Trees, Forests and People 23 (2026) 101155

Contents lists available at ScienceDirect

Trees, Forests and People

journal homepage: www.sciencedirect.com/journal/trees-forests-and-people

Physical presence, practical absence: Accessibility of timber inventory in the eastern US

Gaurav Dhungel[a,*], Justin Baker[a], Jesse D. Henderson[b]

[a] Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC, USA
[b] USDA Forest Service, Southern Research Station, Research Triangle Park, NC, USA

ARTICLE INFO

Keywords:
Timber availability
Constraints
White oak
Amenity
Accessibility
Carbon additionality

ABSTRACT

Forest resources in the eastern US are located on heterogeneous landscapes with widely varying biophysical, social, and market characteristics. As such, the total inventory is rarely available for harvest within a region. Understanding the distinction between physical timber inventory and accessible inventory is crucial for conducting market analyses, developing forward-looking resource assessments, estimating the extractive ("active") resource base, and, in general, ensuring the continued, sustainable flow of timber. To this end, we employ a mix of regression and spatial analysis to estimate and visualize timber and carbon accessibility on eastern forest land in the US – and how species-specific estimates vary, in our case, white oak (*Quercus alba*). The logistic regression shows that all seven biophysical and social characteristics, i.e., site physiography, productivity, slope, road distance, amenity value, ownership, and past harvest experience, significantly explain the lack of harvest/management decisions on forested lands in the eastern US. The subsequent spatial analysis illustrates that the higher timber accessibility spots/timber basins are mostly concentrated in the coastal Atlantic plains, gulf coast of the Southeast, and most of Maine, whereas the lower timber accessibility spots/timber basins are largely concentrated along the mountainous region of the Appalachia, the Ozarks, Ouachita, parts of the upper Midwest, and drier parts of west Texas. Results of this study have important applications and implications for timber supply models, policies, programs, and services that affect eastern forest land, and the benefits accrued from these forests, particularly concerns related to timber accessibility, white oak sustainability, and carbon additionality.

1. Introduction

The term *timber supply* can be a misnomer in common forestry parlance in the sense that timber supply is often considered the same as *timber inventory,* and these two terms have been used interchangeably in previous literature (e.g., Dhungel et al. (2024), Gadzik et al. (1998)). Timber inventory is a subset of biological potential timber supply and is a physical estimate of total timber volume for some forest area, whereas timber supply is a subset of physical timber inventory and reflects the timber available under existing market conditions (Straka, 2010). A key distinction between inventory and supply is that physical forest inventory estimates do not reflect the costs of accessing and extracting the resource, or societal preferences for preserving forest composition and related ecosystem services (among other factors). As forest resources are located on heterogeneous landscapes with widely varying biophysical, social, and market characteristics, the total inventory is rarely, if ever, available for harvest within a region at any specific point in time. Understanding this distinction between timber inventory and timber availability is crucial for conducting market analyses, developing forward-looking resource assessments, estimating the extractive ("active") resource base, and, in general, ensuring the continued, sustainable flow of timber through policy and management interventions.

Forests comprise approximately one-third of the US landscape, with the South[1] being the most forested region (46 %), followed by the North[2] (43 %) (Oswalt et al., 2019). Among the myriad ecosystem services, timber is the most tangible and financially important provisioning

* Corresponding author at: North Carolina State University Raleigh, NC United States.
E-mail address: gdhunge@ncsu.edu (G. Dhungel).

[1] South constitutes RPA's southern states: AL, AR, FL, GA, KY, LA, MS, NC, OK, SC, TN, TX, VA.
[2] North constitutes RPA's northern states: CT, DE, IL, IN, IA, ME, MD, MA, MI, MN, MO, NH, NJ, NY, OH, PA, RI, VT, WV, WI. Together the North and the South encompasses the geographical scope of eastern US in this study.

https://doi.org/10.1016/j.tfp.2026.101155

Available online 9 January 2026

service provided by these forests. The US is the world's leading producer of industrial roundwood timber, pulp and paper, and wood pellets (FAO, 2021) – and a plurality or the majority of these are sourced from the South. Despite the economic contributions and global market share that US forests provide, harvests occur on less than 2 % of forest land per year (Oswalt et al., 2019), although this value varies considerably across regions. Across the US, 58 % of the forest land is privately owned (Butler et al., 2016), and collectively, these private forest lands provide 89 % of the nation's annual timber removals (Oswalt et al., 2019) – an estimated 46 % from corporate forests and 42 % from family forests (Butler and Sass, 2023). Private lands in the South account for 58 % of the national timber removals, and private lands in the North account for another 14 % (Oswalt et al., 2019), mostly from family forest owners (FFOs) in the region (Butler and Sass, 2023). Since harvests occur on just a small portion of forest land, and mostly on privately owned forests, it is important to examine the social, political, economic, and biophysical context in which timber is accessed and utilized so as to maintain a reliable resource base, better assist and achieve policy targets, and shape realistic expectations or outlooks for future timber supply or forest sector modeling.

Most studies examining timber harvesting behavior measure either landowners' intention to harvest/manage (Joshi and Arano, 2009; see Silver et al. (2015) for literature synthesis) or their observable harvesting and management behaviors (see Beach et al., 2005 for detailed reviews). Given that data availability and/or access has been a longstanding issue in forestry, both research avenues are immensely valuable from an information standpoint (to inform policy design choices and market analyses); however, they are not without shortcomings. Silver et al. (2015) point out that relying on studies that measure behavioral intention to harvest timber is unlikely to provide accurate results, as stated preferences are not always revealed preferences. This distinction between harvest intention and actual harvest is important because attitudes and intentions often do not align with planned behavior (Young and Reichenbach, 1987).

On the other hand, econometric studies using observable harvest or management data usually leave unexplained most of the variance in landowners' harvesting behaviors (Bashir et al., 2020; Zhao et al., 2020; Pattanayak et al., 2003) which could be attributed to uncertainty in market variables, measurement error, spatial and temporal inconsistency of datasets, information asymmetry, inadequate characterization of landowner preference heterogeneity, among other things (Beach et al., 2005; Lee, 1997). Furthermore, the diversity of forest landowners across the region with varying forest management objectives complicates the empirical analysis of factors that explain timber harvest and forest management decisions. For many FFOs, the decision to harvest may be triggered by an unexpected opportunity or need (Kittredge, 2004), such as "volvo harvests"[3](Johansson and Lofgren, 1985), rendering an additional challenge in modeling the behavior of FFOs. While the goal of aforementioned studies has been common i.e., to examine landowners' harvest/management decision, disparate research approaches have been applied due to limited access (and/or availability) of quality data and disjointed datasets, which limits our understanding of timber accessibility, harvest likelihood, and the potential additionality of forest ecosystem services gained through changes in management interventions, including increased carbon sequestration and storage. Nevertheless, several recent studies are bridging this research gap by coupling the Forest Inventory and Analysis (FIA) database and its rich representation of physical and management characteristics, with the National Woodland Owner Survey (NWOS) and Timber Products Output (TPO) (Butler and Sass, 2023; Thompson et al., 2017; Butler et al., 2010).

While there is a relatively broad consensus that many forest landowners hold forest land beyond the sole purpose of harvesting timber (Butler et al., 2021; Kilgore et al., 2015), results on which determinants affect landowners' timber supply and management behavior are mixed at best for FFOs. Studies have shown that both corporate landowners and FFOs are responsive to market prices (Newman and Wear, 1993; Prestemon and Wear, 2000); FFOs, however, are less responsive to market signals than their corporate counterparts (Beach et al., 2005) – the behavior attributed to higher values they place on non-market benefits derived from forests (Newman and Wear, 1993). Demographic characteristics, on the other hand, have been found to have little or no effect on harvest outcomes, except for income and, in some cases, age (Thompson et al., 2017; Beach et al., 2005). Contrary to what some research suggests (Silver et al., 2015; Beach et al., 2005), Thompson et al. (2017) found no significant association between tenure or plot size and harvest probability, but the relationship was significantly positive in predicting harvest intensity. Other studies deem resource conditions such as site productivity, growing stock, and distance to roads as consistent, positive, and strong predictors of landowners' harvest behavior (Thompson et al., 2017; Beach et al., 2005). Further, policies such as technical assistance programs and/or cost-share programs can also be important factors driving harvest decisions (Kilgore and Blinn, 2004; Hyberg and Holthausen, 1989; Boyd, 1984), but more so for FFOs than corporate owners and for reforestation activities than for harvest (Beach et al., 2005).

Structural timber supply models such as SRTS (Abt et al., 2009), LURA (Latta et al., 2018), and FASOM (Adams et al., 1996) assume that FIA inventory is entirely accessible for management/harvest and complement this accessibility assumption with rules governing what forest types and age classes can be harvested, including rotational assumptions (Baker et al., 2023). The global partial equilibrium model GLOBIOM, which is applied extensively for policy and environmental change analysis, distinguishes between planted and naturally regenerated forests, but does not distinguish timberland by ownership class (important in the U.S. context) or define market accessibility explicitly (Augustynczik et al., 2025; Daigneault et al., 2022). By treating total inventory as the current and future extractable resource pool, these models are likely to overstate effective timber supply and bias projections of prices and available resource base. The Global Timber Model (GTM) defines accessible, semi-accessible, and inaccessible forests, and allows the model to access semi-accessible and inaccessible forests at added costs, but these accessibility restrictions (at least in the U.S. context) are typically defined by ownership and age class and may not reflect factors that limit harvests and management. Further, market accessibility of timberland is a dynamic concept, subject to change over time under shifting market conditions, forest attributes, and social preferences for non-timber services that forests provide. There is thus a need for continuous inventory monitoring and analysis to update and refine accessibility estimates to support forest sector modeling. Given the importance of forest sector models in guiding timberland investment and policy design, improving the depiction of market accessibility constraints can ameliorate modeled projections of forest markets, management, and ecosystem services like carbon sequestration.

Empirical timber supply studies (Zhao et al., 2020; Fortin et al., 2019; Kittredge and Thompson, 2016; Petucco et al., 2015; Zhang et al., 2015) do incorporate a richer mix of biophysical, social, and economic/market factors to explain landowners' management/harvest decisions, but they are typically region-specific and rely on data — such as owner age, income, and transaction prices — that are proprietary and costly to obtain. As a result, their insights are difficult to scale to broader regions or to embed directly into large-scale structural supply models. However, studies on forest accessibility, mostly in Europe, have mapped operability constraints using road networks (Fraefel et al., 2021; Bont et al., 2018; Đuka et al., 2017) and/or biophysical factors (Phelps et al., 2021; Sferlazza et al., 2021), but these studies generally depend on explicitly georeferenced forest plots, which are confidential in the US

[3] The term "volvo harvest" was coined by Johansson and Lofgren (1985) to describe FFOs who harvest when they need an infusion of cash for big expenses such as a car or college or medical bills.

and therefore difficult to obtain. As such, there is no scalable framework that uses a consistent set of widely available biophysical and social proxies (of the kind used in empirical harvest studies) to moderate forest inventory estimates for accessibility within structural timber supply models. This study addresses that gap by estimating accessibility of forest, carbon, and species inventories over a large geographic area, providing an operational bridge between empirical harvest behavior and regional timber supply modeling. Aside from structural modeling, our results can help inform public policy (e.g., allocation of cost-share resources for forest management interventions) or the establishment of key baseline market metrics to support environmental markets.

Harvesting decisions subsume an amalgam of social and biophysical variables (Thompson et al., 2017). While the demand side is equally important, we focus on the supply side of timber availability; demand depends on market conditions and consumer preferences that go well beyond the forest. Demand also has an element of uncertainty, varies spatially, temporally, and by product class, and in the case of FFOs, may not be the principal motivating factor to harvest (Beach et al., 2005). The main purpose of this article is to identify, analyze, and apply biophysical and social factors that may inhibit timber accessibility using publicly and consistently available FIA data on forest land and forest resource conditions in the eastern US. To that end, we use a mix of regression and spatial analysis to estimate and map out the reduction propensity (or inaccessibility) in timber availability under some established constraints. Additionally, we build on Butler et al. (2010) to apply those plot-specific reduction propensities to estimate accessible wood inventory on timber basins across the eastern US. As pressure on the extractive timber resource base increases due to competing demands for amenities and carbon credits, as well as emergent timber products like Cross-laminated Timber (CLT), such estimates become increasingly important for planning purposes and to support forward-looking resource assessments and economic modeling. We extend our approach to also estimate accessible carbon inventory in the presence of these constraints; this approach might help address additionality concerns for carbon offset projects that require strong baseline assumptions regarding harvest or management likelihood. Lastly, as an adjunct to the overall availability of timber, we also provide an estimate of the accessible inventory of white oak (*Quercus alba*) under assumed constraint thresholds. With growing sustainability concerns for this species, our findings would be of special interest and relevance to stakeholders in white oak growing regions and have direct implications for the initiatives and policies aimed at maintaining a sustained supply base of white oak timber.

This study is novel in two key ways. First, it leverages consistent, publicly available FIA attributes across 33 eastern US states to assess how biophysical and management-related factors — especially non-market amenities and incidence of past management — constrain management and harvest decisions. Second, our analysis offers a scalable approach for estimating the accessibility of forest inventories (timber and carbon for commercial species) across multiple spatial units, including stands, counties, timber basins, and states.

To avoid potential semantic confusion, this paper defines accessibility as a portion of the physical inventory that can be reasonably accessed after accounting for several potential constraints related to site characteristics, non-timber management objectives, and past management/harvest experience. A major contribution of our study is that it formalizes and strengthens the anecdotal understanding that the actual available timber inventory is far less than the total presented by the FIA inventory numbers. First, we identify potential site and management-related constraints and establish a relationship between those identified constraints and management/harvest across the forested plots in the eastern US. Second, we use hot spot analysis and a heat map to visualize the spatial clustering of forested plots with varying percent of inventory reduction propensity (or inaccessibility). Lastly, as a testament to the applicability and scalability of the methodical approach, we estimate the accessibility of inventory across 142 timber basins in the eastern US.

2. Materials and methods

2.1. Data and metrics

This analysis leveraged the Forest Inventory and Analysis (FIA) database collected and managed by the US Forest Service on accessible forest land[4] (Bechtold and Patterson, 2005). The FIA program gathers, publishes, and analyses state, regional, and national inventory information for different forest ownership types in the US (Smith, 2002). The sample plots represent the permanent FIA network of ground plots, which has a spatial sampling intensity of approximately one plot per every 6000-acre hexagonal cell (Bechtold and Patterson, 2005). All states in the eastern US (barring west TX and west OK) are inventoried over 5–7 years, after which plots are remeasured (Burrill et al., 2023). We use a total of 127,056 plots from the most recent FIA database (FIA DataMart) in this analysis, representing the Northeast, Southeast, and Lake States regions (Supplement Fig. 2). Our sample reflects FIA's recently updated tree volume, biomass, and carbon attributes (Westfall et al., 2024). For this analysis, volume represents the net cubic-foot stem timber volume per acre[5]; carbon is the aboveground carbon of timber and bark per acre[6]; and white oak volume is the net cubic-foot stem timber volume of *Quercus alba* per acre. The results are presented in terms of percentages, a metric-neutral measure that circumvents the complications of using expansion factors and allows us to generate population estimates. This approach also allows our findings to be extrapolated and integrated into timber supply models.

The selection of empirical variables to represent the theoretical constraints was governed by the availability of consistent data across the region and the literature. The threshold at which a variable is deemed a constraint was based on a past study (Butler et al. 2010), followed by a logistic regression test; all the threshold levels chosen were found to significantly reduce the harvest/management probability of plots (Supplement Table 1). We loosely categorized variables into three bio-

Table 1
Summary of constraint thresholds for estimating reduction propensity on eastern US forest lands.

Constraint	Threshold level
Biophysical	
Site physiography	Hydric
Site productivity (cubic feet/acre/year)	< 20
Slope (%)	> 40
Social	
Ownership group	Federal
Distance to road (miles)	≥ 1 mile
Amenity index	High
Past Management	No

[4] The area must be at least 1 acre in size and 120 feet wide and has at least 10 percent canopy cover by live tally trees of any size. Tree-covered areas in agricultural production settings or urban settings are not considered forest land (Condition status code = 1 in condition table FIA database) (Burrill et al., 2023).

[5] The net cubic-foot volume of wood in the central stem of timber species, where diameter at breast height (dbh) is measured at dbh $\geq$ 5.0 inches from a 1-foot stump to a minimum 4-inch top diameter; it is calculated for live and standing dead trees and does not include rotten, missing, and form cull. This is a per tree value and must be multiplied by tree expansion factor to obtain per acre information (Burrill et al., 2023).

[6] The carbon, in pounds, of wood and bark in the aboveground portion, excluding foliage, of live and standing dead trees $\geq$ 1.0 inch dbh/drc. This is a per tree value and must be multiplied by tree expansion factor to obtain per acre information. The amount of carbon is calculated based on applying species-specific carbon fractions to the aboveground biomass (Burrill et al., 2023).

physical and four social constraints (Table 1; Fig. 1). Six of the seven variables were recorded on the plots by FIA field crews: site physiography, site productivity, slope, evidence of past management, ownership group, and road distance. Amenity metrics were developed utilizing other inventory attributes recorded on the plots (discussed in detail below).

Site physiography describes the general effect of land form, topographical position, and soil on the moisture available to trees (Burrill et al., 2023). As presented in the table, a biophysical constraint is considered present if a plot is classified as hydric, i.e., sites normally abundant or overabundant moisture all year, such as swamps/bogs, small drains, bays, and wet pocosins. A hydric site can be negatively associated with harvest choice (Polyakov et al., 2010). Site productivity measures the inherent capacity of a site to support forest growth for timber production; it identifies the potential growth in cubic feet/acre/year and is based on the culmination of the mean annual increment of fully stocked natural stands. The availability of timber on plots with a productivity level of less than 20 cubic feet/acre/year is classified as constrained because those plots do not meet FIA's timberland designation (Burrill et al., 2023).

Slope is another important physical factor that affects harvest and costs operations (Lundbäck et al., 2021). Studies have treated the slope of a site as a proxy for harvesting costs and have found a negative association with harvest (Polyakov et al., 2010). Further, some states have adopted various Best Management Practices (BMPs) on riparian zones/streamside management zones (SMZs) for protecting water quality during forest harvests at varying slopes. In Maine, slopes of 50 % or more require a minimum 125 ft wide filter areas (Moesswilde, 2017); in New York, riparian zone has width of 50 ft in 0–10 % slope and over 100 ft in areas of 41–70 % slope (NYS DEC, 2011); in North Carolina, only partial harvest is advised on SMZs with more than 50 ft wide SMZs on very steep slopes (Brogan et al., 2021); in Georgia (Georgia Forestry Commission, 2019), SMZ of at least 100 ft is recommended on steep slope (> 40 %) in case of perennial river. Since the exact percentages vary across states, we deemed a slope of greater than 40 % as a constraint, similar to Butler et al. (2010). Additionally, the FIA data considers plots with a slope greater than 40 percent least viable for operating logging equipment (Burrill et al., 2023). Slope is measured as the predominant or average angle of the slope across the condition to the nearest 1 %.

Private landowners not only dominate the ownership mosaic in the East, but harvest occurs predominantly on private lands in the region

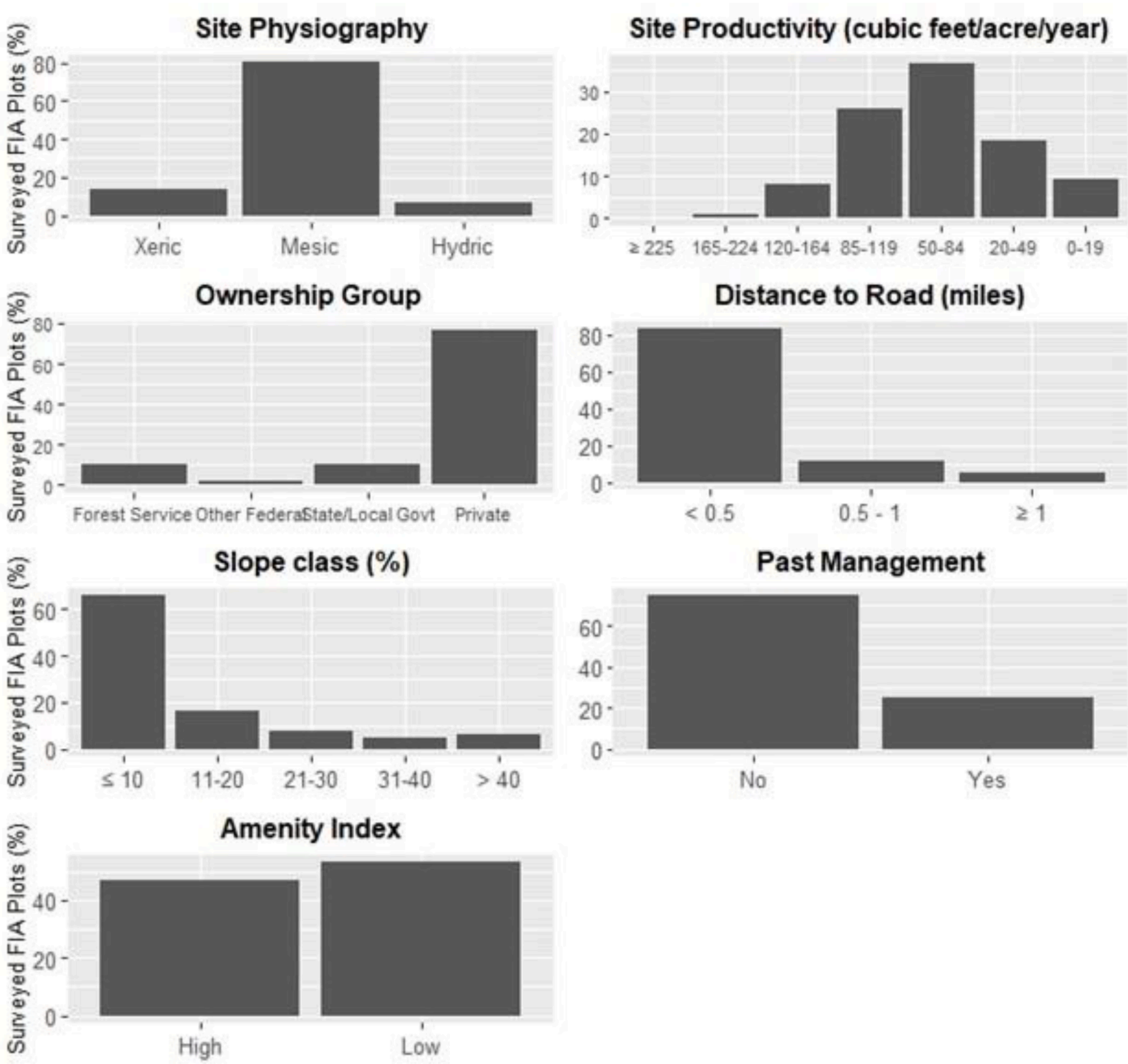

Fig. 1. Distribution of forest land by biophysical and social characteristics in the eastern US.

(Butler and Sass, 2023). However, public forests are managed according to state or local, or federal policies and other regulations, and are more often tasked with multiple management goals rather than one specific goal, such as recreation, water, wildlife, and timber (Oswalt et al., 2019). Thompson et al. (2017) found that the annual probability of a harvest event within a privately owned forest is twice as high as within publicly owned forests in the North, and among public owner classes in the North, the annual probability of harvest is highest on municipally-owned forests, followed by state-owned forests, and is lowest on federal lands. State and local government-owned forest lands become increasingly important in some states in the East, such as Minnesota and Connecticut, as a relatively high proportion of removals occur on forest land under State and/or local holding (Butler and Sass, 2023). Thus, the availability of timber on plots under federal ownership is considered a constraint. Federally managed forests include lands managed by federal agencies like the Forest Service, the National Park Service, the Bureau of Land Management, the Fish and Wildlife Service, the Department of Defense/Energy, and other federal agencies (Burrill et al., 2023).

Distance from a harvest site is an indicator of the relative ease of access to the forest site, as proximity measures pertain to operational logistics and costs associated with logging, including skid trail construction, maintenance, and log hauling. Studies have consistently shown that an increase in distance reduces the likelihood of harvest (Bashir et al., 2020; Thompson et al., 2017; Kline et al., 2004). These longer roads and trails could also be a source of sedimentation – directly in conflict with BMPs' goals. In agreement with Butler et al. (2010), the availability of timber on plots 1.0 mile or more from existing roads was considered a constraint. In the FIA database, the distance from the road is recorded as the straight distance from the center of the plot to the nearest improved road, which is a road of any width maintained, as evidenced by pavement, gravel, grading, ditching, and/or other improvements (Burrill et al., 2023).

Harvest occurs in $<$ 2 percent of forest land per year in the US (Oswalt et al., 2019), which underscores the importance of non-provisioning services and intangible financial benefits provided by forests. While timber production is an important financial asset for virtually all large corporate forest owners (Sass et al., 2021), non-pecuniary benefits in the form of amenities such as beauty or scenery, wildlife habitat, nature/biodiversity protection, and privacy are the primary stated reasons behind owning forest land for FFOs (Butler et al., 2021). Although limited in number, several studies on FFOs have found a negative association with harvest probability and measure of amenities (Beach et al., 2005). Holmes (1986) concludes that subjective valuation of aesthetic benefits has a negative effect on the propensity to harvest in New Hampshire.

Because most of the attributes captured by the FIA database that relate to amenities are either in discrete measures or not available in FIA at the plot level, we develop several indices to measure forest-based amenity characteristics, largely following Lee (1997). Amenity in this case also represents higher costs for harvesting, not just the value of standing forest; sorting various tree species of various sizes is a logistical challenge and costly. The following variables represent our amenity indices considered:

- *Tree diversity*: We emphasized landowner values for the diversity of tree species only. We use a commonly used measure of diversity: Shannon-Weiner (SW) Index. For each plot (i), the index is calculated as:

$$SW_i = -\sum_{k=1}^{K} p_k log p_k \tag{1}$$

where p_k is the proportion of total trees in species k.

- *Number of large trees:* Large diameter trees, greater than 20 inches dbh, are often highly desirable as amenities. (Holmes et al., 1997) found that viewing large trees holds relatively high consumer surplus values for wilderness visitors in the Southern Appalachian highlands.
- *Overstory percent:* Based on Hartman (1976) vision of parklike stands, we used dbh of individual trees from the FIA tree table to construct the overstory profile for individual plots. In our study, the overstory profile is a percentage of trees that are at least 11″ in dbh; thus, it describes the general level of the canopy cover on each plot. Using overstory as an amenity measure, Abt and Prestemon (2003) found that dense overstory significantly influences non-industrial private forest landowners' harvest choices, with more overstory corresponding to lower harvest probability.

We use principal component analysis (PCA) to derive a composite amenity index since we expect these three individual measures to be collinear, and we are interested in the overall amenities of a plot. Principal components allow us to summarize a larger set with a small number of representative variables that collectively explain most of the variability in the original set (James et al., 2021). Pattanayak et al. (2003) similarly used PCA to construct an amenity index in their study on nonindustrial private forest lands. After estimating measures of amenities as explained above, we apply PCA to tree diversity, number of large trees, and overstory percent. We use only the first principal component that (1) is the only component with an eigen value > 1 and (2) explains 52 % of the combined amenities' variance. The amenity index (A) or the scores of the first principal component for an individual plot are given by:

$$A = \sum_{i}^{3} \phi_i \left(\frac{A_i - \overline{A}_i}{\sigma_{Ai}} \right) \tag{2}$$

where i includes tree diversity, overstory percent, and number of large trees; A_i is a measure of amenities; $\overline{A}_i$ is the mean of amenity measures; ϕ_i is principal component loadings or weights. The loadings are -0.5, -0.58, and -0.65, respectively, suggesting that a negative component score measures a site rich in tree diversity, overstory percent, and number (#) of large trees.

In our study, plots with a negative score of the amenity index (A) are considered a constraint because of their overall high measures of amenities. Table 2 provides a statistical summary of amenity measures (see Supplement Table 2 for mean values across timber basins).

While the effect of past forest management on future management/harvest decisions has not been formally studied, it can generally be assumed that – largely drawing from the field of social psychology — past behavior is a strong predictor of future behavior (Gibbons et al., 1998; Janis and Nock, 2008; Ouellette and Wood, 1998; Wood et al., 2002). Butler et al. (2010) used owner attitude index – a composite binary metric of harvest experience, harvest objectives, and harvest intentions—to estimate reductions in wood availability from FFOs in the northern US. In our case, plots with no history of management were considered a constraint, thereby reducing the accessible inventory pool.

2.2. Regression analysis

We used a logit model to estimate the reduction propensity in timber or carbon availability, i.e., the probability of no harvest/management. The dependent variable, i.e., indicator of no harvest/management, is recorded in the FIA data for plots with no occurrence of observable stand treatment since the last measurement or within the last 5 years for new plots.

Mathematically,

$$P(y=1|\boldsymbol{x}) = G(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7) \tag{3}$$

Table 2
Summary statistics of measures of amenities and corresponding amenity index.

Amenities' measure	Minimum	First quartile	Median	Mean	Third quartile	Maximum
Tree diversity	0	0.62	1.1	1.05	1.52	2.59
#large trees	0	0	0	0.48	1	20
Overstory %	0	0.04	0.18	0.21	0.32	1
Amenity index (A)	−14.26	−0.74	0.09	−0.08	0.83	1.7

where P is the response probability; y is an indicator of no harvest; x_1 indicates hydric site; x_2 indicates site productivity class less than 20 cubic feet/acre/year; x_3 indicates federal ownership; x_4 indicates road distance ≥ 1 mile; x_5 indicates slope class greater than 40 %; x_6 indicates no evidence of past harvest/management; and x_7 indicates high amenity. In the logit model, G is the logistic function – the cumulative distribution function takes on values strictly between 0 and 1.

The predicted probability ($\hat{p}_i$) for the i^{th} plot is:

$$\hat{p}_i = \frac{1}{1 + e^{-(\hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \hat{\beta}_3 x_3 + \hat{\beta}_4 x_4 + \hat{\beta}_5 x_5 + \hat{\beta}_6 x_6 + \hat{\beta}_7 x_7)}} \quad (4)$$

2.3. Spatial analysis

The spatial analysis was implemented in two steps using ArcGIS Pro: optimized hot spot analysis and interpolation. The optimized hot spot analysis is a spatial statistics tool that interrogates the data and identifies optimal settings for analysis to create a map of statistically significant spatial clusters of hot spots (high values) and cold spots (low values) using the Getis-Ord Gi* statistic (Getis and Ord, 1992). Mathematically, the Getis-Ord local statistic is given as (Esri. 2017):

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij} x_j - \bar{X} \sum_{j=1}^{n} w_{ij}}{S\sqrt{\frac{\left[n\sum_{j=1}^{n} w_{ij}^2 - \left(\sum_{j=1}^{n} w_{ij}\right)^2\right]}{n-1}}} \quad (5)$$

where x_j is the reduction propensity or the predicted probability ($\hat{p}$) for plot j, w_{ij} is the spatial weight between plot i and j, n is equal to the total number of point features (# plots in our case), and:

$$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n} \ (6); \ S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2} \quad (7)$$

The output of the optimized hot spot analysis is a feature class with a z-score, p-value, and confidence level bin for each point feature. We conduct a hotspot analysis in lieu of aggregating FIA plot-level information to larger geopolitical (state) or ecological (eco-province) levels, allowing the optimized hotspot analysis to interpolate timber and carbon availability measures across the Eastern US. We then categorized the hot and cold spots with confidence level bins.

Because our features of interest were points, not polygons, we interpolated a raster surface from outputs of optimized hot spot analysis (G_i^*) and generated a heat map of inventory reduction propensities. To do so, we used the Inverse distance weighted (IDW) technique (Watson and Philip, 1985). IDW is a spatial analysis tool that determines cell values using a linearly weighted combination of a set of sample points; the weight is a function of inverse distance (Esri. 2017). Mathematically,

$$\hat{Z}(s_i) = \sum_{j=1}^{N} \lambda_j Z(s_j) \quad (8)$$

where $\hat{Z}(s_i)$ is the value we are trying to predict for the location s_i, N is the number of measured sample points surrounding the prediction location, $Z(s_j)$ is the observed value of G_i^* at the location s_j and λ_j are the weights assigned to each measured point:

$$\lambda_j = \frac{d_{ij}^{-p}}{\sum_{j=1}^{N} d_{ij}^{-p}} \ (9); \ \sum_{j=1}^{N} \lambda_j = 1 \quad (10)$$

where d_{ij} is the distance between the prediction location, $s_i$and each of the measured locations, s_j, p is the power parameter. As the distance becomes larger, the weight is reduced by a factor of p.

2.4. Estimation of accessibility across timber basins

Using the plot-specific reduction propensity or the predicted probability ($\hat{p}_i$) from Eq. (4), we estimated the percentage of accessible inventory across 142 timber basins in the eastern US. These timber basins are FIA survey units within each State and form the unit of analysis in regional timber supply models such as SRTS (Abt et al., 2009; Dhungel et al., 2023). The accessibility percentages are estimated as:

$$Accessibility_{basin} = \frac{\sum_{i=1}^{n} (1 - \hat{p}_i) Inventory_i}{\sum_{i=1}^{n} Inventory_i} * 100 \quad (11)$$

where n is the number of plots (i) within a timber basin, and $Inventory_i$ is the initial inventory reported at individual plots.

We estimated the accessibility of three inventory components: timber, carbon, and white oak timber. For the estimation of white oak accessibility, the tree list file was first filtered by white oak (species code 802 in FIA data); plots with no white oaks were not included when assigning constraints and estimating white oak accessibility. We note that the accessibility estimate for carbon is a corollary of timber not being accessible for harvest. When a constraint is present in a plot, it considerably reduces the accessibility of harvestable timber from that plot, thereby reducing the likelihood of the carbon content of that harvestable timber being accounted as a potentially additional source of carbon sequestration. Consequently, this provides estimates of the percentage accessible in aboveground carbon that can be considered additional from a harvest deferral carbon offset standpoint.

3. Results

3.1. Logistic regression

All seven variables used as constraints were found to significantly increase the absence of management/harvest on forest lands in the eastern US (Table 3). In terms of magnitude, hydric sites had the highest impact, while amenity had the smallest impact in explaining the lack of management. When a plot switched from relatively dry and well-drained sites to sites with abundant water, the log-odds of no management decision increased by about 1.57, or alternatively, the odds of no management increased by a factor of about 4.82, holding other variables constant. In the case of site productivity, as the plot switched from a higher productivity class to the lowest, the log-odds of no-management increased by about 1.0664 (odds ratio of 2.9). As expected, federal ownership increased the log-odds of no-harvest by about 0.96 (odds ratio of 2.62) compared to non-federal ownership, such as private and state/local government. Likewise, plots with a slope greater than 40 %, plots 1 mile or further from the road, and plots with a high amenity index increased the log-odds of no harvest/management by about 0.57 (odds ratio 1.78), 0.51 (odds ratio 1.66), and 0.48 (odds ratio 1.61),

Table 3
Logistic regression of No management/harvest.

	Dependent Variable: Harvest/Management (No = 1)
Physiography (Hydric)	1.5720*** (0.0710)
Site class (0–19)	1.0664*** (0.0469)
Ownership (Federal)	0.9639*** (0.0414)
Distance to road (≥ 1 mile)	0.5058*** (0.0559)
Slope (> 40 %)	0.5749*** (0.0802)
Past Management (No)	0.7575*** (0.0190)
Amenity Index (High)	0.4760*** (0.0191)
Observations	127,056
Pseudo R^2	6.45 %
Likelihood ratio test: χ^2 value	5817.2 ($p < 0.00$)
Percent correctly predicted (0.8 cutoff)	81.56 %
Wald test: χ^2 value	4977.5 ($p < 0.00$)
Log Likelihood	−42,180.0200
Akaike Inf. Crit.	84,376.0400
Residual Deviance	84,360.0400 (df = 127,048)
Null Deviance	90,177.2200 (df = 127,055)

Note:*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

respectively. Interestingly, the evidence of no management/harvest in the past increased the log-odds of no present-day harvest/management by about 0.76 (odds ratio 2.13), holding other variables constant. The variance inflation factor was roughly 1 for all the variables, suggesting no multicollinearity among constraints.

To roughly test the performance of constraints, we mapped the occurrences of actual management/harvest (or not) against the number of constraints present (Table 4). In FIA data, when a stand has undergone treatment, primarily harvest, such stands are coded as treated. Of the total harvested/treated plots (14,489), around 30 % occurred on plots with no constraints present, 39 % on plots with one constraint, 27 % on plots with two constraints, and 4 % on plots with three constraints. On the other hand, of the total plots with no management/harvest (112,567), about 12 % of plots had no constraints, 30 % had one constraint, 43 % had two constraints, and 13 % had three constraints. From the perspective of identifying plots with no management/harvest – the primary purpose of this study – in the presence of established constraints, the error rate was (13,293/112,567) *100 = 12 %.

3.2. Spatial clusters of inventory reduction propensity

The optimized hot spot analysis, together with the IDW technique, revealed some distinct patterns of spatial clusters of inventory reduction propensity (Fig. 2 and Fig. 3). The hot spots are increasingly red spots with significant spatial clustering of higher reduction propensity, whereas the cold spots are increasingly blue spots with significant clustering of lower reduction propensity (Fig. 2). The heat map is the interpolated raster surface from the corresponding hot and cold spots of the optimized hot analysis map (Fig. 3). These hot and cold spots are the Getis-Ord Gi* statistic (or the Z score) of the inventory reduction propensity (or the predicted probability); the inventory reduction propensity ranges from 0.75 to 0.99 with a mean of 0.88. The red spots suggest spatial clusters of higher inventory reduction propensity (less accessible) at a 90 % confidence level or higher; these are densely concentrated around central Texas, central Oklahoma, the southern Appalachian corridor (abutting northern Georgia, eastern Tennessee, western North Carolina, western Virginia, and eastern West Virginia), and northern Minnesota. The hot spots are also scattered around Gulf coastal Louisiana, the Ozarks in Arkansas and Missouri, northern New Hampshire, west central Vermont, northeast New York, northwest Pennsylvania, and parts of the Lake States. On the other hand, blue spots suggest a spatial cluster of relatively low inventory reduction propensity (more accessible) at a 90 % confidence level or higher; these are visibly concentrated along the southern outer coastal belt from the Atlantic in Virginia to the Gulf coast in eastern Texas, southern Arkansas, and most of Maine in New England. In support of the optimized hot spot analysis, the heat map mirrors similar patterns of inventory reduction propensity.

3.3. Inventory accessibility across timber basins

The accessibility of timber inventory was heterogeneously distributed across 142 timber basins in the eastern US, ranging between 18 and 2 percent (Fig. 4, see Supplement Table 3 for precise estimates). The higher the value of the inventory reduction propensity, the lower the accessibility percentage and vice versa. The timber accessibility was on the higher end, 12 to 18 percent, in southern Arkansas, most parts of Louisiana except the Deltas, northeast Texas, central and southern Alabama, southern Georgia, coastal plains of the Carolinas, central Wisconsin, and all of Maine. Conversely, the timber accessibility was on the relatively low end – below 8 percent, in central and western Texas, most of Oklahoma, southern Delta in Louisiana, central Florida, northern Georgia, western North Carolina, eastern Tennessee, eastern West Virginia, western Virginia, southern Illinois, northern Minnesota, upper peninsula in Michigan, southern Vermont, and northern New Hampshire. Likewise, the accessibility of carbon inventory followed a similar pattern to timber inventory (Fig. 5). As far as the accessibility of white oak was concerned, the estimates ranged from below 2 percent to 18 percent (Fig. 6). The accessibility was highest in southern Maine and northern Vermont, followed by southeastern Pennsylvania, west central New York, southwestern Alabama, northwestern Louisiana, and northcentral Texas. In contrast, the accessibility of white oak inventory was the lowest in central Texas, northcentral Minnesota, and southern Illinois (for precise estimates, see Supplement Table 3).

4. Discussion

The patterns of inventory reduction propensity (or accessibility) illustrated in the hot spot analysis map (Fig. 2) and the resulting heat map (Fig. 3) are largely consistent with the findings of national-scale forest disturbance datasets such as the NAFD-ATT Forest Canopy Cover Loss dataset from 1986–2010 (Schleeweis et al., 2020) and NACP NAFD Forest Disturbance Intensity for the conterminous United States from 1986 to 2015 (Lu et al. 2023). The cold spots of significant inventory reduction propensity (or high accessibility) largely fall in regions with evidently large forest disturbance through harvest removal.[7] On the other hand, hot spots of significant inventory reduction propensity (or low accessibility) are primarily concentrated in regions with relatively stable and undisturbed forests.[8] Additionally, the region with no evidence of significant inventory reduction (or accessibility) overlaps with the region with sparsely distributed FIA plots or scattered contiguous forest land.

Our analysis supports the anecdotal understanding that a large portion of physical forest inventory is not readily accessible for timber production under current circumstances, and this is particularly true for naturally regenerated forests in the mountains relative to plantation forests in the coastal plains. The regions with higher inventory reduction propensity or lower share of accessible timber inventory have a higher number of constraints present (Supplement Table 4, Supplement

[7] The coastal Atlantic plains and gulf coasts in the Southeast and most of Maine.

[8] Along the mountainous region of the Appalachia, the Ozarks, Ouachita, the shrubland region of western Texas and Oklahoma, and parts of the upper Midwest.

Table 4
Mapping the occurrences of actual management/harvest against the number of constraints present in FIA plots.

	#Constraints								
	0	1	2	3	4	5	6	7	Total
No management/harvest	13,293	33,718	47,987	15,125	2311	132	1	0	112,567
Management/harvest	4358	5669	3890	543	29	0	0	0	14,489
Total	17,651	39,387	51,877	15,668	2340	132	1	0	127,056

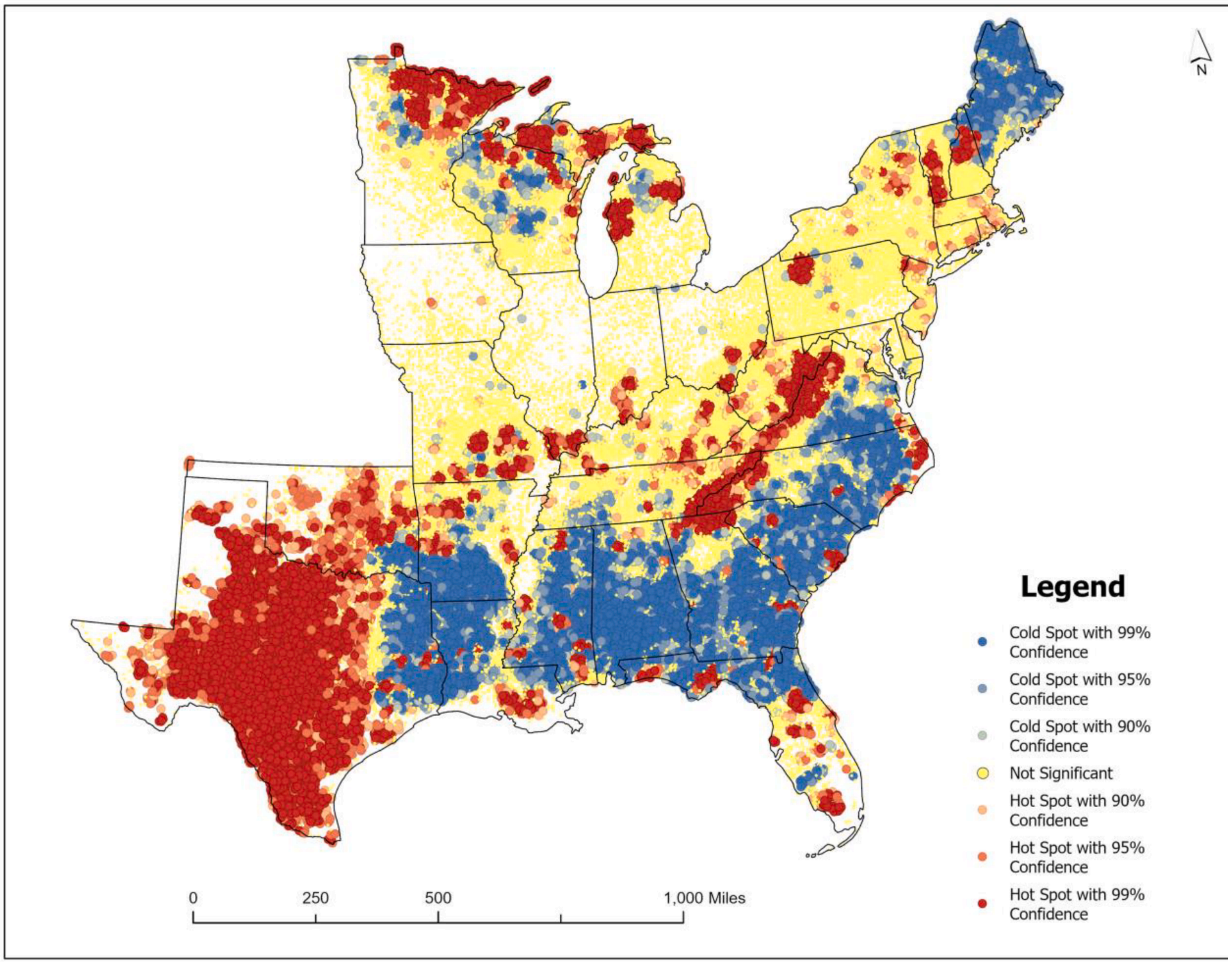

Fig. 2. Identified hot and cold spots of inventory reduction propensity (inaccessibility).

Figure 3), largely attributed to the ecological disposition of these lands[9] (see Cleland et al., 2007 for the ecological map). For instance, in the Appalachian regions constraints such as slope and higher amenity values provided by the diverse forests become more pronounced; in the gulf coast and the lake States constraint such as presence of water year-round limit forest management activity; and the drier part of West Texas the preponderance of lower productivity site class and lack of merchantable trees constraints harvest activity (Supplement Table 4, Supplement Figure 3). On timber basins with an accessibility propensity below 8 percent, harvest constitutes, on average, about 0.5 percent of the total inventory annually, suggesting that these regions already operate at low harvest levels (Supplement Table 5). Conversely, timber basins with somewhat lower inventory reduction propensities, or a higher share of accessible timber inventory, have a relatively low number of constraints present, with evidence of past management, lower amenity values, and higher private ownership[10] (Supplement Table 4, Supplement Figure 3). On timber basins with accessibility propensity above 12 percent, harvest constitutes, on average, about 2.43 percent of the total inventory, suggesting that these regions have relatively high harvest activity (Supplement Table 5).

While the magnitude of our findings on timber accessibility (or reduction propensity) may seem low (or high), our numbers are reasonable compared to a similar work by Butler et al. (2010) on family forest land in the North. Butler et al. (2010) estimated the cumulative reduction in wood availability at around 62 %, with a reduction propensity ranging from 50 % in Maine to 95 % in Delaware. However, it is no surprise that our estimates do not align perfectly with their findings,

[9] These regions included the Prairie parkland and shrubland in west Texas, the Ouachita mountains in Oklahoma, the marshy gulfcoast and inland bays in Louisiana, the Ozarks in Arkansas and Missouri, the Adirondack highlands in New York, and the Blue Ridge and Alleghany mountains in the central Appalachian broadleaf forest.

[10] These regions include the southern Atlantic and gulf coast plains, southwest Arkansas, and the Northeast mixed forest in Maine.

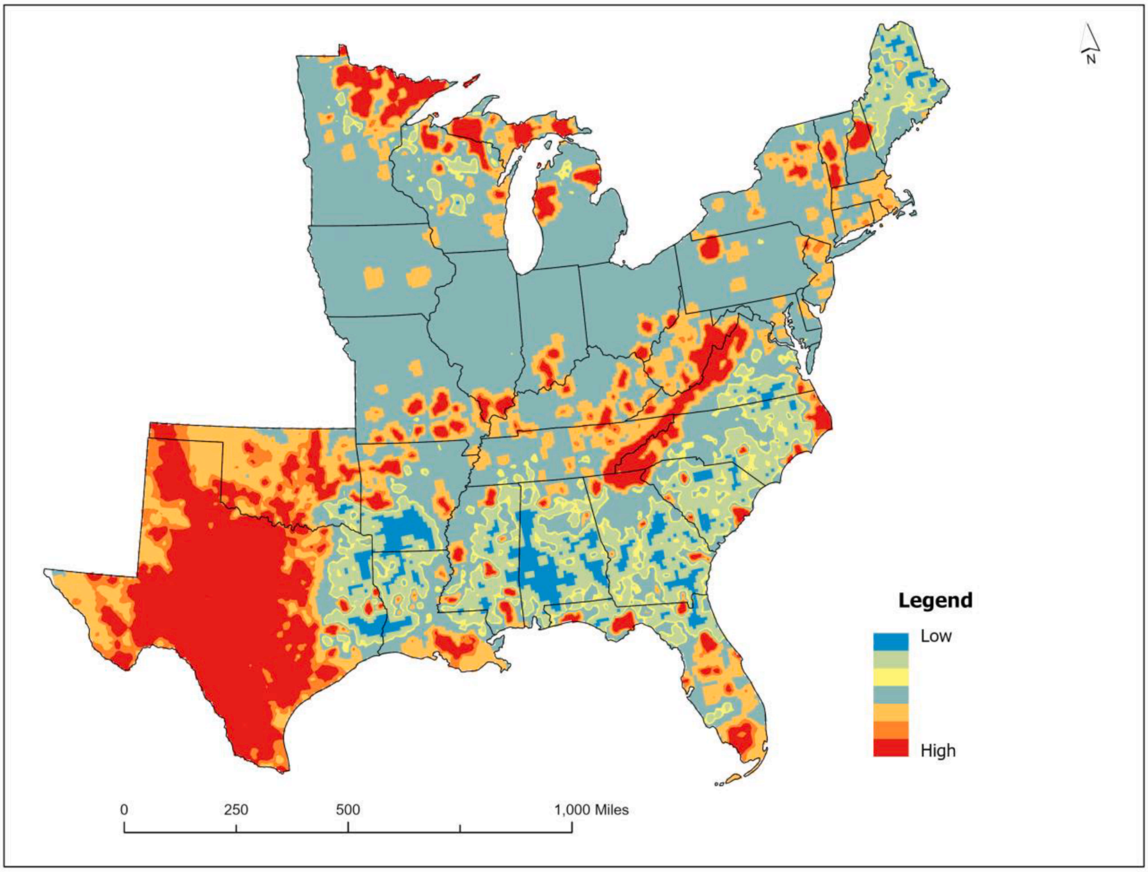

Fig. 3. Heat map of identified hot and cold spots of inventory reduction propensity (inaccessibility).

given the differences in variables incorporated, time frame of the analysis, methodology adopted, and the scale of application. Both studies, however, have four constraints in common (site physiography, site productivity, distance to roads, and slope), and our regression analysis corroborates the choice of constraints included in this analysis and their relative impact on timber accessibility. Interestingly, in Butler et al. (2010), owner attitude index (a function of ownership objectives, harvesting experience, and harvest intentions) accounted for about 53 % of the estimated reduction in wood availability. In our case, we used the amenity index and the evidence of past management to capture the owner's attitude index; we found that higher amenity plots and plots with no evidence of past management significantly increase the probability of no-management/harvest. Additionally, just under 50 % of plots provide high amenity values, and just over 65 % of plots had not been harvested/managed in the past (Fig. 1).

It is important to note that the higher average inventory reduction propensity of about 88 % and the overall lower accessibility of inventory below 18 % is not surprising because the average harvest as a percentage of total inventory in the eastern US is around 1 % (Supplement Table 5). The highest harvest activity was in southeast Georgia at 5 %, while harvests are virtually nonexistent in western Oklahoma and forested areas in central and western Texas. Overall, the inventory reduction propensity was found to be lower and the accessibility propensity higher in timber basins with fairly high harvest/management activity – all timber basins with over 2 percent harvest activity were in the Southeast, except one timber basin in Maine (Supplement Fig. 1).

Similar studies using national forest inventory (NFI) data have been conducted in Europe at both national and continental scales. Antón--Fernández and Astrup (2012) found that, in Norwegian forests, the probability of final felling increased with site index and standing volume, and decreased with slope, distance to road, and stand maturity; they also reported that areas with high timber value and low harvesting costs were more likely to be harvested. Levers et al. (2014) identified hotspots of high harvesting intensity primarily in traditional wood-producing countries, with the share of plantation species, terrain ruggedness, and country-specific characteristics together explaining more than half of the model's variance. Suvanto et al. (2025) present the first harmonized assessment of harvest regimes across 11 European countries and show that regions dominated by even-aged rotation management exhibit low frequencies but high intensities of harvest events. Taken together, these findings are broadly consistent with our logistic regression and accessibility results: steep slopes, remoteness, and low-productivity sites are significantly associated with no management or harvest, whereas highly accessible areas are concentrated in the plantation belt of the southeastern United States —a traditional wood-sourcing region with intensive even-aged plantation regimes. Alberdi et al. (2020) estimated that forests not available for wood supply (FNAWS) account for 5–25 % of forest area, which is considerably lower than our basin-level estimates of 80–98 %. Our estimates are more comparable to those reported in a similar U.S. study (Buter et al. 2010); the discrepancy with Alberdi et al. (2020) likely reflects differences in spatial scale (country-level versus stand-level estimates aggregated to micromarket basins), as well as differences in how accessibility constraints and environmental restrictions are defined and vary between Europe and the US.

4.1. Practical application and implications

The results of this study have important implications for policies, programs, and services that affect eastern forest land in the US and the benefits accrued from these forests. First, by incorporating forest-based amenities and evidence of past management or harvesting experience,

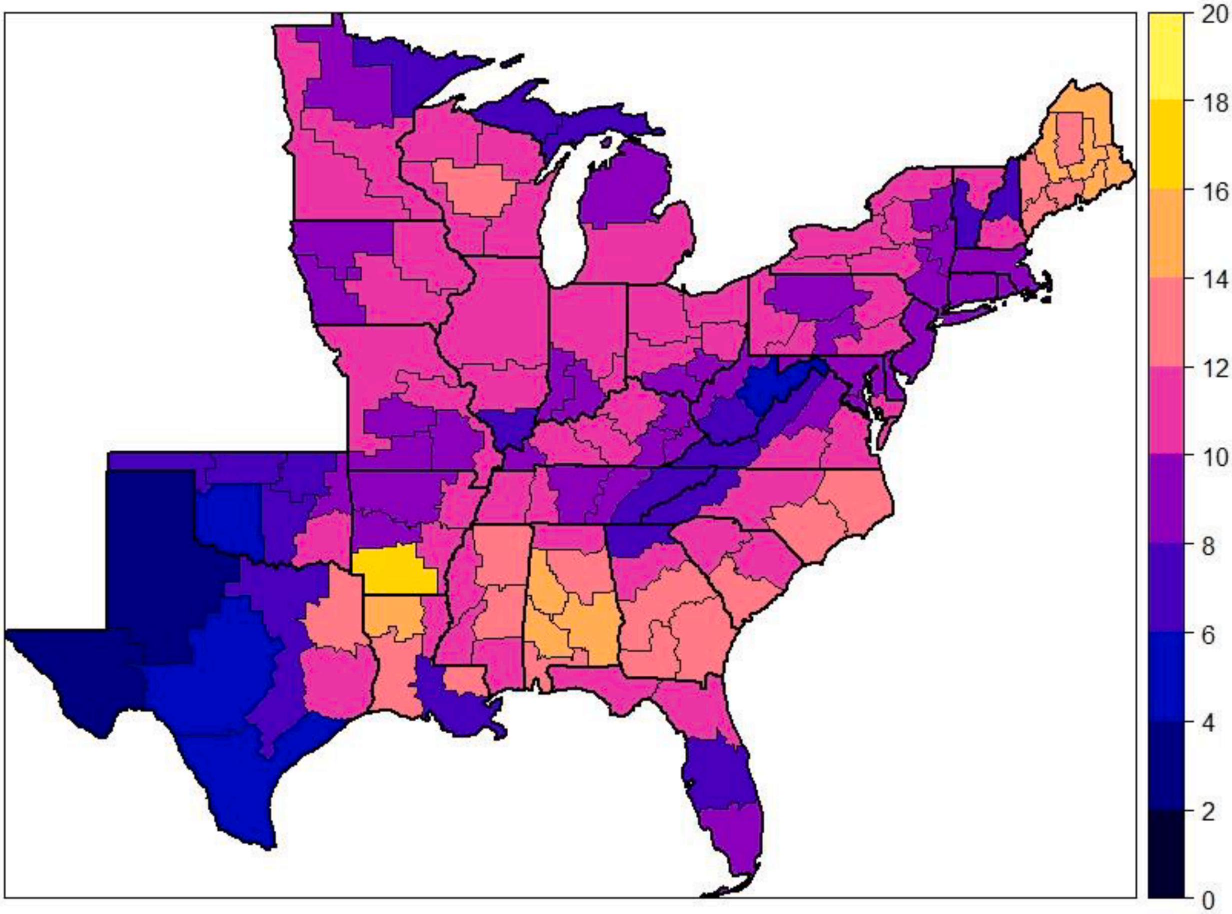

Fig. 4. Accessibility (%) of timber inventory across timber basins.

we provide evidence to the anecdotal understanding of the role of non-timber objectives and lack of management experience in forest management/harvest, and the resulting effect on timber accessibility. As amenity values become increasingly important (Sass et al., 2023), forest land is effectively removed from the timber base (Lee, 1997) unless a dramatic shift in forest land owner preferences were to occur. As such, timber supply models based on timber inventory or land area may overestimate the potential timber supply available from forest land if the constraints deterring forest harvest activity are not accounted for. The impacts of biophysical and social characteristics on timber availability could provide insights into future supplies with results and/or approach potentially incorporated into projection models, such as those used by the Renewable Resource Planning Act Assessment (Wear et al., 2013), the SubRegional Timber Supply model (Henderson et al., 2024), or models used for U.S. forest carbon projections such as the Global Timber Model (Tian et al., 2018) and the Forest and Agricultural Sector Optimization Model (Favero et al., 2024; Baker et al., 2023; Wade et al., 2022). The Global Timber Model (GTM) currently classifies some forests as semi-accessible or inaccessible due to some of the aforementioned factors, though these forests can be accessed in the model at higher costs. That is, if marginal returns to timber production are high enough, then what forests we deem "available" for market production is a dynamic variable, endogenous to changing market conditions and landowner preferences – this relationship emphasizes the need for continued empirical analysis of factors affecting regional timber and carbon availability to inform larger forest sector modeling efforts. Results from this study or its flexible empirical approach could be used to periodically update estimates of timber accessibility and related constraints in forest sector models.

Second, identification of unharvested and harvested plots with high potential for harvest (i.e., presence of few physical or socioeconomic constraints) could lead to more informed policies or voluntary markets that are designed to expand, limit, or temporarily defer forest harvest. This could be in terms of easing constraints on currently and/or potentially active timber base (or forested plots) with the goals of increasing the flow of timber. Conversely, goals could involve identifying lands of high harvest likelihood for harvest deferral carbon offset contracts (Sharma and Kreye, 2022). Incentives to encourage or reward harvest deferrals through the carbon payments program will not affect additional carbon sequestration if landowners already extend their rotation for amenity purposes or have no intent to harvest due to other biophysical characteristics of forested plots.

Third, by further evaluating a commercially valuable species with a niche market like white oak, we highlight how timber availability may be very different when specific species are examined. According to our estimates, the accessibility of white oak is below 10 % (Fig. 6, Supplementary Table 3) in timber basins located in most parts of the central hardwood region (southern and central Appalachia, the Ozarks, and some Midwestern states), where white oak is a critical resource supporting the distilleries and other niche forest product sectors. Our results could provide insights into the current and future sustainability of the harvestable white oak timber base, including prioritization for the White Oak Initiative Assessment and Conservation Plan (White Oak Initiative, 2021). Results from this study can help prioritize areas where management related to white oak sustainability would be most likely to succeed, as policies designed to increase stand-level sustainability may be counterproductive if current management objectives are not considered.

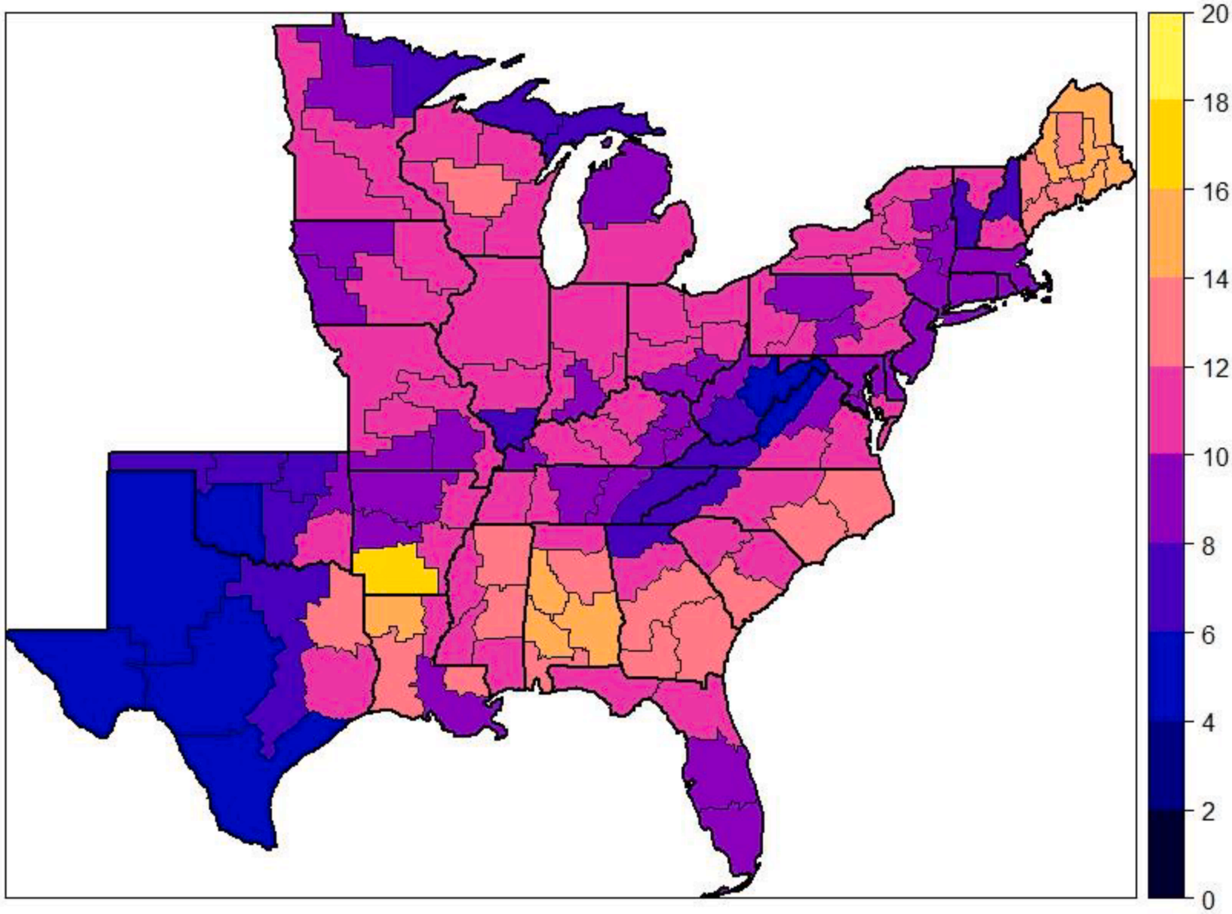

Fig. 5. Accessibility (%) of carbon inventory across timber basins.

Although our estimates indicate that less than 20 % of the total standing inventory is currently accessible under our constraint assumptions, this does not imply an imminent shortage of harvestable timber, given that average annual removals are on the order of 1 % of standing volume (Supplement Table 5). Moreover, roughly 70 % of plots show no evidence of past management, and nearly half are characterized by high amenity values (Fig. 1); both factors are strongly associated with the absence of harvest activity in our model. By contrast, only a relatively small share of plots is constrained by biophysical factors (e.g., steep slopes, remoteness), which are largely fixed in the short run. From a future timber-availability perspective, this suggests considerable scope to increase supply through improved dissemination of forest management information and enhanced market access, as landowners may not have access to management information, and some may even be willing to trade a portion of amenity benefits for timber income under appropriate incentives. Our analysis also provides insights that could lead to a more accurate natural capital accounting of timber, as the constraints analyzed can be used to fine-tune what is considered timber. In addition to defining actively managed timberland, our estimates can be used to proxy for harvest likelihood or related parameters that can be used to establish baseline and additionality criteria for forest carbon offset programs and related environmental markets.

4.2. Study limitations

While our estimates help advance the literature on factors influencing the market accessibility of timberland, there are several limitations worth pointing out. The list of variables included in our analysis is not exhaustive. An inclusion of a few more variables would have further reduced the error rate (Table 4), but they were not included due to data limitations or other reasons. First, tract size is an important determinant influencing timber harvestability as it is directly related to economies of scale (Row, 1978). Apart from uneconomical operational costs associated with smaller parcels, other issues could also arise with multiple owners abutting a harvest area (Catanzaro et al., 2007).

Second, inclusion of variables capturing market factors is almost ubiquitous in timber supply studies (Beach et al., 2005). Unlike econometric studies, stumpage price could not be incorporated in our study due to the nature of our estimation approach; however, an index based on distance and volume to sawmills, similar to Butler and Sass (2023), could capture the impact of the timber market on harvestability. Both these limitations can be addressed by using FIA data in conjunction with NWOS and TPO mill data, all collected under the auspices of the FIA program. However, the confidentiality of information related to tract size and mill data precludes public sharing of full datasets. Additionally, the relationship between the FIA forest plot and NWOS is a many-to-one relationship, i.e., an FIA plot represents only a fraction of an owner's holdings, but the owner's characteristics correspond to all of their acres (Butler et al., 2010). As a result, the coupling of all three datasets leads to an obvious trade-off between sample size and a richer set of descriptive attributes.

Third, the availability of wood in the long run will also be influenced by development pressures on the forest land. Stein et al. (2005) estimate that over 11 % of private forests — particularly in the East — are likely to see dramatic increases in housing development in the next three decades, with 12 states in the Northeast and the South being hit the hardest by the shift from rural to exurban. While we do not explicitly account for potential reduction in timber availability due to potential landuse

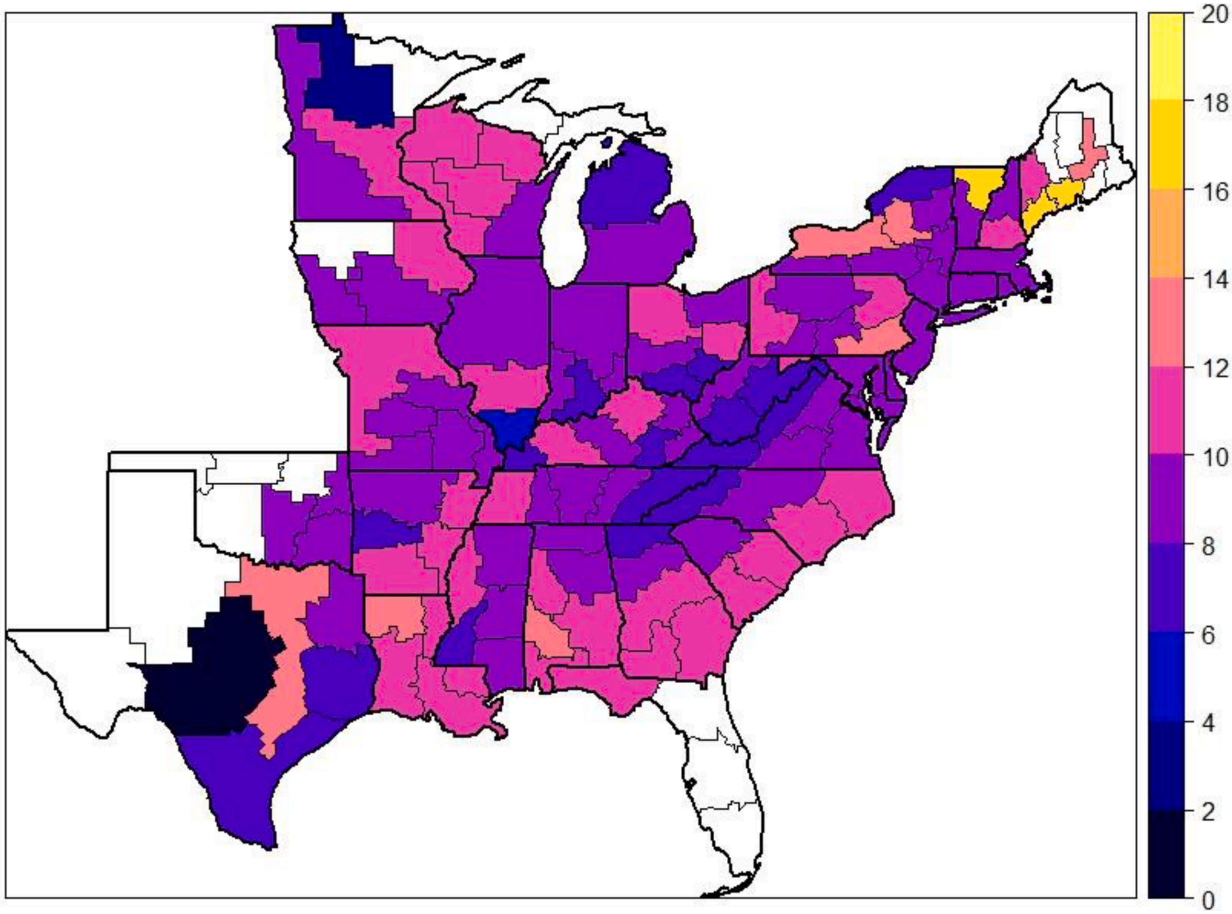

Fig. 6. Accessibility (%) of white oak inventory across timber basins.

change, such as urban development, variables such as slope and distance to roads should capture (to some extent) their approximate impacts, as plots with relatively flat terrain and shorter distance to nearest roads offer a proxy for the vicinity of urban centers.

5. Conclusion

The estimates in this study are static estimates. To our knowledge, this is the first study to provide basin-level estimates of accessible inventory — encompassing timber, carbon, and high-value species — using a common estimator across wood basins in the eastern US. Our approach and findings offer a concrete starting point for benchmarking baseline inventory availability and for designing measures aimed at increasing national wood supply, both at the extensive margin (by bringing currently unmanaged or marginally accessible stands into production) and at the intensive margin (by optimizing harvest intensity and product mix on already accessible stands). Given that most empirical studies on timber harvests have perennial limitations in that they leave unexplained most of the variance in landowners' harvesting behaviors, our approach could help bridge the gap between empirical models and practical applications of such models by translating the effects of variables into estimates that vary across spatial scales. While the application of hot spot analysis in forestry is not new (Sodiya et al., 2023), our study contributes to the literature by providing a mix of statistical and spatial tools that can be adopted at various scales to identify and target accessible timber basins for forest investment, such as mill establishment or additional carbon offset supplies. However, more empirical research is needed to fine-tune the thresholds for specific constraints and to develop appropriate inventory reduction propensities at a more granular level. Since markets for wood products and landowner preferences/objectives vary considerably, and data related to economic factors such as price and product mix are not consistently available across the wider 33-state region, it may be appropriate to use similar methods with additional variables to generate estimates at state or even timber basin scales.

CRediT authorship contribution statement

Gaurav Dhungel: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Justin Baker:** Writing – review & editing, Supervision, Software, Resources, Project administration, Funding acquisition, Conceptualization. **Jesse D. Henderson:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2026.101155.

Data availability

Data will be made available on request.

References

Abt, K.L., Prestemon, J.P., 2003. Optimal Stand management: traditional and neotraditional solutions. In: Sills, E.O., Abt, K.L. (Eds.), Forest in a Market Economy. Springer, Dordrecht, pp. 41–57. https://doi.org/10.1007/978-94-017-0219-5.

Abt, R.C., Cubbage, F.W., Abt, K.L., 2009. Projecting southern timber supply for multiple products by subregion. For. Prod. J. 59, 7–16.

Adams, D.M., Alig, R.J., Callaway, J.M., McCarl, B.A., Winnett, S.M., 1996. The forest and agricultural sector optimization model (FASOM): model structure and policy applications. Res. Pap. - US Dep. Agric. For. Serv. PNW-RP-495.

Alberdi, I., Bender, S., Riedel, T., Avitable, V., Boriaud, O., Bosela, M., Camia, A., Cañellas, I., Rego, F.C., Fischer, C., Freudenschuß, A., Fridman, J., Gasparini, P., Gschwantner, T., Guerrero, S., Kjartansson, B.T., Kucera, M., Lanz, A., Marin, G., Mubareka, S., Notarangelo, M., Nunes, L., Pesty, B., Pikula, T., Redmond, J., Rizzo, M., Seben, V., Snorrason, A., Tomter, S., Hernández, L., 2020. Assessing forest availability for wood supply in Europe. For. Policy Econ. 111, 102032. https://doi.org/10.1016/j.forpol.2019.102032.

Antón-fernández, C., Astrup, R., 2012. Empirical harvest models and their use in regional business-as-usual scenarios of timber supply and carbon stock development. Scand. J. For. Res. 27, 379–392. https://doi.org/10.1080/02827581.2011.644576.

Augustynczik, A.L.D., Gusti, M., Deppermann, A., Nakhavali (André), M., Jia, F., di Fulvio, F., Havlík, P., 2025. Adapting forest management to climate change impacts and policy targets in the EU: insights from the coupled GLOBIOM/G4M-i3PGmiX model. One Earth 8. https://doi.org/10.1016/j.oneear.2025.101313.

Baker, J.S., Van Houtven, G., Phelan, J., Latta, G., Clark, C.M., Austin, K.G., Sodiya, O.E., Ohrel, S.B., Buckley, J., Gentile, L.E., Martinich, J., 2023. Projecting U.S. forest management, market, and carbon sequestration responses to a high-impact climate scenario. For. Policy Econ. 147, 102898. https://doi.org/10.1016/j.forpol.2022.102898.

Bashir, A., Sjølie, H.K., Solberg, B., 2020. Determinants of nonindustrial private forest owners' willingness to harvest timber in Norway. Forests 11, 1–16. https://doi.org/10.3390/f11010060.

Beach, R.H., Pattanayak, S.K., Yang, J.C., Murray, B.C., Abt, R.C., 2005. Econometric studies of non-industrial private forest management: a review and synthesis. For. Policy Econ. 7, 261–281. https://doi.org/10.1016/S1389-9341(03)00065-0.

Bechtold, W.A., Patterson, P.L., 2005. The Enhanced Forest Inventory and Analysis Program - National sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, p. 85.

Bont, L.G., Fraefel, M., Fischer, C., 2018. A spatially explicit method to assess the economic suitability of a forest road network for timber harvest in steep terrain. forests 9, 1–21. https://doi.org/10.3390/f9040169.

Boyd, R., 1984. Government support of nonindustrial production: the case of private forests. South. Econ. J. 51, 89. https://doi.org/10.2307/1058324.

Brogan, S., Gerow, T., Gregory, J., Gueth, M., Hamilton, R., Hughes, K.M., Swartley, B., Swift, L., Lang, A.J., 2021. North Carolina Forestry Best Management Practices: Manual to Protect Water Quality. North Carolina Forest Service.

Burrill, E.A., DiTommaso, A.M., Turner, J.A., Pugh, S.A., Menlove, J., Christensen, G., Perry, C.J., Conkling, B.L., 2023. The Forest Inventory and Analysis Database: Database Description and User Guide Version 9.1 For Phase 2. U.S. Department of Agriculture, Forest Service, p. 1066.

Butler, B.J., Butler, S.M., Caputo, J., Dias, J., Robillard, A., Sass, E.M., 2021. Family Forest Ownerships of the United States, 2018: Results from the USDA Forest Service, 199. National Woodland Owner Survey, p. 57. Gen. Tech. Rep. NRS-199.

Butler, B.J., Hewes, J.H., Dickinson, B.J., Andrejczyk, K., Markowski-Lindsay, M., Butler, S., 2016. Family Forest Ownerships of the United States, 2013: findings from the USDA Forest Service's National Woodland Owner Survey. J. For. 114, 638–647.

Butler, B.J., Ma, Z., Kittredge, D.B., Catanzaro, P., 2010. Social versus biophysical availability of wood in the Northern United States. North. J. Appl. For. 27, 151–159. https://doi.org/10.1093/njaf/27.4.151.

Butler, B.J., Sass, E.M., 2023. Wood supply from Family forests of the United States: biophysical, social, and economic factors. For. Sci. 69, 629–642. https://doi.org/10.1093/forsci/fxad034.

Catanzaro, P., Damery, D.T., D'Amato, A., Ferrare, K., 2007. Economic Viability of Ownerships in the Deerfield River Watershed. UMass Extension Report, p. 29.

Daigneault, A., Baker, J.S., Guo, J., Lauri, P., Favero, A., Forsell, N., Johnston, C., Ohrel, S.B., Sohngen, B., 2022. How the future of the global forest sink depends on timber demand, forest management, and carbon policies. Glob. Environ. Chang. 76, 102582. https://doi.org/10.1016/j.gloenvcha.2022.102582.

Dhungel, G., Ochuodho, T.O., Lhotka, J.M., Stringer, J.W., Poudel, K., 2024. Sustainability of White Oak (Quercus alba) Timber Supply in Kentucky. J. For. 122, 79–90. https://doi.org/10.1093/jofore/fvad041.

Dhungel, G., Rossi, D., Henderson, J.D., Abt, R.C., Sheffield, R., Baker, J., 2023. Critical market tipping points for high-grade white oak inventory decline in the Central Hardwood region of the United States. J. For. 121, 224–234. https://doi.org/10.1093/jofore/fvad005.

Đuka, A., Grigolato, S., Papa, I., Pentek, T., Poršinsky, T., 2017. i Forest. iForest 10, 886–894. https://doi.org/10.3832/ifor2471-010.

Esri, 2017. How hot spot analysis (Getis-Ord gi*) works. http://pro.arcgis.com/en/proapp/tool-reference/spatial-statistics/h-how-hot-spot-analysis-getis-ord-gi-spatialstati.htm. Date accessed 22 April 2025).

Favero, A., Wade, C.M., Cai, Y., Ohrel, S.B., Baker, J., Creason, J., Ragnauth, S., Latta, G., Mccarl, B.A., 2024. US land sector mitigation investments and emissions implications. Nat. Commun. 1–8. https://doi.org/10.1038/s41467-024-53915-w.

Food and Agriculture Organization of the United Nations (FAO), 2021. Forest Product Statistics. Forest product consumption and production. https://doi.org/10.4060/cb9360en.

Fortin, M., Pichancourt, J.-B., Melo, L.C.de, Colin, A., Caurla, S., 2019. The effect of stumpage prices on large-area forest growth forecasts based on socio-ecological models. Forestry 92, 339–356. https://doi.org/10.1093/forestry/cpz016.

Fraefel, M., Bont, L.G., Fischer, C., 2021. Spatially explicit assessment of forest road suitability for timber extraction and hauling in Switzerland. Eur. J. For. Res. 140, 1195–1209. https://doi.org/10.1007/s10342-021-01393-w.

Gadzik, C.J., Blanck, J.H., Caldwell, L.E., 1998. Timber Supply Outlook For Maine : 1995-2045, Maine Department of Agriculture, Conservation and Forestry. Maine Department of Conservation, Maine Forest Service. Forest Service Documents, p. 39.

Georgia Forestry Commission, 2019. Georgia's best management practices for forestry.

Getis, A., Ord, J.K., 1992. The Analysis of Spatial Association 24. https://doi.org/10.1111/j.1538-4632.1992.tb00261.x.

Gibbons, F.X., Gerrard, M., Blanton, H., Russell, D.W., Gibbons, F.X., Gerrard, M., Blanton, H., Daniel, W., 1998. Reasoned action and social reaction : willingness and intention as independent predictors of health risk 74, 1164–1180.

Hartman, R., 1976. the harvesting decision Whena standing forest has valuea. Econ. Inq. 14, 52–58. https://doi.org/10.1111/j.1465-7295.1976.tb00377.x.

Henderson, J.D., Abt, R.C., Abt, K.L., 2024. Forest carbon under increasing product demand and land use change in the US Southeast. For. Policy Econ. 167, 103296. https://doi.org/10.1016/j.forpol.2024.103296.

Holmes, T., Sohngen, B., Pendleton, L., Mendelsohn, R., 1997. Economic value of ecosystem attributes in the Southern Appalachian Highlands. Gen. Tech. Rep. SRS-17. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, pp. 187–190.

Holmes, T.P., 1986. An Economic Analysis Of Timber Supply From Nonindustrial Private Forests In Connecticut. The University of Connecticut.

Hyberg, B.T., Holthausen, D.M., 1989. The behavior of nonindustrial private forest landowners. Can. J. For. Res. 10, 1014–1023.

James, G., Witten, D., Hastie, T., Tibshirani, R., 2021. An Introduction to Statistical Learning With Applications in R, Second. ed. Springer.

Janis, I.B., Nock, M.K., 2008. Behavioral forecasts do not improve the prediction of future behavior : a prospective study of self-injury 64, 1–11. https://doi.org/10.1002/jclp.

Johansson, P.-O., Lofgren, K.G., 1985. The Economics of Forestry and Natural resources, I. ed. Basil Blackwell Inc. Blackwell Pub, New York.

Joshi, S., Arano, K.G., 2009. Determinants of private forest management decisions: a study on West Virginia NIPF landowners. For. Policy Econ. 11, 118–125. https://doi.org/10.1016/j.forpol.2008.10.005.

Kilgore, M.A., Blinn, C.R., 2004. Policy tools to encourage the application of sustainable timber harvesting practices in the United States and Canada. For. Policy Econ 6, 111–127. https://doi.org/10.1016/S1389-9341(02)00116-8.

Kilgore, M.A., Snyder, S.A., Eryilmaz, D., Markowski-Lindsay, M.A., Butler, B.J., Kittredge, D.B., Catanzaro, P.F., Hewes, J.H., Andrejczyk, K., 2015. Assessing the relationship between different forms of landowner assistance and family forest owner behaviors and intentions. J. For. 113, 12–19. https://doi.org/10.5849/jof.13-059.

Kittredge, D.B., Thompson, J.R., 2016. Timber harvesting behaviour in Massachusetts, USA : does price matter to private landowners ? Small-scale For 15, 93–108. https://doi.org/10.1007/s11842-015-9310-1.

Kittredge, D.B., 2004. Extension/outreach implications for America's Family forest owners. J. For. 102, 15–18.

Kline, J.D., Azuma, D.L., Alig, R.J., 2004. Population growth, urban expansion, and private forestry in Western Oregon. For. Sci. 50, 33–43. https://doi.org/10.1093/forestscience/50.1.33.

Latta, G.S., Baker, J.S., Ohrel, S., 2018. A Land Use and Resource Allocation (LURA) modeling system for projecting localized forest CO2 effects of alternative macroeconomic futures. For. Policy Econ. 87, 35–48. https://doi.org/10.1016/j.forpol.2017.10.003.

Lee, K.J., 1997. Hedonic Estimation of Nonindustrial Private Forest Landowner Amenity Values. North Carolina State University.

Levers, C., Verkerk, P.J., Müller, D., Verburg, P.H., Butsic, V., Leitão, P.J., Lindner, M., Kuemmerle, T., 2014. Drivers of forest harvesting intensity patterns in Europe. For. Ecol. Manage. 315, 160–172. https://doi.org/10.1016/j.foreco.2013.12.030.

Lundbäck, M., Häggström, C., Nordfjell, T., 2021. Worldwide trends in methods for harvesting and extracting industrial roundwood. Int. J. For. Eng. 32, 202–215. https://doi.org/10.1080/14942119.2021.1906617.

Lu, J., Huang, C., Tao, X., Schleeweis, K., 2023. NACP NAFD Project: Forest Disturbance Intensity for CONUS from Landsat, 1986-2015. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/2059.

Moesswilde, M., 2017. Best Management Practices For Forestry: Protecting Maine's Water Quality. Department of Agriculture, Conservation and Forestry, Maine Forest Service.

Newman, D.H., Wear, D.N., 1993. Production economics of private forestry: a comparison of industrial and nonindustrial forest owners. Am. J. Agric. Econ. 75, 674–684. https://doi.org/10.2307/1243574.

NYS, D.E.C., 2011. New York State Forestry: Best Management Practices for Water Quality. Watershed Agricultural Council Forestry Program.

Oswalt, S.N., Smith, W.B., Miles, P.D., Pugh, S.A., 2019. Forest Resources of the United States, 2017: a technical document supporting the Forest Service 2020 RPA assessment. USDA For. Serv. Gen. Tech. Rep. WO-97, p. 223 p.
Ouellette, J.A., Wood, W., 1998. Habit and intention in everyday life : the multiple processes by which past behavior. Predicts Future Behavior 124, 54–74.
Pattanayak, S.K., Abt, K.L., Holmes, T.P., 2003. Timber and amenities on nonindustrial private forest land. In: Sills, E.O., Abt, K.L. (Eds.), Forests in a Market Economy, pp. 243–258. https://doi.org/10.1007/978-94-017-0219-5_14.
Petucco, C., Abildtrup, J., Stenger, A., 2015. Influences of nonindustrial private forest landowners' management priorities on the timber harvest decision-A case study in France. J. For. Econ. 21, 152–166. https://doi.org/10.1016/j.jfe.2015.07.001.
Phelps, K., Hiesl, P., Hagan, D., Hagan, A.H., 2021. The Harvest Operability Index (HOI): a decision support tool for mechanized timber harvesting in Mountainous. Terrain. forests 12, 1–17.
Polyakov, M., Wear, D.N., Huggett, R.N., 2010. Harvest choice and timber supply models for forest forecasting. For. Sci. 56, 344–355.
Prestemon, J.P., Wear, D.N., 2000. Linking harvest choices to timber supply. For. Sci. 46.
Row, C., 1978. Economies of tract size in timber growing. J. For. 76, 576–582.
Sass, E.M., Butler, B.J., Caputo, J., Huff, E.S., 2023. Trends in United States Family forest owners' Attitudes, behaviors, and general characteristics from 2006 to 2018. For. Sci. 69, 689–697. https://doi.org/10.1093/forsci/fxad040.
Sass, E.M., Markowski-Lindsay, M., Butler, B.J., Caputo, J., Hartsell, A., Huff, E., Robillard, A., 2021. Dynamics of large corporate forestland ownerships in the United States. J. For. 119, 363–375. https://doi.org/10.1093/jofore/fvab013.
Schleeweis, K.G., Moisen, G.G., Schroeder, T.A., Toney, C., Freeman, E.A., Goward, S.N., Huang, C., Dungan, J.L., Inventory, F., Service, U.S.F., Mountain, R., 2020. US National maps attributing forest change : 1986 –2010. Forests 11, 1–20. https://doi.org/10.3390/f11060653.
Sferlazza, S., Maltese, A., Ciraolo, G., Dardanelli, G., Maetzke, F.G., Salvatore, D., Mela, L., Sferlazza, S., Maltese, A., Ciraolo, G., Dardanelli, G., 2021. Forest accessibility, Madonie mountains (northern Sicily, Italy): implementing a GIS decision support system. J. Maps ISSN 17, 476–485. https://doi.org/10.1080/17445647.2021.1962751.
Sharma, S., Kreye, M.M., 2022. Forest owner willingness to accept payment for Forest carbon in the United States: a meta-analysis. Forests 13. https://doi.org/10.3390/f13091346.
Silver, E.J., Leahy, J.E., Kittredge, D.B., Noblet, C.L., Weiskittel, A.R., 2015. An evidence-based review of timber harvesting behavior among private woodland owners. J. For. 113, 490–499. https://doi.org/10.5849/jof.14-089.
Smith, W.B., 2002. Forest inventory and analysis: a national inventory and monitoring program. Environ. Pollut. 116, 233–242. https://doi.org/10.1016/S0269-7491(01)00255-X.
Sodiya, O.E., Parajuli, R., Abt, R.C., Gray, J., 2023. Spatial analysis of forest product manufacturers in North Carolina. For. Sci 24–36.
Stein, S.M., McRoberts, R.E., Alig, R.J., Nelson, M.D., Theobald, D.M., Eley, M., Dechter, M., Carr, M., 2005. Forest on the edge: housing development on America's private forests. Gen. Tech. Rep. PNW-GTR-636. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, p. 16.
Straka, T.J., 2010. Timber supply fundamentals for extension forestry professionals. J. Ext. 48, 8–10. https://doi.org/10.34068/joe.48.04.30.
Suvanto, S., Muelbert, A.E., Schelhaas, M.J., Astigarraga, J., Astrup, R., Cienciala, E., Fridman, J., Henttonen, H.M., Kunstler, G., Kändler, G., König, L.A., Benito, P.R., Senf, C., Stadelmann, G., Starcevic, A., Talarczyk, A., Zavala, M.A., Pugh, T.A.M., 2025. Understanding Europe's forest harvesting regimes. Earth's Futur. 13, 1–20. https://doi.org/10.1029/2024EF005225.
Thompson, J.R., Canham, C.D., Morreale, L., Kittredge, D.B., Butler, B., 2017. Social and biophysical variation in regional timber harvest regimes. Ecol. Appl. 27, 942–955. https://doi.org/10.1002/eap.1497.
Tian, X., Sohngen, B., Baker, J., Ohrel, S., Fawcett, A.A., 2018. Will U.S. forests continue to be a carbon sink? Land Econ 94, 97–113. https://doi.org/10.3368/le.94.1.97.
Wade, C.M., Baker, J.S., Jones, J.P.H., Austin, K.G., Cai, Y., de Hernandez, A.B., Latta, G. S., Ohrel, S.B., Ragnauth, S., Creason, J., McCarl, B., 2022. Projecting the impact of socioeconomic and policy factors on greenhouse gas emissions and carbon sequestration in U.S. Forestry and agriculture. J. For. Econ. 37, 127–161. https://doi.org/10.1561/112.00000545.
Watson, D.F., Philip, G.M., 1985. A refinement of inverse distance weighted interpolation. Geoprocessing 2, 315–327.
Wear, D.N., Huggett, R.N., Li, R., Perryman, B., Liu, S., 2013. Forecasts of Forest conditions in U.S. Regions under future scenarios: a technical document supporting the Forest Service 2010 RPA assessment. Gen. Tech. Rep. SRS-170. U.S. Department of Agriculture Forest Service, Southern Research Station, Asheville, NC.
Westfall, J.A., Coulston, J.W., Gray, A.N., Shaw, J.D., Radtke, P.J., Walker, D.M., Weiskittel, A.R., MacFarlane, D.W., Affleck, D.L.R., Zhao, D., Temesgen, H., Poudel, K.P., Frank, J.M., Prisley, S.P., Wang, Y., Meador, A.J.S., Auty, D., Domke, G. M., 2024. A national-scale tree volume, biomass, and carbon modeling system for the United States. Gen. Tech. Rep. WO-104. U.S. Department of Agriculture, Forest Service, Northern Research Station, Washington, DC, p. 37.
White Oak Initiative, 2021. Restoring sustainability for White Oak and Upland Oak communities: an assessment and Conservation plan.
Wood, W., Quinn, J.M., Kashy, D.A., 2002. Habits in everyday life : thought, emotion, and action 83, 1281–1297. https://doi.org/10.1037//0022-3514.83.6.1281.
Young, R.A., Reichenbach, M.R., 1987. Factors influencing the timber harvest intentions of nonindustrial private forest owners. For. Sci. 33, 381–393. https://doi.org/10.1093/forestscience/33.2.381.
Zhang, D., Sun, X., Butler, B.J., Prestemon, J.P., 2015. Harvesting choices and timber supply among landowners in the southern United States. Can. J. Agric. Econ. 63, 409–429. https://doi.org/10.1111/cjag.12060.
Zhao, J., Daigneault, A., Weiskittel, A., 2020. Forest landowner harvest decisions in a new era of conservation stewardship and changing markets in Maine, USA. For. Policy Econ 118, 102251. https://doi.org/10.1016/j.forpol.2020.102251.