control variables	
Land area in km^2	.030*** (.004)
Drivers of change	
Acreage in Forest Conservation Program, 1989	.008*** (.002)
Tree removals, the 1980s	2.411*** (.109)
Size of urban communities in county	2.320*** (.443)
R^2 (Adj.)	.462
N of counties	999

***$p < .001$, **$p < .01$, *$p < .05$

Table 5 Patterns of change in natural tree cover between the 1970s and 2010s

Control variables	
Land area in km^2	.061*** (.006)
Total area in forest, the 1970s	− .292*** (.018)
Drivers of change	
Acreage in the Conservation Reserve Program, 1989	.004* (.002)
Proportion of county with first- and second-class agricultural lands	− 55.32*** (9.37)
Tree removals, the 1980s	− 1.232*** (.173)
R^2 (Adj.)	.427
N of counties	999

***$p < .001$, **$p < .01$, *$p < .05$

The results are consistent with Meyfroidt and Lambin's (2008) finding that forest transitions are often not the result of a single process or policy, but rather of a combination of responses to forest scarcity, agricultural change, economic development, and market integration. This in turn suggests that there may be multiple ways to stimulate forest transitions. Economic development and support for increasing agricultural productivity and intensification can change land use patterns and allow forests to naturally regenerate as certain lands are no longer cultivated (Meyfroidt and Lambin 2008). The long-term fate of these forests remains open, as in some cases they are replaced with planted forests. Development of forest product markets and tree planting can promote the more intensive forestry option of tree plantations, either with predominantly native species as in the U.S. South or with mostly non-native species as in Chile (Heilmayr et al. 2016).

Individual mixes of drivers produce particular and complex pathways to forest transitions, which ultimately result in forests with different characteristics and benefits, such as biodiversity, water, biomass, and timber (Wilson et al. 2017). Many conservation issues, such as biodiversity conservation and watershed protection, will depend on the stand characteristics and spatial arrangement of forest cover and are beyond the scope of this paper. Nevertheless, forest benefits ultimately form the basis for society's efforts to restore forests, so some discussion is warranted. FIA data on standing volume, growth, and removals (Online Resource Tables S1 and S2), while an imperfect surrogate for forest carbon, provide some useful preliminary data related to carbon sequestration. In contrast to naturally regenerated softwoods, planted softwoods have slightly higher levels of standing volume and similar growth to removal ratios. This suggests that they may have positive carbon benefits, although more research is needed and differences in hardwood and softwood, planted versus natural, and wood density need to be included if such carbon accounting is to be done more comprehensively. Gu et al. (2019) analyzed the carbon balance in the U.S. South, estimating the life history of harvest removals, and found a shifting of southern forests from a sink in the 1980s to a source in the early 2000s. However, their remote sensing–based analysis was unable to distinguish between planted and natural forest, so it is difficult to tie the change in southern forests from sink to source to the shift in the composition of southern forests to an increasing proportion of planted forests.

Regional analyses of forest transitions raise a number of questions about changing forest cover. The economic development pathway can lead to naturally regenerated forests, generally as certain lands become economically unproductive. But these naturally regenerated forests, essentially representing lands not economically useful at that time, may face new pressures over time; they may be subject to development, be protected through government or private conservation, or be converted to more intensively managed forests. Forest scarcity and forest product demand, by making tree planting more attractive, draw more agricultural land into planted forest while also reducing the area of naturally regenerated forests. Growing populations, increased demand for forest products, and implementation of government promotions of reforestation will likely lead to more planted forests in future forest transitions (Rudel et al. 2016). It will be important to understand the relationships of naturally regenerated forests and planted forests in future forest transitions, as well as the role of broader socioeconomic patterns and specific policies in shaping them.

The forest transition theory, including recent work identifying multiple forest transition pathways and outcomes, provides a framework for examining increases in forest cover in response to broad societal trends. This is important because any effort to increase forest cover must operate within larger economic, land use, and policy processes. As governments become interested in promoting increased forest cover for various environmental and social objectives, they are essentially endeavoring to facilitate regional forest transitions. While the context in U.S. South differs in many ways from other regions of the world, the uncommon availability of long-term forest inventory, land use capability, and census data at the county level over a four-decade time period presented a unique opportunity for analysis.

Naturally regenerated forests from earlier forest transitions may have a significant conservation value. But lands that drop out of economic productivity for a time may be subject to other land use changes in the future, including both forest clearing and conversion to planted forests. Planted forests, while varying across many attributes, generally provide fewer environmental benefits. But, as land use intensifies globally and governments implement policies to facilitate increased forest cover, forest transitions increasingly include more planted forest. New planted forest may reforest agricultural lands and replace natural forests, and we show how this differs geographically in accordance with certain drivers. Prime agricultural land is unlikely to be reforested. Demand for wood products is a significant driver of tree planting, and tree planting and subsequent management may not be attractive to landowners in places where such demand does not exist. Forest plantations are often close to urban areas because these favor transportation and mill location, while remote areas with steep topography and unfavorable conditions for intensive silviculture are more likely to remain in naturally regenerated forests. Based on wood volume, planted forests here appear to be modestly favorable for carbon sequestration while providing a significant output of wood products. Future research on carbon balances is needed to transform wood volume into carbon and to account for the fate of carbon in harvested trees, but we emphasize the need to account for different management regimes of forests in this research. Policy interventions may be necessary both to maintain natural forests and to enhance the environmental benefits of planted forests.

Conclusion

It is necessary to account for different pathways and outcomes in forest transition research, particularly the differences and relationships among planted and naturally regenerated forests. These two types of forests have different drivers and co-occur in complex patterns on the landscape. Forest landscape restoration and government reforestation programs must pay greater attention to different forest transition pathways, forest-type outcomes, and suites of social and environmental benefits if they are to meet their stated objectives. Finally, we would encourage forest restoration to consider forest types in ways beyond the two extremes of natural forests and planted forests by looking at a variety of silvicultural systems and new forests that produce different suites of environmental, social, and economic benefits.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10113-020-01725-3.

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