Journal of Forestry, 2023, **XX**, 1–11
https://doi.org/10.1093/jofore/fvad005
Advance access publication 20 February 2023
Research Article - economics

Critical Market Tipping Points for High-Grade White Oak Inventory Decline in the Central Hardwood Region of the United States

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Abstract

This study expands the spatial scope of the Subregional Timber Supply (SRTS) model to include states in the central hardwood region and examine critical market tipping points of high-grade (large diameter) white oak under a set of illustrative scheduled demand scenarios. In light of the growing concern for future white oak timber supply, we illustrate the sensitivity of future inventory tipping points to market structure and price responsiveness. Particularly, we examined the importance of market demand parameters, including growth rates for product demand and supply/demand elasticities, in influencing future inventory trajectories in different subregions over the projection horizon. Results of this study indicate that more elastic demand and more inelastic supply response concomitantly defers the time before inventory culminates. This modeling framework shows promise in examining key ecological, climatic, and economic interrelationships that will drive future resource changes.

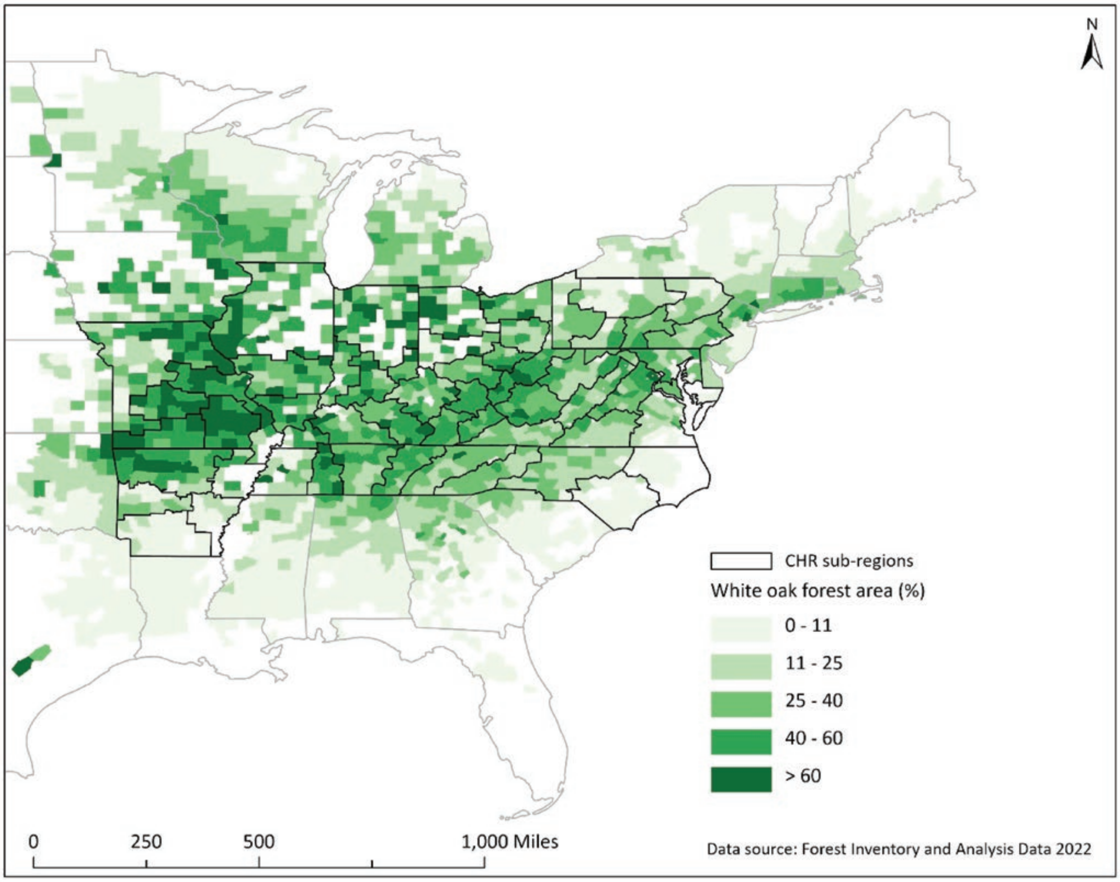
Study Implications: This study examines critical market tipping points of high-grade white oak growing stock in the central hardwood region under alternative demand growth scenarios. The main finding of this article is that high-quality white oak inventory tipping points depend critically on the annual rate of increase in quantity demanded and on the sensitivity of supply and demand to changes in white oak log prices. This study helps better inform white oak–dependent stakeholders on sustainability assessment and highlights how policy design that incorporates both management and market interventions could help maintain the white oak resource base.

Keywords: subregional timber supply model, central hardwood regions, high-grade, white oak, demand

White oak is an important commercial tree species in the United States. The species is dominant across the central, northern, and Appalachian hardwood regions from the mid-South to the upper Midwest (figure 1). White oak roundwood is primarily used for manufacturing interior decorative products such as furniture, cabinets, millwork, and hardwood flooring. It is also used in industrial applications such as caskets, pallets, railroad ties, mine timbers, and truck flooring (Cassens 2007). However, the exclusive use for tight cooperage (such as whiskey barrels and wine casks) is what makes white oak unique from other oak species and white oak stave logs a niche market in the timber industry. Whereas the federal standards of identity for distilled spirits require American bourbon be made in charred new oak containers (Office of the Federal Register 2018), it is the structural features of white oak—the presence of medullary rays and tyloses—that makes the wood impervious (Conner et al. 2003), thus making white oak ideal for bourbon barrel manufacturing. In Kentucky, which produces almost 95% of the world's bourbon, oak barrels are the top wood product export (Stringer et al. 2019) and the distilling industry contributes roughly $8.6 billion to the state's economy annually (Kornstein and Coomes 2019). As such, maintaining a sustainable supply of white oak timber is critical to white oak dependent industries and to the regional economy of the growing region and beyond.

However, historical and future environmental change could exacerbate the challenge of managing white oak inventories in the coming decades. The "oak regeneration problem" is one of the widely discussed ecological issues in eastern US forests (Abrams 1996, 1998, 2003; Dey 2014; Loftis 2004; Loftis and McGee 1993; Nowacki and Abrams 2008; Whitney 1994). This problem is defined by the reduced regeneration and recruitment potential in mature oak stands, leading to an aging inventory with sapling and midstory "oak bottleneck" (Nowacki and Abrams 1992). Fire suppression policies beginning around the 1920s primarily created room for closed-canopy forests to grow, thereby thwarting the ability of fire-adapted species like oak to regenerate in the understory and recruit into the midstory, and increasingly giving way to shade-tolerant species like

Received: July 21, 2022. **Accepted:** January 18, 2023.



Data source: Forest Inventory and Analysis Data 2022

Figure 1. Delineation of fifty-seven subregions in the central hardwood region for SRTS model.White oak forest area is based on acreage of white oak dominated forests as a percent of all timberland area at county level; white oak dominated forests includes three forest types following FIA forest type classification: 503 (white oak/red oak/hickory), 504 (white oak), and 506 (yellow-poplar/white oak/northern red oak).

maples (Nowacki and Abrams 2008). Harvesting practices like selective logging and single tree selection throughout the 20th century (McGee 1972; Miller and Kochenderfer 1998) favored shade-tolerant species that replaced oak and dominated forest understories in the absence of regular fire occurrence (Dey 2014). The sunlight available to the forest floor in small openings created by single-tree harvesting is not sufficient to ensure successful regeneration of oaks during periods of fire exclusion (Clark 1993). Consequently, "mesophication" has ensued, thereby rapidly altering the structure and composition of historically-oak dominated forests in the eastern United States (Nowacki and Abrams 2008).

Emerging threats to white oak include rapid white oak mortality (Reed et al. 2017) and new pathogens or pests (Conrad et al. 2020), thus further complicating oak management in the region. Exacerbating these ecological threats is the lack of active forest management (Butler and Butler 2016) and aggressive partial harvesting practices such as large-diameter (Luppold and Bumgardner 2018b) and high-grade white oak selection (Brandeis 2017), which is driven by market demands and higher associated market prices for higher quality white oak sawlogs and stave logs (Stringer et al. 2019). Selective harvesting of high-grade and large-diameter white oak could further fuel the mesophication loop, foreshadowing sustainability concerns of high-quality white oak sawlogs in the future.

The central hardwood region (CHR) is a critical ecosystem in the eastern US. The region is overwhelmingly dominated by deciduous hardwood species such as oaks and hickories (Fralish 2003) that provide significant ecological and economic benefits to the local, regional, and national communities (Schmidt and Mcwilliams 2003)[1]. Within the CHR, hardwoods make up roughly 80% of the volume of all live trees across these states (USDA Forest Service 2022) and approximately 71% of the white oak growing stocks in the country (USDA Forest Service 2022). Furthermore, white oak comprises roughly 9% of all growing stock volume and white oak-dominated forest types comprise roughly 31% of all forest type acreage in the CHR (USDA Forest Service 2022). Notably, the CHR region is the primary hardwood lumber producing region in the eastern United States (Luppold and Bumgardner 2018b).

The CHR is undergoing a gradual shift in forest structure and composition marked by relatively rapid advancement of large-sized trees and decreasing relative volume of trees in smaller size classes—more pronounced for select white oak species group and less pronounced for species like hard maple, soft maple, and hickory (Luppold and Bumgardner 2018a). The region is also witnessing a significant decline in oak abundance (from 24.9% to 22.7%), with white oak species declining significantly (from 5.8% to 5.4%) in the eastern United States during the period of 1980–2008 (Fei et al. 2011). Case studies in upland oak forest sites in Indiana, Kentucky, and Mississippi indicate a bottleneck in sapling and midstory oak trees (red and white oak groups) but abundant seedlings and overstory, suggesting low oak recruitment and a gradual replacement by opportunistic mesophytic species like maples (Alexander et al. 2021). In the short run, abundance of large-sized timber is beneficial to forest industries because large diameter-sized trees generally produce large clean boles and are thus more economical to harvest and process. Nevertheless, as these large-sized trees are harvested or die out without sufficient presence of young trees for replenishment, these forests cannot sustain themselves in perpetuity unless actively managed. Furthermore, the region is expected to undergo a major shift in response to changes in climate and fire regimes. This will ultimately result in maple-dominated forests, thereby altering ecological processes and stumpage values throughout the region (Ma et al. 2016).

Quantitative studies providing future outlook of timber supply in the hardwood region are lacking. Specifically, there is an important gap in the literature pertaining to the influence of future market demands on white oak management and inventory changes. Although timber market models have advanced in recent years (Baker et al. 2019), recent studies typically provide regional-, national-, or global-scale projections (Latta et al. 2018; Tian et al. 2018; Wear and Coulston 2015), and often lack detail on the effects of market drivers on future inventory change for particular forest types and/or species groups. This is a critical knowledge gap, as white oak–dependent stakeholders can use baseline projections to develop sustainability plans and make timely investment in forest management to mitigate white oak inventory decline.

To this end, we expand a bioeconomic model that captures linkages between regional markets and forest inventory dynamics model to explore linkages between forest product demand scenarios and white oak harvest activity. Specifically, we expand the spatial scope of the model to include the twelve states in the CHR (figure 1) and add new market demand sources for high-grade (large diameter) white oak. We develop a scenario design that includes exogenously compounding demand growth to quantify critical market tipping points in time when the inventory begins to collapse. We illustrate the importance of market demand parameters, including annual growth rates for product demand and price elasticities, in influencing inventory expansion and eventual collapse at different points of time and across different subregions. Our analysis can help inform sustainability assessments, investment in white oak management, and in the development of white oak management plans to counteract mounting economic pressures.

Methods

Application of the Subregional Timber Supply Model to the CHR

The Subregional Timber Supply (SRTS) model is a bioeconomic model of timber stumpage markets (Abt et al. 2009) that has been applied in regional market analysis (Parajuli et al. 2019), climate change projections (Henderson et al. 2020), hurricane impact assessment (Henderson et al. 2022), and renewable energy policy analysis (Galik and Abt 2016). The model solves for an equilibrium harvest across age classes, forest types, and subregions in 1-year time steps given regionwide demand projections for various roundwood products (Abt et al. 2009). In this article, we extend the spatial scope of the model by processing 2017 Forest Inventory and Analysis (FIA) data (average plot remeasurement year across all states in CHR) over a detailed set of hardwood species and forest types typically managed by private landowners in the CHR. Figure 1 shows this expanded regional scope and how forest inventory data is broken up across fifty-seven hardwood subregions based on FIA survey units (Bechtold and Patterson 2005). The original SRTS model includes all of the southeastern United States.

The economic module in SRTS defines isoelastic supply functions for each subregion (i), and roundwood product (j) in each year (t) of the projection. The supply function for product j $\left(Q^S_{ijt}\right)$ is a function of stumpage price $\left(P_{jt}\right)$ and inventory (I_{ijt}). Supply functions are parameterized using product-specific price elasticities of supply[2] $\left(\gamma_j\right)$ and product-specific inventory elasticities[3] (τ_j). Although values for individual forest products are not available in the literature, the general consensus is that the supply, demand, and inventory responses are inelastic (Pattanayak et al. 2002). Table 1 summarizes a few econometric studies and their elasticities. The model sums individual supply curves for each subregion to obtain market-wide aggregate supply $\left(Q^S\right)$. Similarly, aggregate product demand (Q^D_{jt}) is an isoelastic function of product stumpage price (P_{jt}), parameterized by a product-specific price elasticity of demand[4] (ϵ_j) and an exogenous demand shifter (G_{jt}). The competitive equilibrium price for product j in year t equates aggregate supply to the regionwide demand:

Table 1. Summary of a few econometric studies and their elasticities.

Parameter	Ownership	Product	Range	Source
Demand price elasticity	-	Hardwood	-0.77	(Polyakov, Teeter, and Jackson 2005)
		Hardwood and softwood	-0.5	(Abt, Cubbage, and Pacheco 2000)
Supply price elasticity	Corporate	Hardwood	0.407 to 0.454	(Adams and Haynes 1996)
		Hardwood and softwood	0.273 to 1.2	(Adams and Haynes 1980) (Newman and Wear 1993) (Haynes and Darius 1985)
	Non-corporate	Hardwood	0.48 to 0.509	(Adams and Haynes 1996)
		Hardwood and softwood	0.17 to 0.39	(Adams and Haynes 1980) (Newman and Wear 1993) (Haynes and Darius 1985)
	All	Hardwood	0.35 to 0.454	(Polyakov, Teeter, and Jackson 2005) (Pattanayak, Murray, and Abt 2002)

$$\sum_{i=1}^{57} Q_{ijt}^{S}\left(P_{jt}; I_{ijt}, \gamma_j, \tau_j\right) = Q_{jt}^{D}\left(P_{jt}; G_{jt}, \epsilon_j\right) \tag{1}$$

SRTS applies a bisection algorithm (e.g., Miranda and Fackler 2002) to obtain a computational solution to (1). On an annual time step, the model first computes the competitive equilibrium price P_{jt}^{*} for each product according to (1). Then, the model uses the individual supply functions to determine the competitive equilibrium harvest volume that would prevail within each subregion at the market-clearing price: $Q_{ijt}^{S}\left(P_{jt}^{*}; I_{ijt}, \gamma_j, \tau_j\right)$. Next, the model uses the competitive equilibrium for each product as a set of target harvest levels in a linear goal programming problem (Abt et al. 2009). This problem determines actual harvest volume across age classes and forest types within each subregion. After actual harvests are determined for a given subregion (H_{ijt}^{*}), inventory in that subregion grows according to the equation of motion:

$$I_{ij,t+1} = I_{ijt} \ + I_{ijt} - H_{ijt}^{*} \tag{2}$$

where ΔI_{ijt} represents the growth in inventory, net of mortality. Hence, each scenario which defines an alternative sequence of exogenous demand shifters (G_{jt}) will yield an alternative inventory trajectory (I_{ijt})

Model Initialization and Input Data

The initial conditions in SRTS are computed from the FIA plot data (Bechtold and Patterson 2005). This data contains information on growing stock inventory, growth, mortality, and removals. We summarized plot data by each subregion shown in figure 1 to develop initial inventory conditions. The summarized data retains heterogeneity across forest management types (forest type groups), species groups, age classes, and size classes across six physiographic regions. Tables S1 and S2 provide detailed description of the forest management types and species groupings used by the model. The initial state of forest inventory is provided by an estimate of growing stock volume in each subregion by ten species groups, five forest management types, and within eleven 10-year age classes, with merchantable volume starting at age 20. Within the model, volume is annualized by assuming a uniform distribution congruent with the 1-year model time step. Because the growth on remeasured FIA plots is highly variable, growth curves from a broader region are calibrated to reflect local growth levels. Estimated growth rates net of mortality is smoothed by a regression on age class, state, and physiographic region.

Given that partial harvesting is commonplace in hardwood forests, we incorporated a partial harvesting routine that was previously developed for the SRTS model (Sendak et al. 2003). To incorporate partial harvesting activity in the model, we estimated from FIA data the proportion of total forestland area that is partially harvested each year and the proportion that is clearcut each year. We defined clearcut activity as harvests that covers at least 75% of the stand volume removed within a plot. We defined any harvesting activity that removes less than 75% of the stand volume within a plot as partially harvested. These proportions are specified across each of the five forest management types listed in Table 2 and are assumed to remain constant over the course of the model's projections. Based on the FIA data used to construct these proportions, we note that yellow pine forests are more likely to be clearcut than hardwood forest types, and that more of each forest type's land area is partially harvested than it is clearcut. The partial harvest parameters are areal percentages. As in prior versions of SRTS, the harvesting algorithm places a weight on achieving the product mix by harvesting across age classes as the summarized FIA data implies. The partial harvest mode comes into play when reallocating harvested acres to new age classes. For clearcut area, the model moves acres to age class zero. For partially harvested acres, the model moves acres to an age class consistent with the leftover volume per acre given the empirical FIA data.

Table 2. Annual percentage of total forest acreage that is partially harvested and clearcut across forest management types in the central hardwood region.

Forest management type	Percent partially harvested	Percent clearcut
Southern yellow pine	17.2%	12.2%
Mixed oak/pine	8.5%	5.3%
Oak	9.1%	2.1%
Bottomland hardwood	6.3%	2.2%
Maple/birch	11.6%	1.5%

Scenario Design

In our study, we defined high-grade white oak sawtimber as trees in the select white oak species group that are at least 16 in. in diameter at breast height (DBH). In the case of white oak, generally high-quality white oak logs are used to make bourbon barrels for the distilling industry. Tree quality is an important consideration in hardwood markets because higher-quality trees are commercially valuable and can cost more than three times the price of their lower-quality counterparts, depending on species (Stringer et al. 2019). In the case of hardwoods, tree quality often is measured by assigning tree grades (1 to 5) using guidelines established by the USDA Forest Service (USDA Forest Service 2019). Although tree grading procedures consider a number of grading factors such as length of grading zone, length of grading section, minimum DBH, minimum DBH at the top of grading deduction, and cull deduction among others, minimum DBH (16 in. for grade 1) is a consistent and convenient grading factor. In addition, large-sized logs generally contain more defect-free lumber, so more high-grade lumber is produced from larger-sized roundwood.

Aggressive harvesting practices such as high-grading signal priority demand of higher quality white oak logs as forest landowners are responding to increasing prices of stave logs (Brandeis 2017; Stringer et al. 2019). Studies indicate substantial reduction in timber quality of commercially valuable hardwood trees (Brandeis 2017; Luppold and Bumgardner 2019). However, substantial annual fluctuations in the volume percentages by grade in FIA data (Brandeis et al. 2017) precludes the use of consistent historical trends for developing demand/harvest scenarios.

Although there is currently more uncertainty about future demand for high-grade white oak than biological supply, reports indicate a surge in demand, with subsequent investments in production facilities and barrel inventory adding roughly 1.7 million barrels of new bourbon to warehouse inventory in 2018, double what it was a decade ago (Kornstein and Coomes 2019). Accordingly, we examined the sensitivity of forest outcomes to a range of hypothetical rising demands in the future. Specifically, we evaluated one constant demand scenario and twelve rising-demand scenarios for high-grade white oak sawtimber (from a 0.5% increase in demand per year to a 10% increase in demand increase per year). The constant demand scenario sets the quantity of high-grade white oak demanded in each year equal to the base year removal volume (obtained from 2017 FIA data) and keeps demand for all other products at that level throughout the projection horizon, that is, 2017 to 2500. Although a projection with a long-time horizon like this is an atypical application of the SRTS model, we were interested in understanding how the market mechanism can be used to explore the inventory tipping point rather than to make a forecast of white oak prices and harvest quantities. Projections spanning over 100 years, although unusually long for an SRTS run, are a typical feature in studies using the Global Timber Model (Daigneault and Favero 2021; Favero et al. 2020; Tian et al. 2016), including Favero, Mendelsohn, and Sohngen (2018), which runs climate change scenarios to 2350 and reports results to 2250. Besides, hardwood forests grow slowly, thus have longer rotation, which means that most of the dynamic is driven by the existing forest but depends critically on harvest rates, which was our key change driver in this study. We acknowledge that many other socioeconomic, technological, and environmental factors will change over long simulation horizons that could affect the structure of timber supply and demand systems. However, the rising demand scenarios (2017 to 2300) are illustrative simulations and do not represent forecasts of demand. Rather, we sought to understand the relationship between compounding annual demand growth and white oak inventory growth via structured sensitivity analysis. To this end, we ran the model for a sufficient time horizon to capture tipping points under alternative compounding demand scenarios (from 2017 to 2300). For the constant demand scenario, we ran the model to 2500, and no tipping point occurred. However, the scenarios allowed us to evaluate the capacity for high-grade white oak inventory to be sustained as demands on the resource base expand. In other words, it allowed us to identify potential tipping points in white oak inventory driven by increasing demand. Each demand scenario was interacted with a range of supply and demand price sensitivities to understand how white oak tipping points change to markets characterized by varying degrees of price responsiveness.

Table 3 provides a summary of base year (2017) demand across all 21 roundwood products. We see that high-grade white oak comprised roughly 2.8% of total roundwood removals and 4.5% of all hardwood removals across the CHR. This level of demand for high-grade white oak was only 0.6% of the total available growing stock across the region. All sizes of white oak roundwood comprised 8.2% of total roundwood removals and 13.5% of all hardwood removals. For all white oak products, the base year removals were only 0.5% of the total available growing stock across the region. An increase in the demand for high-grade white oak of 1% per year raises demand to 121,000 thousand cubic feet (mcf) by 2050 (to 1.1% of the total growing stock) and 199,000 mcf by 2100 (to 1.3% of the total growing stock). A larger increase in the demand for high-grade white oak of 5% per year raises demand to 436,000 mcf by 2050 (to 4.5% of the total growing stock) and 5,001,000 mcf by 2100 (to 165.0% of the total growing stock).

Table 3. Summary of base demand across roundwood products in the central hardwood region.

Product	Size description (inches)	Quantity demanded (mcf)
Southern yellow pine (small roundwood)	5–11	492,728
Southern yellow pine (sawtimber)	≥11	676,938
Select white oak (small roundwood)	5–11	111,777
Select white oak (low-grade sawtimber)	11–16	61,987
Select white oak (high grade sawtimber)	≥16	87,166
Yellow poplar (small roundwood)	5–11	129,319
Yellow poplar (sawtimber)	≥11	188,853
Other red oak (small roundwood)	5–11	119,447
Other red oak (sawtimber)	≥11	166,482
Soft maple (small roundwood)	5–11	72,637
Soft maple (sawtimber)	≥11	59,898
Other soft hardwoods (small roundwood)	5–11	165,970
Other soft hardwoods (sawtimber)	≥11	154,007
Other white oak (small roundwood)	5–11	52,418
Other white oak (sawtimber)	≥11	63,542
Other hard hardwoods (small roundwood)	5–11	187,640
Other hard hardwoods (sawtimber)	≥11	188,476
Select red oak (small roundwood)	5–11	44,022
Select red oak (sawtimber)	≥11	72,318
Other softwoods & conifers (small roundwood)	5–11	23,638
Other softwoods % conifers (sawtimber)	≥11	30,669

Results

The base scenario holds the demand for all products constant, as well as forest productivity and environmental change factors. As expected, we do not find evidence of tipping point in inventory over the projection period through 2500. This is because current annual removals constitute a very small proportion of the available growing stock. Figure S3 shows inventory growth for all CHR subregions in SRTS. Notably, whereas some subregions see limited inventory growth or even slight declines over time, other regions, such as the North Carolina Piedmont, Tennessee Cumberland Plateau, and Arkansas Ozark regions, experience high rates of inventory growth through the simulation horizon.

However, our projections indicated discernible inventory tipping points under demand growth scenarios, and these tipping points change as demand trajectories and elasticity parameters change. Figure 2 illustrates this result across

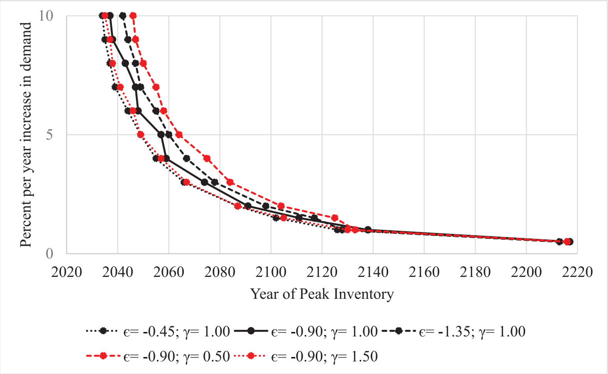


Figure 2. High-grade select white oak growing stock inventory inflection points under alternative price elasticities of supply (γ_{HGWO}) and demand (ϵ_{HGWO}) for high-grade white oak.The non-smoothness of the curves in the figure are due to the approximation error associated with the goal programming solutions.

alternative combinations of supply and demand elasticities. We see in figure 2 that as the annual demand for high-grade white oak increases at a constant annually compounding rate, the year where inventory peaks and begins to decline occurs sooner. Initial inventories do rise as growth exceeds harvest, but they peak as growth equates harvests, and then tail off as harvests exceeds growth as implied from the inventory accounting equation of motion.

Across the entire CHR, we see that as per year demand for high-grade white oak increases, the peak year of growing stock inventory declines. Under base model parameters ($\epsilon_{HGWO} = -0.9$; $\gamma_{HGWO} = 1.0$), and when the demand for high-grade white oak increases at a rate of 3% per year, the growing stock of high-grade white oak peaks in year 2074 at 11.8 million cubic feet (MMCF). If instead demand for high-grade white oak increases at a rate of 5% per year, then the growing stock peaks in 2057 at 9.9 MMCF. In general, the larger the rate of annual increases in demand, the sooner inventory declines and the lower the inventory will be at that peak.

Our alternative assumptions about price sensitivities contribute to our understanding of how sensitive this result is to the capacity for supply and demand to respond to the annual price changes that accompany the scheduled increases in quantity demanded. As demand becomes more inelastic (from $\epsilon_{HGWO} = -0.90$ to $\epsilon_{HGWO} = -0.45$), inventory peaks sooner (as illustrated in figure 2). When instead we subject the rising demand scenario to a function with more elastic demand ($\epsilon_{HGWO} = -1.35$), we see in figure 2 that inventory peaks later. This means that when demand for high-grade white oak sawtimber is less sensitive to price (inelastic), we are simulating a less adaptive behavior of consumers in response to price changes (i.e., a small increase (decrease) in demand of high-quality white oak in response to large decrease (increase) in price). Hence, the demand pattern follows closely that of the requested harvest, thereby leading to an early slump in inventory (year 2049 in case of the 5% scenario). On the other hand, when demand for high-grade white oak sawtimber is sensitive to price (elastic), we are modeling an adaptive behavior of consumers in response to price changes, that is, large increase/decrease in demand of high-quality white oak in response to small decrease/increase in price. Thus, demand patterns deviate from the competitive equilibrium harvest, thereby inducing inventory to peak later (year 2060 in case of the 5% scenario).

Alternatively, when we modeled a market with a relatively inelastic supply (from $\gamma_{HGWO} = 1.00$ to $\gamma_{HGWO} = 0.50$), we see in figure 2 that inventory peaks further out in the future. This simulates a situation where private timberland owners are less willing to harvest their high-grade white oak in response to an increase in its price. This has the effect of delaying the time at which high-grade white oak inventories peak. A doubling of the baseline supply price elasticity can push these peak inventory years out farther than a halving of the baseline demand price elasticity. However, it is evident in figure 2 that when supply elasticities become more elastic ($\gamma_{HGWO} = 1.5$), peak inventory years are projected to occur several years sooner (2046 under 6% rise in demand) but not as soon as we observe under a halving of the demand price elasticity (2044 under 6% rise in demand), given our baseline assumption of the supply price elasticity. Because supply and demand curves for wood products tend to be relatively inelastic, the inelastic set of scenarios ($\epsilon_{HGWO} = -0.90$, $\gamma_{HGWO} = 0.5$) is most likely the closest representation to reality.

Table 4 presents the full set of results from these scenarios and the volume of inventory in that peak year. For instance, when the demand for high-grade white oak increases at a 0.5% per year under the baseline scenario ($\epsilon_{HGWO} = -0.9$; $\gamma_{HGWO} = 1.0$), inventory peaks in year 2217 at a volume of 19,900 MMCF, cutting over only 1.3% of the total available growing stock. However, as demand increases to 3% per year, inventory peaks in year 2074 at a volume of 11,800 MMCF, and removals in that year consist of 2.4%of the total available inventory. Peak inventory volumes are largest under the scenario characterized by relatively inelastic supply ($\epsilon_{HGWO} = -0.9$; $\gamma_{HGWO} = 0.5$) and tend to be lowest under the scenario characterized by inelastic demand ($\epsilon_{HGWO} = -0.45$; $\gamma_{HGWO} = 1.0$). The scenario characterized by elastic supply ($\epsilon_{HGWO} = -0.9$; $\gamma_{HGWO} = 1.5$) will delay the year of peak inventory relative to the scenario characterized by inelastic demand. Generally, the higher the rate of increase in demand, the larger the removal percent of the total inventory, and thus, the sooner the inventory peaks. It is important to note that the percentage of actual removal is based on removals attained from market solutions rather than removals from scheduled changes in quantity demanded.

Results also project spatial variation in peak inventory years across the states in the CHR. We show this for each state using the baseline set of elasticities in figure S4. Under all alternative rising-demand scenarios, inventory peaks much later in Maryland, which is attributable to it having the lowest levels of high-grade white oak growing stock among all states in the region. This suggests that harvest is prioritized to states with relatively larger inventory as aggressive demand growth strains the existing resource base. As a result, inventory culminates much earlier in states with relatively abundant high-grade white oak inventory such as Missouri, Virginia, West Virginia, Tennessee, and Kentucky. Ohio shows a different trend, as inventory of high-grade white oak is relatively low but peak inventory occurs much sooner. Although the growing stock of high-grade white oak is lowest in Ohio (following only Maryland and Indiana), inventory peaks much earlier under rising-demand scenarios of 5% and above, exceeding that of states with more voluminous growing stock.

Although the region-wide and state level projections are informative, they may obscure important differences in timber

Table 4. Percent actual removal of high-grade select white oak growing stock at peak inventory year under 12 alternative demand growth scenarios and a range of supply and demand price elasticities (peak volume in MMCF).

Annual percentage increase in demand	$\varepsilon_{HGWO} = -0.9$ $\gamma_{HGWO} = 1.0$ (Baseline scenario)		$\varepsilon_{HGWO} = -0.45$ $\gamma_{HGWO} = 1.0$		$\varepsilon_{HGWO} = -1.35$ $\gamma_{HGWO} = 1.0$		$\varepsilon_{HGWO} = -0.9$ $\gamma_{HGWO} = 0.5$		$\varepsilon_{HGWO} = -0.9$ $\gamma_{HGWO} = 1.5$	
	Year (peak vol.)	% of inventory removed	Year (peak vol.)	% of inventory removed	Year (peak vol.)	% of inventory removed	Year (peak vol.)	% of inventory removed	Year (peak vol.)	% of inventory removed
0.5%	2217 (19,900)	1.3%	2217 (20,500)	1.3%	2213 (18,400)	1.4%	2216 (18,100)	1.4%	2216 (20,100)	1.3%
1%	2138 (15,700)	1.6%	2126 (15,700)	1.6%	2128 (15,700)	1.6%	2133 (16,200)	1.6%	2130 (15,700)	1.6%
1.5%	2111 (14,600)	1.9%	2102 (14,400)	1.9%	2117 (14,300)	1.8%	2125 (15,200)	1.8%	2105 (14,500)	1.9%
2%	2091 (12800)	2.0%	2087 (13,300)	2.1%	2098 (13,200)	2.0%	2104 (13,500)	1.9%	2087 (12,800)	2.1%
3%	2074 (11,800)	2.4%	2066 (11,200)	2.5%	2078 (11,900)	2.2%	2084 (12,300)	2.0%	2067 (11,400)	2.4%
4%	2059 (10,500)	2.6%	2055 (9,900)	2.8%	2067 (11,300)	2.4%	2075 (11,700)	2.4%	2057 (10,000)	2.7%
5%	2057 (9,900)	2.8%	2049 (9,400)	2.9%	2060 (10,800)	2.5%	2064 (10,700)	2.5%	2049 (9,400)	2.8%
6%	2048 (9,400)	2.8%	2044 (8,900)	3.0%	2055 (9,800)	2.8%	2058 (10,500)	2.6%	2046 (8,900)	3.0%
7%	2047 (9,200)	3.1%	2039 (8,600)	3.1%	2049 (9,500)	2.8%	2055 (9,800)	2.9%	2041 (8,700)	3.0%
8%	2043 (8,900)	3.1%	2037 (8,500)	3.1%	2047 (9,200)	2.9%	2050 (9,500)	2.8%	2038 (8,600)	3.1%
9%	2038 (8,500)	3.1%	2035 (8,200)	3.3%	2044 (8,900)	3.1%	2047 (9,300)	2.9%	2037 (8,300)	3.1%
10%	2037 (8,500)	3.2%	2034 (8,100)	3.3%	2042 (8,800)	3.4%	2046 (9,100)	3.1%	2035 (8,000)	3.3%

εHGWO represents demand elasticity of high-grade select white oak growing stock; ***γHGWO*** represents supply elasticity of high-grade select white oak growing stock.

inventory across a local area. Figure S5 provides a further breakdown of spatiotemporal variation in critical inventory tipping points across fifty-seven subregions under alternative rising-demand scenarios with the baseline set of elasticities and figure S6 provides a snapshot of initial inventory (year 2017) across those subregions. At the subregional level, there were some noticeable trends. For example, subregions with larger levels of high-grade white oak inventory (such as northwest West Virginia, the Piedmont region of North Carolina, the Ozark regions of Arkansas and Missouri, and the north–south Piedmont regions of Virginia), inventory peaks earlier as annual demand growth increases. Similarly, in regions with relatively low levels of high-grade white oak inventory (such as the delta regions of Arkansas, lowland Indiana, northeast Ohio, and southeast or west regions of Pennsylvania), inventory is preserved until later in the projection horizon as annual demand growth increases. Nevertheless, such trends are not contemporaneous throughout the subregions. For instance, inventory peaks within the first few years of the projection period in subregions with some of the lowest inventory levels, such as southwest Ohio, the eastern shore of Maryland, west Kentucky, and the northern coastal plain of North Carolina.

Discussion and Conclusion

Our projections illustrate model performance under user-supplied demand scenarios and provide a breakdown of growing stock inventory changes across survey units and products. This highlights the utility of the SRTS model in projecting the sustainability of timber resources over the CHR. Our simulations show that with a scheduled lower annual rate of rising demand for high-grade white oak, a more adaptive demand-price response provides added sustainability of the growing stock inventory, as it delays the time before inventory begins to decline and tends to raise the volume of inventory available by that time. However, our simulations suggest that the sustainability of the white oak growing stock across the CHR is unlikely to be threatened, as it would require annually compounding increases in demand to draw down and eventually deplete growing stock inventories of high-grade roundwood.

Our projections also show that less adaptive supply responses can have the same effect as more adaptive demand responses in the market for high-grade white oak logs. When supply is relatively inelastic (i.e., when harvests increase less with increases in the price), there is a smaller relative reduction in growing stocks under positive shifts in demand. We have shown here how the sustainability of high-grade white oak growing stock can be affected by these changes in price sensitivities across a range of hypothetically rising demand scenarios. This result has implications for policy design, as targeted incentive structures can be developed to compensate forest landowners for other ecosystem service values associated with their lands as well as initiatives or commitments by cooperage companies to use certified oak products, both of which could potentially reduce supply price responsiveness. Alternatively, similar outcomes could be achieved with policies intended to increase the price responsiveness of stave logs purchasers. Such demand-side interventions might include subsidization of technological improvements which more efficiently utilize white oak logs or the promotion of substitutable species used by oak barrel manufacturers, such as European oak or French oak. The welfare implications of both demand- and supply-side interventions depend critically on current elasticities and the scale of the intervention. Before such policies are seriously considered, further research is likely needed to understand the implications of market interventions and the potential welfare impacts or unintended consequences of policies intended to avoid the depletion of white oak growing stocks.

Our results should be interpreted with some caution, as they do not represent forecasts of potential inventory decline or depletion. Instead, the results represent outcomes on inventory under various “what if” demand scenarios for a given set of model parameters, whereby the demands for high-grade white oak sawtimber rise at a compounding rate and the demands for all other forest products remain constant. It is possible that different sets of demand scenarios for other forest products would lead to different peak inventory years for our product of interest, particularly demand scenarios for smaller, lower grade white oak products. Additionally, market shocks from unforeseen events such as a disease pandemic, technological change, and the emergence of markets for new end-uses of forest products would alter the trajectory of demand and white oak timber inventory over a 400-year period. However, the purpose of our projections here is not to accurately predict how much inventory will be available over the CHR, but to instead determine the relationship between compounding demand growth and maximum inventory levels. More realistic demand scenarios would not define annual demand growth as evolving regularly like we have here, but such scenarios would be less useful for measuring the extent to which inventory can withstand large increases in demand. We learned that white oak inventory has a strong capacity to withstand more modest compounding demand growth rates (0.5% to 1%/year) but can experience considerable pressure if demand were to grow at a much larger annual rate (5% to 10%/year).

Demand scenarios simulating lower annual percentage increases in demand (such as 0.5% per year and 1% per year), although hypothetical, follow a more realistic pathway than the extreme demand scenarios (>1% per year). Across the CHR, inventory peaks much farther in the future for the 0.5%–1% per year scenarios, which is attributed to lower removal percentages of the total available growing stock (less than 2%; see Table 3). This result suggests there is substantial volume of large white oak trees (≥16 in. DBH) in the CHR inventory. However, it is also important to note that not all projected inventory of high-grade white oak would be available for harvest in our projected price ranges due to limited accessibility of some forest stands. Supply curves in SRTS are shifted based on changes in total product inventory. Net wood availability is constrained by the size of forest holdings, distance from the harvest site, ownership type, landowner preferences, terrain, tree size, and site productivity among others (Butler et al. 2010; Silver et al. 2015). Unlike planted pine in the South where inventory comprises largely harvestable volume of woods, much of the hardwood base is economically inaccessible. Thus, hardwood growth rates (based on all stands) are typically higher than removal rates (based on a small percentage of harvested stands), suggesting that there is a difference between biological sustainability (growth on all stands exceeds removals) and economic sustainability (growth on economically accessible stands exceeds removals). White oak–dependent industries could therefore be jeopardized even when measured total inventory is increasing, unless inventories are stimulated by rising prices and plantation.

Further, the ongoing mesophication in historically oak-dominated forests could dramatically alter future availability of large-sized white oak trees in the CHR, but we did not explicitly model increased replacement of white oak over the long-term due to environmental change factors. The effect of carbon fertilization that could lead to increased forest growth and inventory in the future (Davis et al. 2022; Henderson et al. 2020) has not been accounted for in the model. Finally, using diameter as the only factor in classifying "high-grade" white oak might have overestimated the actual growing stock inventory of the high-grade white oak sawtimber product class. All things considered, our projection most likely represents the best-case scenario, especially for 0.5%–1% demand scenarios; that is, high-grade white oak resource base in the region might be approaching critical market tipping points earlier than projected.

Although our economic framework uses the best available inventory database, FIA data has an element of sampling error that is unavoidable and can potentially have affected our results. However, we partially overcame this problem by subjecting our key model results to a wide range of scenarios and model parameters. We also acknowledge that modeling natural systems is inherently fraught with uncertainties and there is added complexity when it comes to hardwood forests and their product markets. There are features of hardwood markets that differ greatly from more actively managed pine forests in the southern United States. For example, hardwood timberlands often have longer rotations, are heterogenous in their age classes, structure, and composition, and are subject to unique harvesting practices such as high-grading.

Climate in the eastern United States has been increasingly wet with reduced drought severity and frequency during the last century (Kutta and Hubbart 2018; Pederson et al. 2015), which would be conducive for mesophytic species to outcompete xerophytic species like oaks. Therefore, estimates of future forest dynamics under changing climatic conditions and how market tipping points of economically important species will fare under these changing environmental conditions are subjects for future research. Future work on how forest product markets influence timber harvests should be conducted to better inform forest-dependent stakeholders on sustainable management of oak forests in the region.

In summary, this modeling effort should be regarded as a first step that incrementally enhances our understanding of growing stock sustainability over the CHR. Further economic modeling of the hardwood timber base over this region can be improved through the availability of product specific harvest data, attunement to biological changes such as mesophication, and refinement of model parameters. Additional analysis can be used to identify and evaluate potential management interventions to improve the sustainability of white oak systems in the CHR. For example, the economic costs and benefits of tree planting initiatives, silviculture to support white oak and mitigate mesophication (including prescribed fire treatments), and dynamically shifting the proportion of forest area clearcut or partial harvest across alternative subregions. A future research agenda for studying the sustainability white oak inventories should focus primarily on potential interventions that account for a combination of future environmental changes and market forces.

Supplementary Materials

Supplementary data are available at *Journal of Forestry* online.

Acknowledgements

The authors would also like to thank Dr. Bruno Kanieski da Silva and Dr. Rajan Parajuli for their helpful comments on an earlier version of this manuscript.

Funding

The authors acknowledge financial support from the Virginia Department of Forestry.

Endnotes

1 For this manuscript, we define CHR as the following twelve states: Arkansas, Illinois, Indiana, Kentucky, Maryland, Missouri, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, and West Virginia. Although we took the common approach of defining the CHR by states, we acknowledge that the political boundaries do not define the ecological boundaries of this continuous forested region as delineated in Fralish (2003).

2 For every 1% increase in stumpage price, the quantity of roundwood supplied will increase by γ_j%.

3 For every 1% increase in growing stock inventory, the quantity of roundwood supplied will increase by τ_j%.

4 For every 1% increase in stumpage price, the quantity of roundwood demanded will decrease by ϵ_j%.

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