

Article

Are Trees Heavier Today? Re-Evaluating 1974 Transportation Weight Limits in the Context of Modern Forest Allometry

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Abstract

Forest operations and transportation policies have historically relied on weight-based assumptions created after weighing trees in the 1970s, yet modern silviculture and genetics may have fundamentally altered the geometry of commercial timber. This study investigated temporal shifts in merchantable bole weight and height in the southern United States to determine if these historical assumptions require reassessment. We analyzed USDA Forest Service Forest Inventory and Analysis (FIA) data for loblolly pine (*Pinus taeda*), sweetgum (*Liquidambar styraciflua*), and yellow-poplar (*Liriodendron tulipifera*) in Georgia (1997–2023), Alabama (2000–2023), and Mississippi (2009–2023). Using weighted least squares regression, we modeled temporal changes in bole weight and height while controlling for diameter, age, and site productivity. Results indicate a consistent, statistically significant increase in bole weight across all three states, with annual growth rates ranging from 0.51% to 1.29%. This trend is mechanistically driven by simultaneous increases in tree height within fixed diameter classes. Notably, loblolly pine exhibited a “plantation effect”, where weight accumulation was significantly faster in planted stands compared to natural stands, a trend absent in hardwood species. Our results suggest that the modern forest inventory is allometrically distinct, being taller and heavier for a given diameter than historical stocks. This shift implies that existing transportation limits may be increasingly misaligned with the biological reality of the current forest.

Keywords: forest inventory and analysis (FIA); loblolly pine; timber logistics; forest transportation; silviculture; forest policy



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1. Introduction

Forests are dynamic reservoirs of biomass that respond continuously to environmental variability and anthropogenic interventions [1,2]. Across regions and biomes, long-term inventory networks are revealing systematic shifts in forest structure and demographics that challenge the assumption that forest attributes remain constant over time. In mature tropical forests, for example, long-term plot networks documented a widespread acceleration in stand dynamics, with biomass accumulation increasing significantly during the late 20th century due to growth outpacing mortality [3], a trend that has more recently begun to saturate as mortality rates increase while growth rates level off [4]. This signal of non-stationarity extends to temperate systems as well. In Europe, long-term experimental plots have shown that dominant species are growing significantly faster than the 1960 baselines [5,6]. Notably, these modern stands have been observed to accumulate greater

volume even with lower tree densities, suggesting a shift in individual tree dimensions and weight relative to historical norms [6].

In the United States (U.S.), structural shifts in forest inventory are continuously driven by the combined influence of natural disturbances and anthropogenic interventions [7]. Recent analyses of the conterminous U.S. indicate that the relative stand density has shifted significantly higher over the last two decades, with the area of high-density stands increasing fivefold since 1999 [8]. Furthermore, remote sensing evidence suggests that canopy dynamics are not driven primarily by stand-replacing disturbances but rather by partial canopy loss events such as thinning and harvest [9]. This implies that in managed landscapes, the “typical” forest condition is continually reshaped by silvicultural regimes. Consequently, the structural attributes of the standing inventory, such as tree height, diameter distributions, and stem form, are likely drifting from historical baselines [6,10].

In the southeastern U.S., this structural shift is driven primarily by the region’s rapid transition toward intensive plantation silviculture [11,12]. Since the 1980s, the southern timberland base has shifted fundamentally from naturally regenerated mixed stands to high-yield *Pinus taeda* (loblolly pine) plantations, which now occupy over 34 million acres [7]. This transition represents a wholesale alteration of stand development trajectories. Productivity gains have been achieved through a combination of advanced tree improvement, rigorous vegetation control, and density management [11]. Modern plantation trees are physically distinct from their natural counterparts; they are selected for rapid volume accumulation and straightness and are grown in regimes that prioritize shorter rotation lengths to maximize return on investment [11,13].

This silvicultural intensification has produced significant consequences for wood quality and allometry. The widespread reduction in rotation age means that harvested boles now contain a larger proportion of juvenile wood, fundamentally altering their physical profile compared to mature timber [14–16]. Biologically, juvenile wood in southern pine is characterized by significantly higher moisture content, primarily due to its nature as water-conducting sapwood (lack of heartwood) and lower specific gravity, primarily due to thinner cell walls and a lower proportion of dense summerwood [14,16]. While the lower specific gravity of juvenile fiber reduces the dry biomass density, the dominance of sapwood significantly increases the water fraction. According to the Wood Handbook published by the U.S. Department of Agriculture, loblolly pine sapwood moisture content often exceeds 110%, whereas heartwood is typically near 33% [17]. Furthermore, genetic selection for rapid apical dominance appears to be shifting the height–diameter relationship, producing trees that are taller for a given diameter class than historical norms [18].

While these physiological shifts are most pronounced in intensively managed pines, the region’s diffuse-porous hardwoods, such as yellow-poplar (*Liriodendron tulipifera*) and sweetgum (*Liquidambar styraciflua*), are responding to a different set of anthropogenic drivers. In contrast to the genetic engineering of pine, the southern hardwood resource remains dominated by natural stands, where artificial regeneration is minimal [7,19,20]. Market-driven declines in hardwood harvesting have led to reduced removals and a stagnation of net growth across the South, resulting in an inventory that is increasingly aging and densifying rather than cycling rapidly [21]. Whether driven by genetic selection in softwoods or density-dependent competition in unthinned hardwoods, these changes suggest that the ‘merchantable tree’ of the 2020s functions as a distinct biological unit compared to the merchantable tree of previous decades. Quantifying this change is critical, given its ripple effects on applied forestry and the broader supply chain, influencing harvest productivity, equipment utilization, and, most critically, transportation.

The southeastern forest products sector is deeply reliant on truck transport. If the mass associated with a typical merchantable tree increases over time, after accounting for

observable stand structure, then average payload composition changes in ways that interact with gross vehicle weight (GVW) limits. Federal provisions have long established baseline limits on the Interstate system, most notably the 80,000 lbs (36,287 kg) GVW cap adopted in the mid-1970s [22]. This limit forces a reduction in the volume hauled per load to remain compliant, thereby increasing the number of trips required to transport the same volume of wood [23]. Such inefficiencies inflate fuel consumption and operational costs, which can account for up to 40% of delivered wood costs [24], while increasing trip frequency. While critics often cite infrastructure preservation as a reason to maintain the 80,000 lb limit, recent evidence suggests that increasing gross weight limits on multi-axle configurations and allowing state-legal weights on Interstates can actually reduce net pavement damage per unit of wood delivered by minimizing the total number of axle passes required across the road network [25,26]. Thus, a credible policy discussion regarding transport efficiency requires first establishing whether the biological reality of “what is being hauled” has fundamentally changed.

Accordingly, this study utilizes USDA Forest Service Forest Inventory and Analysis (FIA) annual-estimate summaries to test for temporal changes in merchantable bole weight per tree and associated height patterns across Alabama, Georgia, and Mississippi. In addition to loblolly pine, we examine trends for sweetgum and yellow-poplar because they serve as critical comparative baselines. Sweetgum, for instance, is the fourth most abundant tree species in the nation and the second most abundant in the South, with an estimated inventory of 15 billion stems [7]. While loblolly pine trends reflect the confounding influence of intensive genetic and silvicultural intervention, these hardwoods provide insight into whether broader environmental drivers, such as climate variability or atmospheric changes, are inducing parallel shifts in populations that remain genetically wild. We rely on the FIA database because it provides the only continuous, standardized framework for repeated inventory measurement across state lines, supporting robust inference regarding long-term structural trends [7,20,27,28]. The primary analysis focuses on the years for which continuous annual inventory is available for each state, and we also evaluate trends separately for natural and plantation forest types. By combining (i) a derived ‘merchantable bole weight-per-tree’ metric, calculated from FIA volume and tree-count estimates using species-specific green density assumptions, with (ii) complementary height analyses, this study aims to provide a clear empirical assessment of whether merchantable tree attributes have shifted in ways that necessitate a reassessment of forest operations and policy assumptions.

2. Materials and Methods

2.1. Data Acquisition and Scope

Forest inventory data were obtained programmatically from the USDA Forest Service FIA database using the EVALIDator API [29]. The study focused on Alabama, Georgia, and Mississippi and three commercially significant timber species: loblolly pine (FIA species code 131), sweetgum (species code 611), and yellow-poplar (species code 621).

The primary inferential analysis was restricted to the continuous annual inventory period for each state, extending through 2023. The start of a continuous annual series varied by state: 1997 for Georgia, 2000 for Alabama, and 2009 for Mississippi. Data were retrieved using state-specific Evaluation Groups (EVALIDs) corresponding to these annual reporting years.

The analytical dataset consisted of aggregated annual summary estimates. Observations were indexed by state, year (t), species, and a stratification vector including:

- Forest Origin: natural stands vs. plantations.
- Diameter Class: 2-inch (≈ 5.08 cm) intervals ranging from 2 inches to 41 inches (≈ 104.15 cm)
- Stand Age: 5-year age classes.
- Site Productivity: seven distinct classes based on potential mean annual increment, ranging from Class 1 (high productivity; >225 ft³/acre/year; approximately >15.74 m³/ha/yr) to Class 7 (low productivity; <20 ft³/acre/year; approximately <1.39 m³/ha/yr).

2.2. Derivation of Merchantable Bole Weight

The primary response variable was the merchantable bole green weight per tree (W , kg/tree). To calculate this metric, we extracted two specific aggregate estimates for each stratum-year cell:

1. Volume: net merchantable bole wood volume of live trees (≥ 5 inches [≈ 12.7 cm] d.b.h.) in cubic feet (FIA variable VOL_NET_LIVE, Option 574172).
2. Tree Count: number of growing-stock trees (≥ 5 inches d.b.h.) (FIA variable TREE_COUNT_GS, Option 8).

First, net merchantable bole volume was converted to cubic meters ($1 \text{ ft}^3 \approx 0.0283 \text{ m}^3$). Next, we calculated the mean volume per tree by dividing the aggregate tree volume by tree count. Finally, volume per tree was converted to green weight per tree. Because FIA merchantable volume estimates exclude bark [30], we applied species-specific green density constants that accounted for the weight of both wood and bark per unit of wood volume [31]. The applied density constants were 958 kg/m^3 for loblolly pine, 921 kg/m^3 for sweetgum, and 932 kg/m^3 for yellow-poplar, resulting in an estimate of total green bole weight (wood + bark).

2.3. Statistical Analysis

All regression analyses used log-linear fixed-effects models, estimated separately by state and species using the state-specific annual inventory periods defined above. Analyses were conducted using Python 3.13 in Jupyter Notebook 7.4.

2.3.1. Time-Trend Modeling of Bole Weight

To test for temporal changes in tree weight while controlling for stand structure, we modeled the natural logarithm of merchantable bole weight per tree ($\log W$). The logarithmic transformation was selected to satisfy regression assumptions regarding the normality and homoscedasticity of residuals and to reflect the multiplicative nature of allometric biological relationships. The primary model specification was

$$\log(W_{it}) = \alpha_i + \beta(\text{Year}_t - t_0) + \varepsilon_{it} \quad (1)$$

where

- i denotes a unique stratum defined by the combination of diameter class, age class, site productivity class, and forest origin.
- t_0 is the start year of the continuous annual inventory for a specific state (GA: 1997; AL: 2000; MS: 2009).
- α_i represents the stratum-level fixed effect.
- β represents the average annual within-stratum change in bole weight.

Estimates of annual percent change were derived from the log-scale coefficient via $100 \times (e^\beta - 1)$. Standard errors were cluster-robust, clustered at the stratum level (i) to account for serial correlation.

To assess whether trends differed by forest origin, we estimated a secondary interaction model:

$$\log(W_{it}) = \alpha_i + \beta (Year_t - t_0) + \theta[(Year_t - t_0) \times Origin_i] + \varepsilon_{it} \quad (2)$$

where $Origin_i$ is an indicator variable for forest origin, and θ captures the differential trend between plantation and natural stands. To ensure that estimated natural–plantation differences in growth trends were identified within comparable stand conditions, the interaction model was restricted to diameter–age–site strata that contained observations from both management types and at least two years of data within each type. Although this restriction substantially reduced the number of strata, it ensured that estimated slope differences were identified from within-stratum temporal contrasts rather than from between-stratum compositional differences.

2.3.2. Variance Estimation and Regression Weights

Models were estimated using weighted least squares (WLS). Inverse-variance weights were derived using the Delta method based on FIA-reported percent standard errors for merchantable volume ($SE\%_V$) and tree counts ($SE\%_N$). Assuming negligible covariance between volume and count estimators within stratum–year cells, the variance of the log-transformed response was approximated as

$$\text{Var}[\log(W_{it})] \approx \left(\frac{SE\%_V}{100}\right)^2 + \left(\frac{SE\%_N}{100}\right)^2 \quad (3)$$

Regression weights were then defined as

$$w_{it} = \frac{1}{\text{Var}[\log(W_{it})]} \quad (4)$$

To prevent excessive leverage from sparsely populated strata, variance estimates were floored at the 1st percentile of positive values prior to inversion.

2.3.3. Complementary Analysis: Trend in Tree Height

To assess whether the observed trends in merchantable bole weight were driven by changes in tree form, we conducted a complementary analysis of tree height conditional on diameter class, site productivity class, and forest origin. The input dataset consisted of annual estimates of growing-stock tree counts tabulated by height class (10-foot intervals [≈ 3.05 m]), diameter class intervals ranging from 2 inches [≈ 5.08 cm] to 41 inches [≈ 104.15 cm], site productivity class, and forest origin (natural stands versus plantations).

Because FIA height data are reported as discrete class distributions rather than continuous means, height class bounds were converted to class midpoints. For closed height classes, the midpoint was calculated as the average of the lower- and upper-class bounds. For open-ended upper classes (e.g., “90+ feet”), midpoints were approximated as the lower bound plus one-half of the median closed-class width observed within the corresponding state dataset.

For each stratum–year cell, defined by diameter class, species, site productivity class, forest origin, and year, mean tree height ($\bar{H}$) was estimated as the tree-count-weighted average of height-class midpoints:

$$\bar{H} = \frac{\sum_k N_k h_k}{\sum_k N_k}, \quad (5)$$

where N_k denotes the number of growing-stock trees in height class k , and h_k is the midpoint height (feet) of class k . Mean heights were converted to meters prior to analysis.

Temporal trends in mean height were analyzed using a log-linear fixed-effects model analogous to that used for the merchantable bole-weight analysis, with mean height modeled on the natural logarithmic scale to stabilize variance and allow coefficients to be interpreted as proportional (percentage) changes over time. The model evaluated whether mean tree height changed over time within the same diameter class, site productivity class, species, and forest origin, based on repeated annual observations of identical strata. Within each species, we estimated

$$\log(\bar{H}_{g,t}) = \alpha_g + \beta \text{Year}_{c,t} + \varepsilon_{g,t}, \quad (6)$$

where g indexes a unique stratum defined by the combination of diameter class, site productivity class, and forest origin; t denotes year; α_g represents stratum fixed effects that control for all time-invariant differences in mean height across strata; and $\text{Year}_{c,t}$ is the centered year variable. The coefficient β captures the average within-stratum change in mean tree height over time.

Models were estimated using weighted least squares, with analytic weights proportional to the total number of trees contributing to each stratum–year mean height estimate ($\sum_k N_k$). Because the same diameter–site–origin strata were observed repeatedly over time, standard errors were clustered at the stratum level to account for within-stratum serial correlation.

3. Results

3.1. Temporal Trends in Merchantable Bole Weight

3.1.1. Alabama

Figure 1 presents a descriptive overview of the unadjusted average merchantable bole green weight per tree for loblolly pine, sweetgum, and yellow-poplar in Alabama. See Appendix A.1 for a supplementary figure of average merchantable bole green weight per tree over time by grouped diameter class for natural and plantation forests. Appendix A.1 includes all available historical observations in addition to the continuous annual inventory period used in the main analysis, providing broader context for long-term patterns in tree weight.

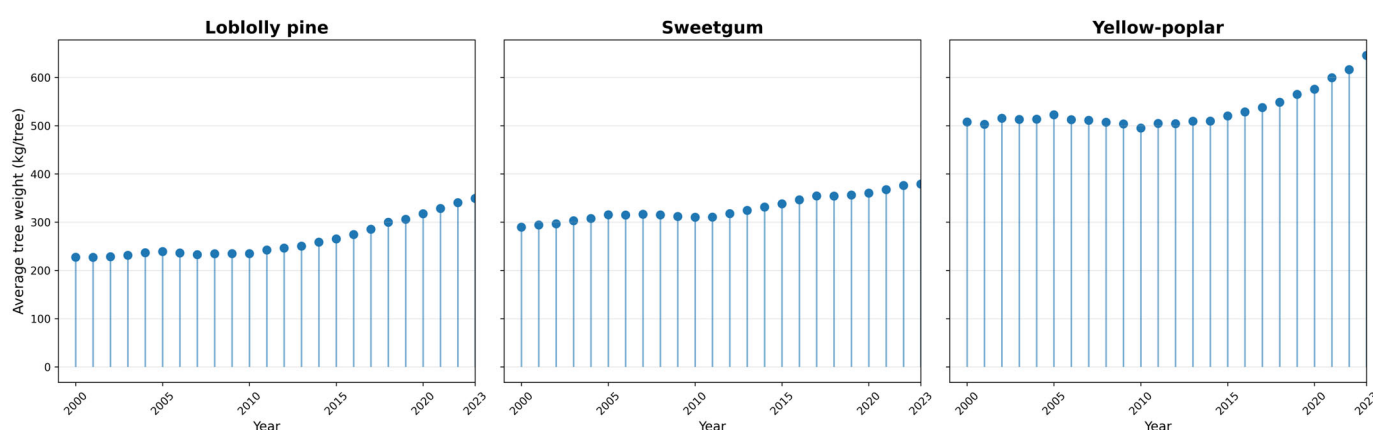


Figure 1. Trends in average merchantable bole green weight per tree in Alabama for loblolly pine, sweetgum, and yellow-poplar (2000 to 2023). Each circle represents an annual estimate, and vertical lines are used for visualization of the trend.

The regression results confirm that the observed increases are not merely due to a change in stand demographics but reflect a significant underlying shift in allometry across the study period (2000–2023) (Table 1). In a weighted fixed-effects model controlling for diameter class, age class, site, and stand origin, the estimated annual growth trend was 0.68% per year for loblolly pine, 0.90% per year for sweetgum, and 0.80% per year for yellow-poplar (p -values < 0.01). All estimated trends were positive, indicating consistent increases in mean tree weight over time across all species. Since these estimates are derived from weighted fixed-effects models, they confirm that tree allometry is shifting independently of stand demographics or site quality.

Table 1. Fixed-effects estimates of annual changes in merchantable bole green weight per tree by state and species.

State	Species	Data Period	Number of Strata	Number of Observations	Estimate (β)	Annual Change (% yr ⁻¹)	95% CI (% yr ⁻¹)	R ² (Adj. R ²)
AL	Loblolly Pine	2000–2023	1361	21,441	0.007 ***	0.680	[0.622, 0.738]	0.992 (0.992)
AL	Sweetgum	2000–2023	1096	15,952	0.009 ***	0.903	[0.809, 0.996]	0.981 (0.979)
AL	Yellow-poplar	2000–2023	1037	13,919	0.008 ***	0.800	[0.690, 0.911]	0.984 (0.982)
GA	Loblolly pine	1997–2023	1330	22,328	0.005 ***	0.507	[0.461, 0.553]	0.993 (0.993)
GA	Sweetgum	1997–2023	1088	16,552	0.008 ***	0.755	[0.684, 0.826]	0.983 (0.982)
GA	Yellow-poplar	1997–2023	1124	16,413	0.005 ***	0.551	[0.482, 0.620]	0.987 (0.986)
MS	Loblolly pine	2009–2023	1463	14,851	0.013 ***	1.291	[1.175, 1.406]	0.993 (0.992)
MS	Sweetgum	2009–2023	1041	10,104	0.012 ***	1.232	[1.026, 1.437]	0.973 (0.970)
MS	Yellow-poplar	2009–2023	779	6961	0.009 ***	0.953	[0.667, 1.240]	0.975 (0.972)

Notes: Significance levels: *** p < 0.01.

Decomposing the aggregate trend by stand origin reveals a clear divergence in allometric shifts between coniferous and deciduous species (Table 2). For loblolly pine, the rate of weight accumulation differed significantly between natural and planted stands (interaction p < 0.01). While natural pine stands exhibited a steady baseline increase in bole weight of 0.63% per year, planted stands demonstrated a significantly steeper trajectory, accumulating mass at 0.80% per year.

Table 2. Fixed-effects estimates of differential annual trends in merchantable bole green weight per tree between natural stands and plantations.

State	Species	Number of Strata	Number of Observations	Base Trend (β)	Interaction (θ)	SE (θ)	Natural Stands (% yr ⁻¹)	Plantations (% yr ⁻¹)	R ² (Adj. R ²)
AL	Loblolly pine	407	14,790	0.006	0.002 ***	0.001	0.625	0.800	0.990 (0.990)
AL	Sweetgum	203	6846	0.009	−0.001	0.001	0.898	0.787	0.968 (0.967)
AL	Yellow-poplar	169	5307	0.008	0.002	0.002	0.800	0.995	0.969 (0.968)
GA	Loblolly pine	369	14,430	0.005	0.002 ***	0.000	0.476	0.703	0.992 (0.991)
GA	Sweetgum	194	6681	0.008	−0.001	0.002	0.769	0.703	0.971 (0.970)
GA	Yellow-poplar	128	4075	0.005	0.000	0.002	0.538	0.586	0.969 (0.968)
MS	Loblolly pine	454	10,237	0.012	0.003 ***	0.001	1.230	1.542	0.990 (0.990)
MS	Sweetgum	220	4708	0.014	−0.005 *	0.003	1.374	0.830	0.951 (0.948)
MS	Yellow-poplar	142	2708	0.010	−0.003	0.004	0.980	0.632	0.945 (0.942)

Notes: Significance levels: * p < 0.10, *** p < 0.01.

In contrast, no significant interaction between year and stand origin was detected for sweetgum (p = 0.46) or yellow-poplar (p = 0.40). For these hardwood species, the upward shift in tree weight was statistically uniform across the landscape regardless of management history. Sweetgum weight increased by 0.90% per year in natural stands compared to 0.79% in plantations, while yellow-poplar increased by 0.80% (natural) and 0.99% (planted), with neither species showing a statistical difference between groups (Table 2).

3.1.2. Georgia

Figure 2 illustrates temporal patterns in the unadjusted mean merchantable bole green weight per tree for loblolly pine, sweetgum, and yellow-poplar in Georgia. Appendix A.2 shows average merchantable bole green weight per tree over time by diameter class for natural and plantation forests, including all available historical observations.

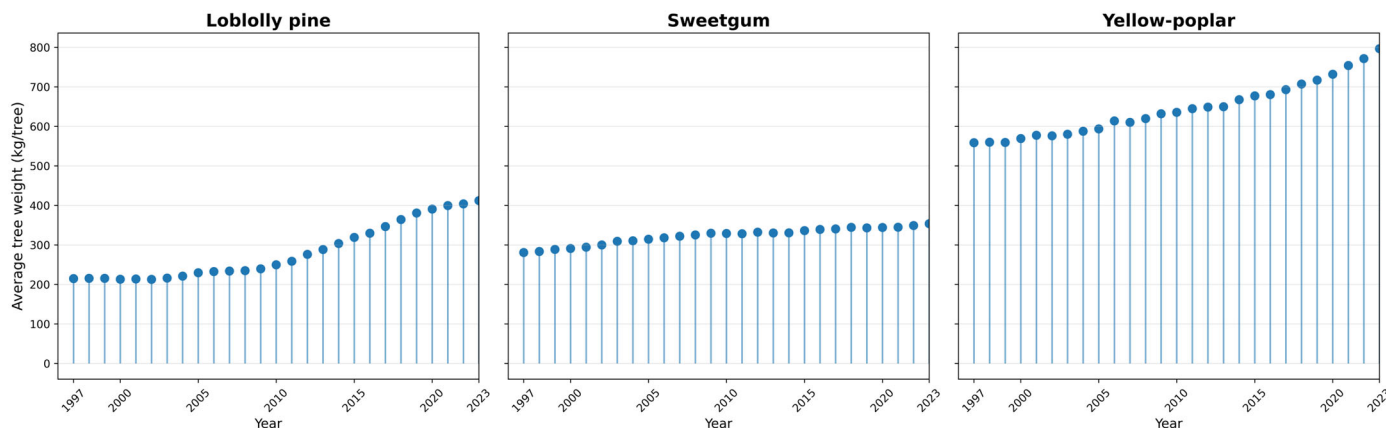


Figure 2. Long-term trends in average merchantable bole green weight per tree in Georgia for loblolly pine, sweetgum, and yellow-poplar (1997 to 2023). Each circle represents an annual estimate, and vertical lines are used for visualization of the trend.

From our statistical inquiry for the 1997–2023 interval, the fixed-effects models again detected significant positive change across all species (Table 1). Controlling for the same vector of stand determinants—diameter, age, site productivity, and origin—the analysis revealed that loblolly pine accumulated mass at a baseline annual rate of 0.51% ($p < 0.001$). Hardwood species mirrored this trend, with sweetgum and yellow-poplar growing heavier by 0.76% and 0.55% per year, respectively (all $p < 0.001$).

Stratifying the analysis by stand origin revealed a divergence between softwood and hardwood dynamics that closely mirrors the Alabama findings (Table 2). For loblolly pine, the effect of management intensity was detected: plantation stands accumulated mass at an estimated rate of 0.70% per year, significantly outpacing the 0.48% per year baseline observed in natural stands (interaction $p < 0.001$). This widens the allometric gap between the two management regimes over time.

Conversely, hardwood allometry appeared insensitive to management classification (Table 2). Sweetgum exhibited statistically indistinguishable growth trends across strata ($p = 0.69$), with annual weight gains of 0.77% in natural stands and 0.70% in plantations. Yellow-poplar followed an identical pattern of uniformity, showing no significant divergence between natural (0.54%) and planted (0.59%) populations ($p = 0.84$). This replication of the results with divergent trajectories for pines versus parallel trajectories for hardwoods suggests that the mechanisms driving weight change differ fundamentally by species group.

3.1.3. Mississippi

Figure 3 summarizes the observed, unadjusted trends in average merchantable bole green weight per tree for loblolly pine, sweetgum, and yellow-poplar in Mississippi. See Appendix A.3 for a supplementary figure summarizing average merchantable bole green weight per tree by diameter class for natural and plantation forests over time for Mississippi, combining historical records with the annual inventory used in the main analysis.

Within the stable 2009–2023 observation window, our weighted fixed-effects models identified the most rapid allometric shifts observed in the region (Table 1). Loblolly pine bole weight increased at an estimated annual rate of 1.29%, while sweetgum and yellow-poplar followed closely with annual gains of 1.23% and 0.95%, respectively. All three trends were statistically significant ($p < 0.01$), demonstrating that the phenomenon of “heavier trees” is intensifying over time, even when comparisons are strictly controlled for diameter, age, and site quality.

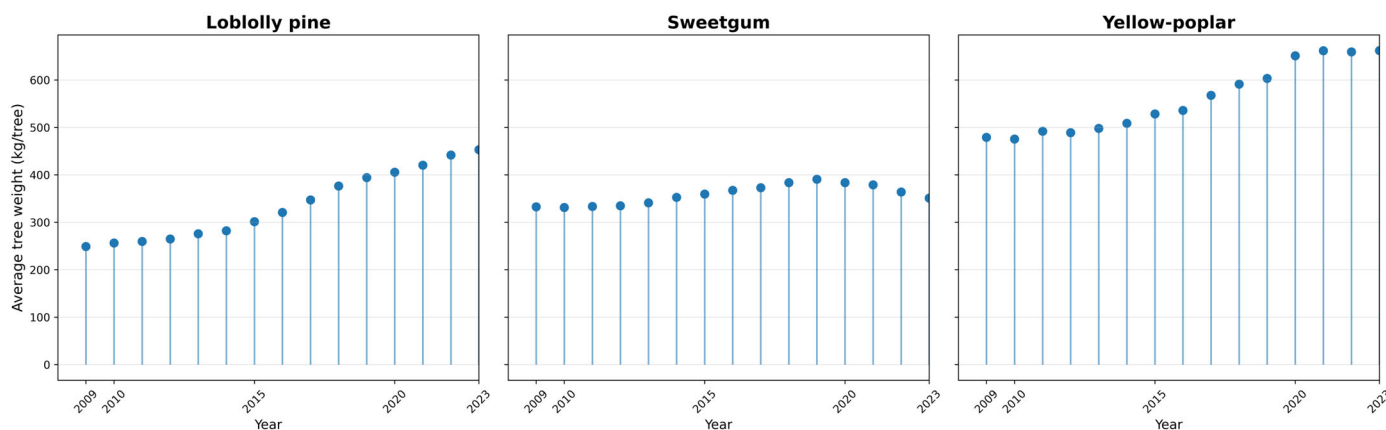


Figure 3. Long-term trends in average merchantable bole green weight per tree in Mississippi for loblolly pine, sweetgum, and yellow-poplar (2009–2023). Each circle represents an annual estimate, and vertical lines are used for visualization of the trend.

Stratifying these robust aggregate trends by stand origin revealed complex dynamics unique to the western range of the study area (Table 2). For loblolly pine, the “plantation effect” was highly evident: planted stands accumulated mass at 1.54% per year, significantly exceeding the 1.23% per year observed in natural stands (interaction $p = 0.006$). However, a divergence emerged within the hardwood strata. Unlike the uniform patterns in Alabama and Georgia, sweetgum in Mississippi exhibited a marginally significant trend inversion ($p = 0.09$), with natural stands gaining weight faster (1.37%) than plantation stands (0.83%). Yellow-poplar followed a similar directional pattern with natural stands (0.98%) exceeding plantations (0.63%), though this difference did not reach statistical significance ($p = 0.42$). These results suggest that while silviculture drives pine allometry, the high baseline growth in natural hardwood stands in Mississippi may be linked to distinct regional environmental factors.

3.2. Temporal Trends in Tree Height

To complement the weight analysis, we examined temporal shifts in vertical allometry to determine if the observed mass gains were driven by changes in tree geometry. By modeling total height as a function of year while holding diameter, origin, and site conditions constant, we isolated specific shifts in the height–diameter relationship independent of stand demographics.

3.2.1. Alabama

In Alabama, the fixed-effects models revealed a significant upward drift in vertical structure across all three species (Table 3). Loblolly pine exhibited the most pronounced structural shift, with mean height increasing at an average rate of $0.61\% \text{ yr}^{-1}$ ($p < 0.001$). This coefficient confirms that for a fixed diameter and site productivity level, modern pine trees are statistically taller than their historical counterparts.

Significant upward trends in height conditional on diameter were also observed for the hardwood species, although the magnitude of the vertical shift was notably lower than in pine. Yellow-poplar height increased by 0.41% yr^{−1} ($p < 0.001$), while sweetgum exhibited a more moderate annual increase of 0.31% yr^{−1} ($p < 0.001$). These estimates provide evidence that the height–diameter curve itself has drifted upward across the study period, contributing to the bole weight gains identified in the previous section.

Table 3. Fixed-effects estimates of annual percentage change in total tree height by state and species.

State	Species	Data Period	N (Observation)	N (Strata)	Estimate (β)	% Change yr ^{−1} (95% CI)	R ² (Adj. R ²)
AL	Loblolly pine	2000–2023	2622	133	0.006 ***	0.615 (0.550, 0.680)	0.990 (0.989)
AL	Sweetgum	2000–2023	2111	106	0.003 ***	0.309 (0.266, 0.353)	0.992 (0.991)
AL	Yellow-poplar	2000–2023	2181	119	0.004 ***	0.408 (0.357, 0.458)	0.987 (0.986)
GA	Loblolly pine	1997–2023	2701	126	0.004 ***	0.413 (0.305, 0.522)	0.989 (0.988)
GA	Sweetgum	1997–2023	2053	107	0.004 ***	0.352 (0.274, 0.429)	0.992 (0.991)
GA	Yellow-poplar	1997–2023	2229	117	0.003 ***	0.293 (0.214, 0.371)	0.990 (0.989)
MS	Loblolly pine	2009–2029	1918	152	0.012 ***	1.196 (1.059, 1.333)	0.988 (0.987)
MS	Sweetgum	2009–2023	1420	115	0.006 ***	0.636 (0.501, 0.771)	0.989 (0.988)
MS	Yellow-poplar	2009–2023	1337	114	0.006 ***	0.596 (0.454, 0.737)	0.983 (0.982)

Notes: Significance levels: *** $p < 0.01$.

3.2.2. Georgia

In Georgia, the fixed-effects models revealed consistent increases in mean tree height over time for all three species after accounting for diameter class, site productivity, and forest origin (Table 3). Among the species examined, loblolly pine again showed the strongest upward trend, with mean height increasing at an estimated rate of 0.41% yr^{−1} ($p < 0.001$).

Height trends for the hardwood species were also positive and statistically significant, though of smaller magnitude. The mean height for sweetgum increased by approximately 0.35% yr^{−1} ($p < 0.001$), while yellow-poplar exhibited an average annual increase of 0.29% yr^{−1} ($p < 0.001$). As in Alabama, these estimates represent within-stratum temporal changes identified from repeated annual observations of identical diameter–site–origin combinations, confirming that the upward shift is a cross-state phenomenon.

3.2.3. Mississippi

In Mississippi, the temporal signal for vertical extension was the strongest observed in the region. After controlling for diameter class, site productivity, and forest origin, estimated trends were positive and highly significant for all three species (Table 3).

The magnitude of the shift was particularly acute for loblolly pine, which increased in height at an average rate of 1.20% yr^{−1} ($p < 0.001$). This rate is nearly double that observed in Alabama or Georgia, indicating substantial height gains over time within comparable diameter–site–origin strata.

Hardwood species also exhibited pronounced upward trends relative to the regional baseline. Sweetgum showed an estimated annual increase of 0.64% yr^{−1} ($p < 0.001$), while yellow-poplar increased by approximately 0.60% yr^{−1} ($p < 0.001$). These accelerated rates suggest that the drivers influencing tree geometry, whether environmental or silvicultural, are operating at their highest intensity in the western portion of the study area.

4. Discussion

The primary objective of this study was to assess whether merchantable tree attributes have shifted sufficiently to warrant a recalibration of operational and policy assumptions. Our results indicate a persistent and statistically significant temporal increase in merchantable bole weight per tree across all states and species studied. The estimated annual growth trend in merchantable bole weight per tree ranged from approximately 0.5% yr⁻¹ to 1.3% yr⁻¹ across states and species. In Georgia, annual increases ranged from 0.51% to 0.80% yr⁻¹, while Alabama exhibited intermediate rates of 0.68% to 0.90% yr⁻¹. Mississippi showed the largest increases, with estimated annual gains of 0.95%–1.29% yr⁻¹. Although modest on an annual basis, these rates compound over multi-decadal periods. When expressed on a decadal basis, estimated increases ranged from approximately 6%–13% per decade for loblolly pine, 7%–13% per decade for sweetgum, and 5%–10% per decade for yellow-poplar, depending on the state. Importantly, the consistency of positive trends across species with distinct growth characteristics suggests that these patterns are not driven by species-specific anomalies but reflect broader changes affecting tree growth and form. These findings provide empirical confirmation that fixed allometric assumptions are increasingly diverging from the biological reality of current forest stocks.

An interesting finding of this study is the notable disparity in trend magnitude between Mississippi and its neighboring states. While significant growth was observed across all species, the rate of increase was consistently higher in Mississippi, particularly for loblolly pine. While Alabama and Georgia exhibited moderate annual weight increases in loblolly pine (0.68% and 0.51%, respectively), the rate in Mississippi was nearly double, at 1.29% per year. This discrepancy likely reflects, in part, the shorter and more recent temporal coverage of the Mississippi dataset (2009–2023), which coincides with a period of intensive forest management across much of the Southeast, compared with the longer time series available for Alabama (2000–2023) and Georgia (1997–2023). Management factors such as planting density, thinning history, fertilization, herbicide application, and other tending practices may also have contributed to the stronger Mississippi trends. Additionally, regional variations in site conditions may also have contributed to these state-level differences. FIA summaries indicate that Mississippi contains more forest area in Site Classes 3 and 4 and less in Site Classes 5 and 6 than Alabama and Georgia. Although the site productivity class was included in the model, this pattern is consistent with broader regional differences in growth potential. Physiographic province, geology, and soil-related rooting restrictions are also important determinants of loblolly pine productivity in the southeastern U.S. [32], and soil resource descriptions for Mississippi identify fertile alluvial and loess-derived soils as important components of several regions of the state [33].

Further, the divergence in trends between natural and plantation stands highlights the role of differing management intensities and physiological strategies between softwoods and hardwoods. We observed a distinct “plantation effect” in pine across all three states; for example, in Mississippi, plantation loblolly pine weight accumulation (1.54% per year) significantly outpaced natural stands (1.23% per year). A similar trend was observed in Georgia (0.70% vs. 0.48%) and Alabama (0.80% vs. 0.63%). This pattern aligns with expectations, as plantation systems leverage the cumulative gains of genetic improvement and intensive silvicultural practices. In contrast, differences by origin were generally not significant for hardwood species. The only exception was sweetgum in Mississippi, where natural stands showed marginally greater weight accumulation than plantations; however, this result was weakly supported statistically and should be interpreted cautiously rather than as evidence of a consistent hardwood stand-origin effect.

This difference is likely due to loblolly pine's high carrying capacity and lower mortality relative to competitors like slash pine (*Pinus elliottii*) [34,35]. This biological predisposition for rapid productivity has been strongly enhanced through tree improvement programs. In plantation systems, deployment has progressed from open-pollinated families to advanced-generation genotypes, including full-sib families and clones, specifically selected to maximize volume growth, stem straightness, and disease resistance [13,35]. The “plantation effect” observed here likely reflects the realization of this genetic potential through precise site management, including optimized planting density and age structures [11,36,37]. Furthermore, intensive cultural regimes, specifically rigorous fertilization and vegetation control, accelerate aboveground biomass accumulation [34,37]. Notably, loblolly pine efficiently converts high-resource environments (e.g., increased nitrogen and phosphorus availability) into taller, heavier stems, fundamentally altering historical biomass allocation patterns [34].

In contrast, the hardwoods (sweetgum and yellow-poplar) displayed a more muted response to management intensity. Despite the strong baseline gains, interaction models revealed no significant “plantation effect” for these species. For instance, yellow-poplar in Georgia showed no statistical difference between natural (0.54%) and plantation (0.59%) trends, and in Alabama, the difference for sweetgum was similarly non-significant. At the same time, the presence of positive trends in natural stands indicates that increasing merchantable bole weight is not solely a plantation phenomenon. This lack of management-driven difference is rooted in the distinct biological and silvicultural context of Southeastern hardwoods. Hardwoods in this region are predominantly naturally regenerated [7,20]; even when classified as “planted” in inventories, they often lack the structural and genetic uniformity of pine plantations. While both natural and plantation hardwoods are accumulating mass at significant rates, the differential between these management classes has remained stable, as the hardwood sector has not yet seen the widespread, standardized deployment of advanced breeding and chemical vegetation control that has accelerated the gap in pine systems [7,11,38].

The observed trends are mechanistically supported by our complementary analysis of tree height. The simultaneous increase in mean height within fixed diameter classes suggests that the “weight gain” is primarily driven by a shift in tree slenderness (height-diameter ratio). This alignment is remarkably consistent across the pine dataset; for example, in Mississippi, the annual increase in loblolly pine bole weight (1.29%) was nearly identical to the annual increase in mean height (1.19%). This pattern holds across the study region, with weight and height trends scaling closely in Alabama (0.68% vs. 0.61%) and Georgia (0.51% vs. 0.41%), respectively. The fact that weight growth consistently exceeds height growth by a narrow margin (approximately 0.07% to 0.10%) across all three states suggests that vertical extension relative to radial growth is the dominant driver of the observed weight trends [18,39]. Consequently, a tree of a specific diameter harvested today is geometrically distinct: it is taller and more voluminous than a conspecific of the same diameter harvested two decades ago. This shift toward a more cylindrical stem form implies a reduction in stem taper, which has profound implications for both log recovery efficiency and the accuracy of historical biomass equations [18,39].

4.1. Implications for Logistics and Transportation Policy

One of the most immediate and economically significant implications of these findings lies in the forest transportation sector. The logistics of the timber supply chain are governed by strict GVW and axle-weight limits, rooted in the Federal Bridge Formula mechanisms established in 1974. These regulatory frameworks were designed based on the biological

characteristics and wood density profiles of the “natural forest” prevalent in the mid-20th century.

Our results demonstrate that the modern “industrial tree” is different from historical baselines. As trees accumulate more bole weight per unit of diameter, a shift associated with the corresponding increases in height observed in our models, the density of the “input material” for the logging sector effectively increases. Because this analysis focuses on merchantable bole weight for trees meeting FIA standards ($\text{DBH} \geq 5$ inches), these implications directly target the transportation of commercial roundwood, including sawtimber and pulpwood, and exclude saplings, non-merchantable biomass, or other small-diameter material. Consequently, for merchantable material, this creates a payload-volume conflict for log hauling. As the weight-to-volume ratio of the raw material shifts, haulers remain constrained by the weight limits. In the studied states, loaded trucks are generally limited to a federal maximum of 80,000 lbs (36,287 kg) on Interstate highways, whereas state and local routes allow a 10% statutory weight tolerance up to 88,000 lbs (39,916 kg) (with Mississippi allowing up to 88,000 lbs on Interstates via a special permit [40]). As a result, haulers may now hit these legal weight caps before fully utilizing their trailer volume, forcing them to transport lower volumes of usable wood fiber per trip to remain compliant [41,42].

When harvested timber reaches legal payload limits before fully utilizing trailer volume, transportation becomes less efficient. More trips are required to move a given volume to the mill, increasing diesel fuel consumption and contributing to wear on transportation infrastructure. These costs are borne across the supply chain, including landowners, logging contractors, loggers, and mills. Higher trip frequency also increases emissions per unit of delivered wood [25,43], particularly where haul distances are long.

The economic relevance of these transportation effects is intensified by the importance of the forest sector in the region. Forestry contributes approximately 3.9% of total GDP in Alabama, 2.4% in Georgia, and 4.1% in Mississippi, ranking these states 5th, 9th, and 3rd nationally in economic dependence on forestry, respectively [44]. Therefore, weight-driven reduction in payload efficiency is not only an operational concern for log haulers but also a potential cost pressure within a regionally important supply chain.

As biological drivers continue to alter the weight-to-volume relationships of southern timber, a re-evaluation of transportation policies may be necessary. Regulatory frameworks established in 1974 may no longer align with the biological reality of the modern, genetically improved forest or with current operating conditions. This does not imply that higher truck-weight limits are universally appropriate, because road safety, bridge capacity, pavement damage, and enforcement remain important constraints. However, the results support the need to reassess whether existing timber-hauling limits adequately balance transportation efficiency, infrastructure protection, and environmental outcomes under present forest conditions.

4.2. Limitations and Future Research

Several limitations should be considered when interpreting these results. First, merchantable bole green weight was estimated by combining FIA merchantable volume with fixed, species-specific green density constants. While this approach is standard and internally consistent, it does not allow for temporal variation in wood moisture content or green wood density. However, to address this limitation, we conducted a Monte Carlo sensitivity analysis with 100 simulations in which annual density values were randomly adjusted within $\pm 5\%$, $\pm 10\%$, and $\pm 15\%$ of baseline values. Estimated temporal trends remained robust, with positive and statistically significant trends retained in 97%–100% of simulations.

Likewise, the fixed-effects framework isolates within-stratum temporal trends but does not identify the underlying drivers of those trends. Long-term changes in merchantable bole weight may reflect a combination of factors that have been widely debated in the literature, including atmospheric CO₂ enrichment, nitrogen deposition, climate variability, genetic improvement, and intensification of silvicultural practices. The present analysis does not attempt to attribute causality among these mechanisms and instead documents the net outcome observed in repeated inventory measurements.

Furthermore, regarding the height analysis, mean heights were reconstructed from discrete height-class distributions using class midpoints, an approach that is appropriate for grouped FIA data but introduces approximation error. This quantization may obscure subtle year-to-year changes in vertical growth that would be detectable with continuous tree-level height measurements. Nevertheless, the consistency of height trends across strata suggests that this limitation is unlikely to overturn the qualitative conclusions.

Another consideration is that the analysis conditions on trees that remain in the inventory and do not explicitly account for harvested or dead individuals. As a result, survivorship effects may influence observed trends. If smaller or lighter trees are removed more aggressively through thinning or natural mortality in recent decades than in the past, the mean weight of remaining trees could increase even in the absence of proportional growth gains among all individuals. While the fixed-effects design mitigates compositional change across strata, it cannot fully eliminate survivorship bias inherent in repeated cross-sectional inventory data.

Finally, although some studies suggest that faster-growing plantation pines may exhibit lower wood specific gravity due to a greater proportion of juvenile wood [16,45], the present analysis focuses on green weight rather than dry biomass. Any reduction in dry density would therefore have a muted effect on green mass relative to volume expansion. Moreover, the magnitude of observed increases in merchantable volume and height, particularly for loblolly pine, suggests that geometric growth likely dominates any countervailing density effects at the scale examined here.

Future research can build directly on these results by combining inventory-based analyses with studies that measure trees more intensively in the field. In particular, destructive sampling that directly measures stem mass, wood density, taper, and bark thickness would help clarify how much of the observed increase in merchantable bole weight reflects changes in tree size versus changes in wood properties. Expanding this framework to account explicitly for harvest, mortality, and stand density would also improve understanding of how management and survivorship influence long-term shifts in average tree weight. In addition, linking within-stratum trends in merchantable bole weight to environmental conditions or management histories could reveal whether the observed increases represent temporary responses or persistent structural changes as newer genetic selections and silvicultural practices continue to develop.

5. Conclusions

Using three decades of continuous annual FIA data and a weighted fixed-effects framework, this study documents an increase in merchantable bole green weight per tree across three major commercial species in the southeastern United States. Across Alabama, Georgia, and Mississippi, estimated annual increases in merchantable bole weight ranged from approximately 0.5%–0.9% per year in Alabama and Georgia to 0.9%–1.3% per year in Mississippi, with all time trends statistically significant. Because these estimates are based on repeated observations within identical diameter, age, site productivity, and forest-origin strata, they indicate that trees of a given structural class are heavier today than their historical counterparts.

Allowing time trends to differ by forest origin revealed that plantations often experienced faster increases in merchantable bole weight than natural stands, particularly for loblolly pine. Plantation loblolly pine exhibited significantly higher growth rates than natural stands in all three states, with differences on the order of 0.2–0.3 percentage points per year. In contrast, differences between natural and plantation stands were generally smaller and statistically indistinguishable for sweetgum and yellow-poplar. The presence of positive trends in natural stands across species and states indicates that broader factors beyond plantation management are likely contributing to these long-term changes.

The height analyses show that trees within diameter classes have also become taller over time, but at rates generally lower than corresponding increases in merchantable bole weight. Mean height increased by approximately 0.3%–0.6% per year in Alabama and Georgia and by as much as 1.2% per year for loblolly pine in Mississippi. The disparity between weight and height trends suggests that rising merchantable mass cannot be explained by vertical growth alone and is consistent with broader changes in tree form or biomass allocation within the merchantable stem. Together, these findings demonstrate a sustained shift in tree-level allometry across southeastern U.S. forests, indicating that current timber supply chains are operating with biological inputs that differ measurably from historical baselines.

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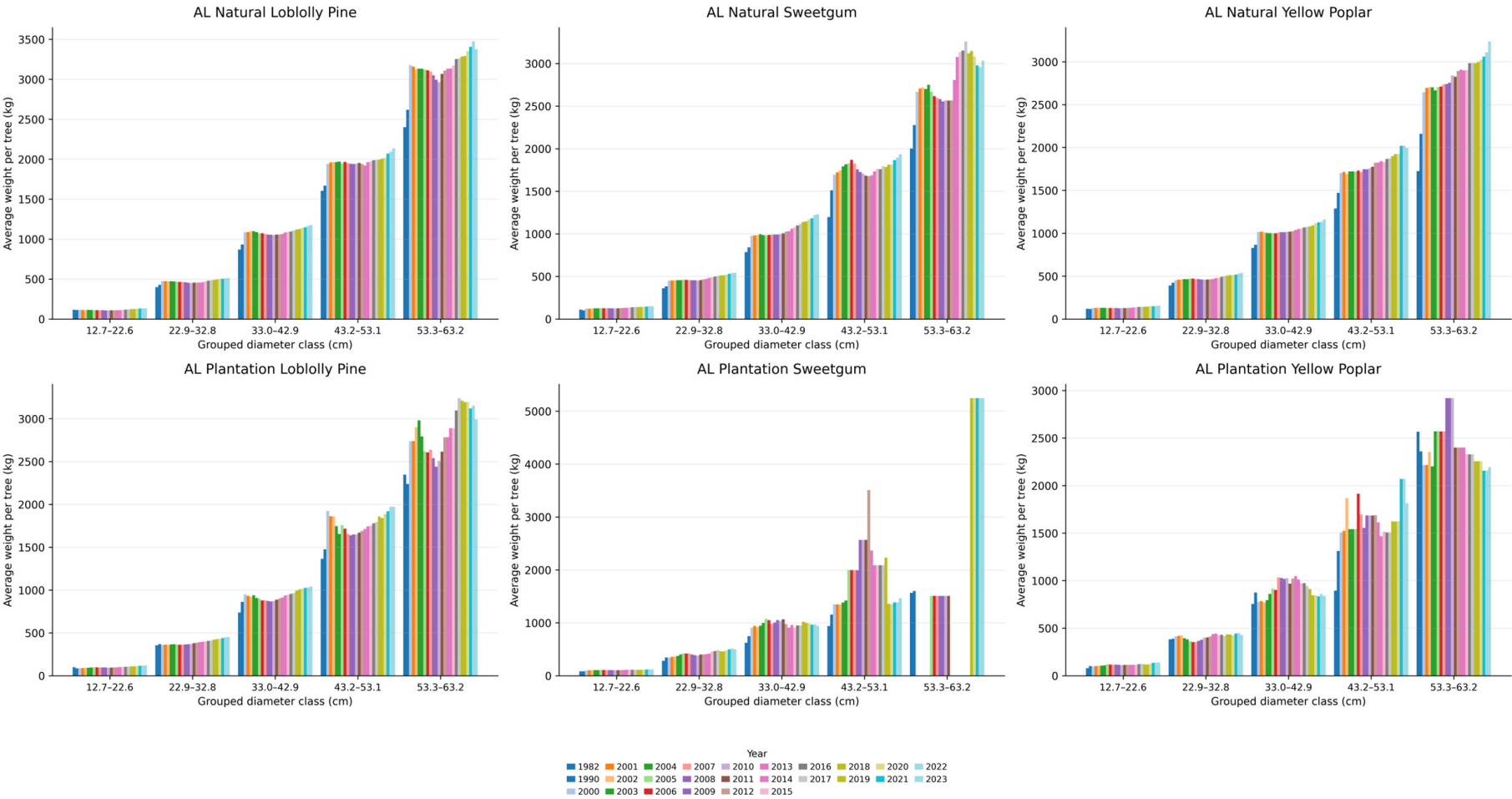
Funding: This work was supported by the U.S. Department of Agriculture (USDA) National Institute of Food and Agriculture (NIFA) under Grant No. 205314 USDA-2023-70500-38914-TG.

Data Availability Statement: The data used in this study are publicly available from the USDA Forest Service Forest Inventory and Analysis (FIA) program and were accessed using the FIADB EVALIDator API (<https://apps.fs.usda.gov/fiadb-api/evalidator> (accessed on 6 January 2026)).

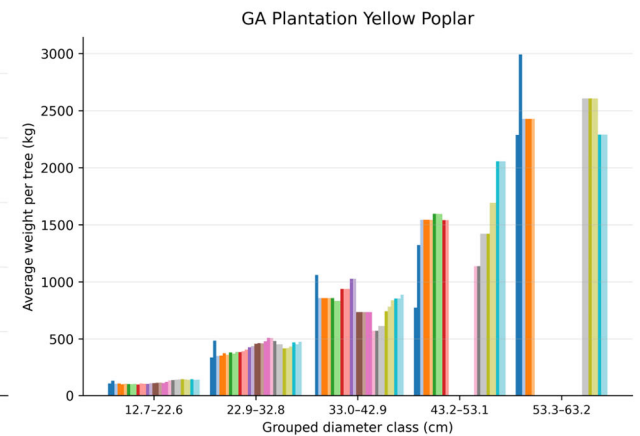
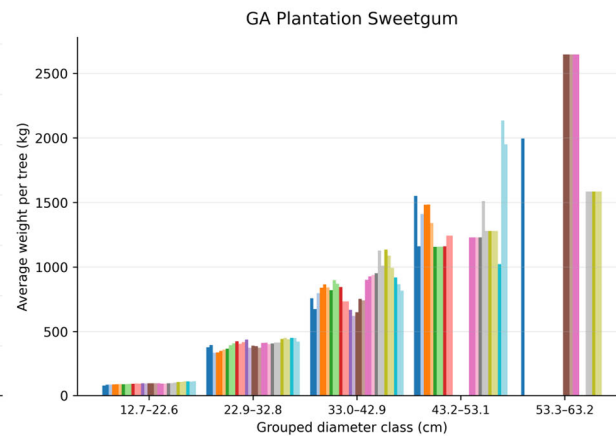
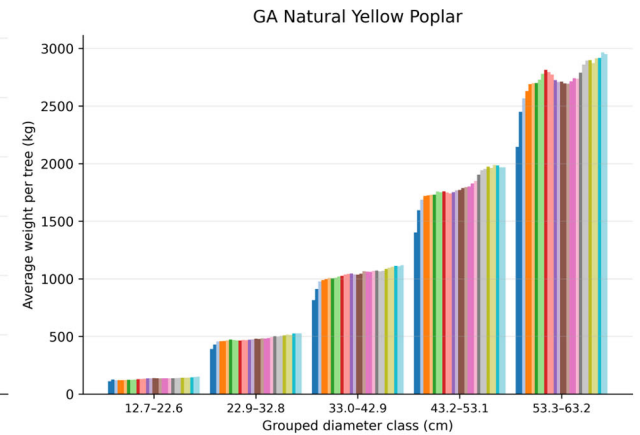
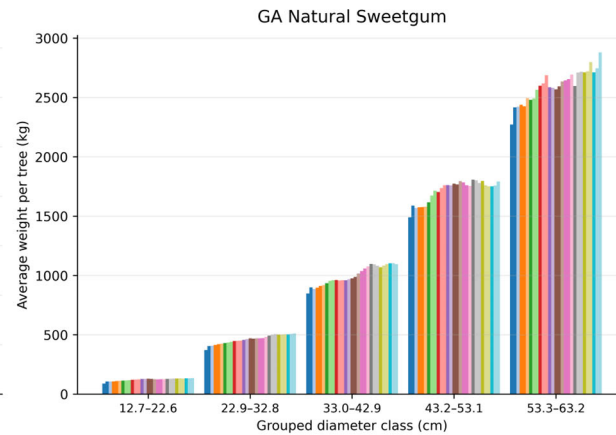
Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Long-Term Trends in Merchantable Bole Green Weight per Tree by Diameter Class (Natural and Plantation Forests) for Loblolly Pine, Sweetgum, and Yellow-Poplar Across Alabama, Georgia, and Mississippi

Appendix A.1. Alabama



GA Natural Loblolly Pine



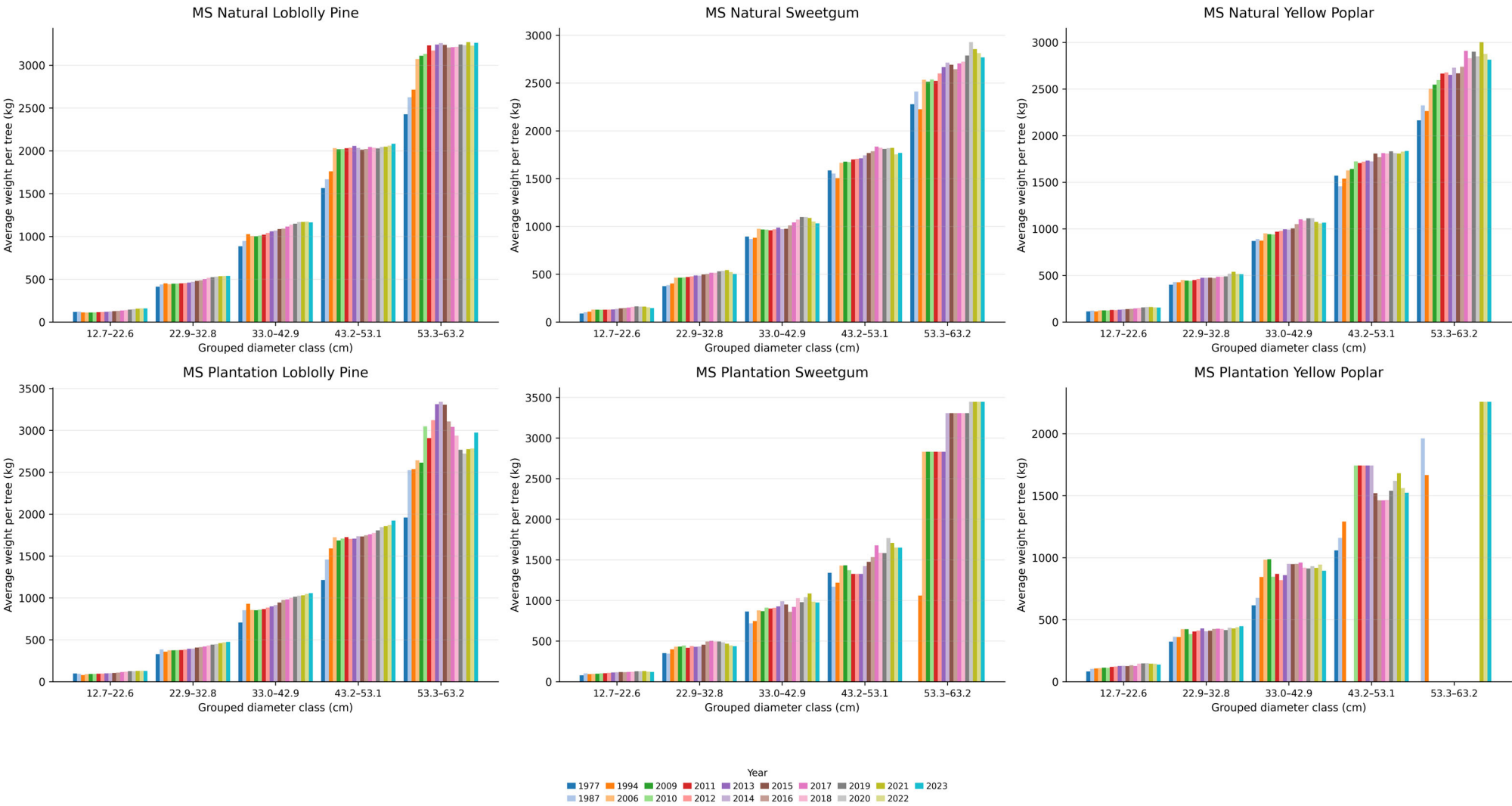
Year

1982 1998 2001 2004 2007 2010 2013 2016 2019 2022

1989 1999 2002 2005 2008 2011 2014 2017 2020 2023

1997 2000 2003 2006 2009 2012 2015 2018 2021

Appendix A.3. Mississippi



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