RESOURCES for the FUTURE

A Comparative Analysis of Forest Harvesting, Timber Supply, and Tree Planting across Regions of the United States

David N. Wear and John W. Coulston

Working Paper 24-09
July 2024

About the Authors

David N. Wear is a nonresident senior fellow and director of the Land Use, Forestry, and Agriculture Program at Resources for the Future (RFF). Prior to his arrival at RFF, he spent more than 30 years with US Forest Service Research and Development, most recently as a senior research scientist and leader of national and regional resource assessments.

John W. Coulston is a project leader and supervisory research forester at the Southern Research Station for the US Forest Service.

About the Project

This work was supported by the USDA Forest Service, Southern Research Station, through Joint Venture Agreement 21-JV11330180084 with Resources for the Future.

About RFF

Resources for the Future (RFF) is an independent, nonprofit research institution in Washington, DC. Its mission is to improve environmental, energy, and natural resource decisions through impartial economic research and policy engagement. RFF is committed to being the most widely trusted source of research insights and policy solutions leading to a healthy environment and a thriving economy.

Working papers are research materials circulated by their authors for purposes of information and discussion. They have not necessarily undergone formal peer review. The views expressed here are those of the individual authors and may differ from those of other RFF experts, its officers, or its directors.

Sharing Our Work

Highlights

- This first detailed assessment of subregional patterns of harvesting and tree planting derives from remeasured inventory plots and indicates a broad range of harvest intensity, up to 3.8 percent of plots in the South-Central region.
- Estimated harvest choice models indicate that harvest decisions are consistent with economic rationality in nearly all regional and ownership settings and that timber supply is generally price inelastic.
- Estimated tree-planting models indicate that planting on private land in high-production regions is responsive to timber returns.
- Nearly all long-run growth potential for US timber supply resides in the East and predominantly in the South.

Abstract

Much of the United States is heavily forested, and these forests support the world's largest and most diverse wood products sector while providing several other ecosystem services. Forest management in the form of timber harvesting and reforestation determines the overall sustainability of all service values. We use remeasured forest inventory plots to define harvest rates and intensities and estimate comparable economic harvest choice and tree-planting models for all subregions and ownership groups of the United States. Annual harvest rates range from near zero in the southern Rockies to 3.8 percent of forest plots in the South-Central region. We test hypotheses regarding the economic rationale of harvest choice and find that all regions and ownerships except public ownerships in the Pacific Coast region are responsive to changes in timber prices. We estimate regional timber supply equations using Monte Carlo simulations of harvest choices applied to the plots constituting the current inventory. This approach to supply uniquely accounts for not only the quantity of standing biomass but also the detailed composition of inventory. Timber supply is shown to be more responsive to sawtimber prices than pulpwood prices and is mostly inelastic (one-period price elasticities <1); the exception is the Pacific Northwest, where supply is price elastic (~1.5). Estimated tree-planting models indicate that tree planting on private land is responsive to price signals in the South, Northeast, Pacific Northwest, and Northern Rocky Mountains. Combining estimated harvest and tree-planting choice models with long-run inventory plot projections, we find no indications of unsustainable harvesting or increasing timber scarcity. Projected shifts in long-run timber supply indicate that nearly all potential for growth in the forest products sector is in the eastern United States, especially in the South and mainly in the South-Central region.

Contents

1. Introduction

In the United States, annual timber harvests of about .40 billion cubic meters (Oswalt et al. 2019) provide the primary inputs to the world's largest wood and paper sector, with a $293 billion annual contribution to US GDP between 2012 and 2017.[1] At the same time, forests provide natural infrastructure for generating several ecosystem services, including water quality, recreation, biodiversity, and climate change mitigation. Forest management for timber production alters the provision of all services through changes in forest conditions, in some cases defining negative externalities (e.g., water quality impacts) and in other cases defining positive externalities (e.g., enhancing carbon sequestration). Forest assessments including the US Resources Planning Act Assessment and forest policy analysis require an understanding of how market-driven changes in forest management could alter trajectories of forest conditions and therefore the provision of all competing and complementary ecosystem services. This paper examines timber harvest and forest investment regimes in all regions of the conterminous United States. One objective of this paper is to compare the forest management regimes of all regions of the United States based on consistent microdata describing timber harvesting and tree planting following harvests. Another is to develop aggregate supply models consistent with individual choices in a way that allows analysts to link timber market activity to future forest conditions to support the joint analysis of ecosystem service flows.

We analyze forest management activities as recorded in the nation's forest inventory conducted by the US Forest Service in partnership with state forestry agencies. The Forest Inventory and Analysis (FIA) dataset measures change at more than 110,000 forested plots on a systematic grid, and these field observations are used to construct estimates of forest conditions at various scales (Miles et al. 2001; Westfall et al. 2022). Plot observations of forest management activities define where and how forest management is conducted in terms of species and sizes harvested, harvest intensity, and regeneration activities. We use these data to characterize management profiles for the various regions of the United States.

To define the linkage between timber market conditions and forest management choices, we model the propensity of forest owners to harvest timber in response to prevailing timber prices and their forests' conditions. While most previous empirical harvest choice models (e.g., Dennis 1990) derive from optimal forest rotation assumptions and treat the harvest choice as an even-aged clear-cutting decision, we observe from the FIA data that considerable harvesting uses partial cutting within forests with diverse species conditions and multiple ages, suggesting a different decision calculus. Not surprisingly, previous models have proven most effective in

[1] Contribution is defined, using Bureau of Economic Analysis data, as the value added by manufacturing by the solid wood products, pulp and paper, and furniture industries plus the cost of materials (mainly timber inputs provided by the timber sector).

describing harvest choices and derivative timber supply for species and regions where even-aged, single-species management predominates, especially pine forests in the southeastern United States (Prestemon and Wear 2000; Polyakov and Wear 2010), but have failed to describe harvest choices in other settings. We posit that this is because the even-aged optimal rotation model does not capture how timber values vary substantially across species and age cohorts of a multiaged stand.

We generalize the harvest choice model to account for valuation and management choices based on species, size, and structure within the stand, in addition to ownership. Remeasured forest plot records define forest volume growth, mortality, harvesting, and other disturbance dynamics at the tree level, which we summarize to species cohorts, and they provide an account of land use changes. Timber value dynamics can then be derived by applying species-specific prices, which have a wide range of values. These data also define harvest intensity (the proportion of timber volume or value removed by a harvest) and reforestation decisions that can be summarized for subregions and ownership type groups.

Market supplies of timber in the United States derive from individual harvest choices across highly variable forested landscapes. Forest sector models (Adams and Haynes 1980; Baker et al. 2023; Sohngen et al. 2019) generally approximate regional supply as a function of timber prices and an aggregate measure of timber stocks (e.g., the quantity of biomass contained in a region's forests). In these models, accounting for inventory dynamics at regional levels (e.g., aggregate growth, mortality, and harvests) provides a means to shift supply over time but cannot explain how other conditions of forests (e.g., species and size composition) would influence the availability of timber supply. Our approach, building timber supply from individual choices to aggregate outcomes, represents a way to estimate the structure of supply that links harvests to future forest conditions. Two previous studies (Prestemon and Wear 2000; Polyakov and Wear 2010) demonstrate the plausibility of linking harvest choices to timber supply in the US South, a region with a large area of planted pine forests.

Our analysis has two objectives. One is to characterize and compare the structure of timber supply at a regional level as an aggregation of choices across heterogenous forest conditions and management settings. The other is to provide spatially explicit probabilities of timber harvesting and forest regeneration activities and aggregate timber supply relationships. The latter is especially important for understanding how harvest activities, timber supply, and management at the intensive margin might respond to policies that shift the demand for forest products such as forest bioenergy. The former is critical for understanding how policy might affect changes in ecosystem services at relevant spatial scales.

2. Methods

Our study of harvest choices is based on the US Forest Service FIA inventory of land and forest conditions using a set of remeasured forest plots (Miles et al. 2001). At each plot location, land use is determined and all forest plots are visited for detailed measures of several forest conditions. Most of these measures relate to individual trees, such as species, height, and diameter, but also include other site-level measures, such as ownership, physiographic class, and slope. Plots are revisited and remeasured at somewhat regular intervals (~7 years in the East, ~10 years in the West), and disturbance and forest management events, including timber harvesting, fire, and windthrow, are also recorded. For modeling timber-harvesting choices, the remeasured plots define a cross section organized by harvested and unharvested plots. The quantity, species composition, and quality of timber removed from each plot can also be estimated from these records.

The objectives of our modeling are to provide a means for understanding and predicting the structure of timber supply—that is, the relationship between harvesting and timber prices; the location of timber harvests across the FIA sampling locations and, more specifically, relative to forest and site conditions; and the propensity to plant forests following harvesting. For projection purposes, these outcomes need to be reconciled within the structure of the inventory system from which they derive. In other words, because our interests extend beyond hypothesis testing to projection and forecasting of future inventory conditions, we need to model the harvest as it is measured within the inventory system.

2.1. Harvest Choice Models

An economic choice logic applied to the harvest decision (Max and Lehman 1988; Provencher 1997) follows the two-period model described by Polyakov and Wear (2010), where the benefits of choosing to harvest (π_1) are compared with the benefits of the no-harvest option (π_0) for each plot location (i).

$$\pi_{i1} = \boldsymbol{p}_{\boldsymbol{t}}'\boldsymbol{R}(z_i) + \delta E[\boldsymbol{p}_{t+n}' v_{t+n,1}(z_i)] - c(\boldsymbol{z}_i) + S_1(\boldsymbol{z}_{\boldsymbol{i}}) + u_1(\boldsymbol{z}_i) \quad \text{(1a)}$$

$$\pi_{i0} = \delta E[\boldsymbol{p}_{t+n}' v_{t+n,0}(\boldsymbol{z}_i)] + S_0(\boldsymbol{z}_i) + u_0(\boldsymbol{z}_i) \quad \text{(1b)}$$

Here harvest revenue is defined as the vector of product and species prices ($\boldsymbol{p}$) times the vector of anticipated harvest removals ($\boldsymbol{R}$) based on the structural attributes of the forest and site ($\boldsymbol{z}_i$). The second term in equation (1a) defines the expected value of standing timber at the end of the evaluation period, defined by the expected biomass volume by relevant product and species classes ($\boldsymbol{v}_{t+n}$), expectations regarding the price vector ($\boldsymbol{p}_{t+n}$), and the discounting factor ($\delta = (1+d)^{-n}$). We anticipate that harvest costs (C) and nontimber utility (u) will vary according to site and forest conditions. We also include a scrap or ending inventory value (S), which defines the appropriately discounted value of all future revenues and costs for the property. By incorporating the scrap value, equation (1) is consistent with an infinite horizon valuation of each option consistent with an optimal harvest rotation problem in the case of even-aged management when $\boldsymbol{R}$ is equal to standing inventory (Max and Lehman 1988; Provencher 1997). Equation (1b) defines the valuation of the no-harvest choice.

The FIA inventory system provides detailed information on forest structure and on harvest removals but does not provide essential elements of the valuations implied by equations (1a) and (1b). Because π_{ij} are unobservable, we estimate the value of the stand at the beginning and end of the measurement period based on estimates of volumes and prices. We also assume that for stands with enough volume to consider harvest for products, the difference in scrap values for harvest and no-harvest options (*S*) is small relative to the revenue and ending inventory values, and thus beyond our ability to deduce given available data, and we therefore exclude them from explicit consideration. Further, assuming a linear functional form results in an econometric model of harvest and no-harvest values:

$$\pi_{i1} = \alpha_1 + \beta(REV_{i1} + \delta EV_{i1}) + \gamma_1' \boldsymbol{z_i} + \epsilon_{i1} \quad (2a)$$

$$\pi_{i0} = \alpha_0 + \beta\delta EV_{i0} + \gamma_0' \boldsymbol{z}_i + \epsilon_{i0} \quad (2b)$$

We condensed the notation to define harvest revenue as $REV_{i1} = \boldsymbol{p}_t' \boldsymbol{R}(z_i)$ and expected ending inventory value as $EV_{ij} = \boldsymbol{p}_{t+n}' E[\boldsymbol{v}(z_i)_{t+n,j}]$. All value and volume units are normalized to per-acre terms. Equations (2a) and (2b) define a binary choice model for harvest (*h* = 1) as follows:

$$Pr(h = 1) = p(\pi_{i1} > \pi_{i0}) = P(\epsilon_{i0} - \epsilon_{i1} < (\alpha_1 - \alpha_0) + \beta[REV_{i1} + \delta EV_{i1} - \delta EV_{i0}] + (\gamma_1 - \gamma_0)\boldsymbol{Z_i}) \quad (3)$$

If we assume that $\epsilon_{i0} - \epsilon_{i1}$ has a logistic distribution, the standard binary logit model results:

$$Pr(h = 1) = \frac{exp\,[f(z,p,v)]}{1 + exp\,[f(z,p,v)]} \quad (4)$$

In addition to the discrete choice to harvest, we assume that the landowner simultaneously determines the intensity of the harvest or the amount of removals, the vector $\boldsymbol{R}(z_i)$, which defines the contribution of the harvest to aggregate supply. Polyakov and Wear (2010) address harvest intensity in the southeastern United States by considering separate choices for full and partial harvests using a conditional logit approach. Another approach, and the one we adopt, is to consider removal intensity as a function of stand conditions so that the harvest decision reflects the silvicultural prescription that depends on stand conditions defined by the vector z_i and consistent with regional forestry practices. Accordingly, we model the expected revenue for a harvest choice for each region as

$$\boldsymbol{REV}_{i1} = \boldsymbol{p_t'}\boldsymbol{R}(z_i) = b_0 + b_1 \boldsymbol{p}_t' \boldsymbol{v}_{t,1}(\boldsymbol{Z}_i) + c'\boldsymbol{Z}_i + \mu_i \quad (5)$$

where revenue is modeled as a function of the total value of standing timber and other forest conditions, which allows for harvest intensity to vary across conditions and values. Equation (5) is estimated using ordinary least squares applied to all harvested plot conditions. In similar fashion, we model the ending inventory value for both harvest and no-harvest choices as a function of conditions observed at the beginning of the measurement period, as follows:

$$\boldsymbol{EV}_{ij} = \boldsymbol{p}'_{\boldsymbol{t}}\boldsymbol{v}_{\boldsymbol{t+n,j}}(z_i) = a_0 + a_1\boldsymbol{p}'_t\boldsymbol{v}_{t,j}(\boldsymbol{Z}_i) + d'\boldsymbol{Z}_i + \epsilon_i \tag{6}$$

Equation (6) is estimated separately for harvested and unharvested plots (i.e., *j* = 0 and *j* = 1). Unlike Polyakov and Wear (2010) and Prestemon and Wear (2000), who compute future standing volumes (*v*) using a model of biological growth, we model changes in standing values (***p'v***) based on inventory measurements. Our approach obviates the need to capture the specific dynamics of changes in product classes, species distributions, and net biomass increment with a biological growth model and takes full advantage of the information provided by remeasured inventory plots.

A rational risk-neutral landowner would trade immediate returns (REV_{i1}) for greater, appropriately discounted expected returns to growth, defined by the difference $EV_{i1} - EV_{i0}$. This allows us to collapse the valuation terms from equation (2) into a single value term in equation (3) using the discount rate:

$$dVAL_i = [REV_{i1} + (1 + d)^{-n}\,(EV_{i1} - \delta EV_{i0})]$$

We thus define a compact harvest choice model:

$$Pr(h = 1) = p(\pi_{i1} > \pi_{i0}) = P(\epsilon_{i0} - \epsilon_{i1}) < (\alpha_1 - \alpha_0) + \beta\, dVAL + (\gamma_1 - \gamma_0)\boldsymbol{Z_i} \tag{3'}$$

The model described by equations (3)–(6) therefore describes the decision environment of a risk-neutral forest landowner evaluating harvest options at time *t* for a period of *n* years (*n* is the remeasurement period for the individual plot). We posit that the plausible management regime is influenced by characteristics of the forest owner and the site condition, which we address either within the vector of *z* variables or by subsetting the dataset. ***Z*** includes dummy variables describing slope class (D_SLOPE), a dummy variable defining the forest as planted (PLANT = 1), a dummy variable defining whether the owner is a commercial entity (COMM = 1), and the number of years between remeasurements (REPERIOD). Another variable in ***Z*** defines the variance of timber values across species within a forest stand, a measure of the complexity of the management context (COMPLEXITY). We also subset the data by broad ownership classes to account for structural differences in institutional setting and management context (Newman and Wear 1993).

We expect that unobserved variables associated with the location of a forest may also influence the harvest choice (i.e., the proximity of wood-processing facilities or the access to transportation networks within the region). We posit that these types of locational effects may predominate in this problem and use a fixed-effects approach to address potential problems with omitted variable bias. Fixed effects are assigned to forest plots based on their location within multicounty subregions defined by state and broad physiographic region (these are the "survey unit" designations within the FIA inventory). We considered county fixed effects as well but found no improvement in the model. Given substantial differences in physiographic conditions, we estimate separate models for each of the nine broad regions shown in Figure 1.

2.2. Tree-Planting Models

To model the reforestation decision, we assume that the landowner is motivated by the future returns to forestry vis-à-vis returns to alternative uses or natural regeneration. We model the probability of tree planting as a function of the realized revenues at harvest, distinguishing between pulpwood revenues (REV_p) and sawtimber revenues (REV_s):

$$Pr(plant = 1) = \alpha + \beta_1 REV_p + \beta_2 REV_s + \delta' \boldsymbol{Z_i} \quad (7)$$

We assume that landowners use their realized returns from the current harvest as a proxy for likely future returns and that returns are positively associated with planting choice. We distinguish between the pulpwood and sawtimber components of revenue because the substantial difference in production periods would affect their discounted future returns and therefore their effects on choices.

We estimate the planting model after screening the data set. We first select all plots that were harvested during the remeasurement period. To account for harvest intensity, we retain only plots with post-harvest inventories at least 60 percent less than preharvest inventories. That is, we assume that partial harvests with >60 percent of residual inventory would not be available for tree planting.

2.3. Timber Supply Models

Following Polyakov and Wear (2010), we construct aggregate timber supply models using a Monte Carlo approach applied to the estimated harvest choice models. Prices are varied across the four broad product types (hardwood, softwood, pulpwood, and sawlogs), used to compute new revenue terms, and predict associated harvest probabilities for each plot in the FIA inventory. We then predict the quantities of timber removed by a harvest consistent with equation (5). We estimate harvest quantity (removal) equations for two product classes (sawtimber and nonsawtimber or pulpwood, indexed by m) based on removal records from harvested plots:

$$\boldsymbol{R}_{m,i} = b_0 + b_1 \boldsymbol{v}_{i,t} + c' \boldsymbol{Z}_i + \mu_i \quad (8)$$

Removal volume is defined as a function of site attributes observed at the beginning of the measurement period. Aggregate harvest quantities for each product for a vector of prices ($\bar{p}$) are therefore defined as

$$\boldsymbol{Q}(p)_{m,i,} = \sum_i pr(h = 1|\bar{p}) * \boldsymbol{R_{m,i}} \quad (9)$$

Monte Carlo modeling of harvest choices resulting from random variation in prices applied to the valuation terms in equation (3') generates a supply relationship that can be summarized in terms of own- and cross-price elasticities by fitting a log-log relationship between harvest quantities (aggregated across all plots—indexed by i—within a region, k) and timber price indices:

$$\ln Q_{m,k} = \alpha + \sum_j \beta_j \ln p_j \tag{10}$$

$\beta_j = \partial lnQ_{m,k}/\partial lnp_m$ defines the own-price elasticity of supply, and where $j \neq m$, $\partial lnQ_{m,k}/\partial lnp_j$ defines the cross-price elasticity.

This approach provides a compact description of timber supply relationships for an existing inventory but not future supply, which requires a description of future forest inventories. To evaluate long-run timber supply trajectories requires projecting the dynamics of the forest inventory at the plot level in response to harvesting but also other intertemporal changes associated with growth, mortality, and other disturbances. We construct future inventories through a plot imputation approach that draws the next period plot from the library of historical plots based on shared attributes at the beginning of the period and whether the plot is harvested (Coulston et al. 2023). By constructing the next period's plot conditions in this manner, we apply observed growth, mortality, and forest disturbances from the remeasured inventory to the simulations. We also apply our discrete choice of tree planting following harvests to allow for price-driven changes in management intensity (equation (8)). We then apply a range of exogenous price paths to investigate implications for future forest inventories and supply.

3. Data

FIA records for remeasured forest plots are the foundation for this analysis. Tree-level measurements provided the beginning and ending total volumes and sawtimber volumes by individual species codes ($\boldsymbol{v}_t$ and $\boldsymbol{v}_{t+n}$), and harvest removals by species ($\boldsymbol{R}$) for harvested conditions. In addition, plots define the elements of $\boldsymbol{Z}$ including slope (percentage), detailed ownership class (commercial, noncommercial private, and public landowner), remeasurement period, harvest occurrence and type, distance to road codes, reserved use code, and location codes (state, county, survey unit).

There is no standard approach to recording timber prices across regions and products in the United States. We compile a set of price records for each region using various reporting services and index prices to a common species. Reports from several state forestry agencies and TimberMart-South provide the price data ($\boldsymbol{p}_t$) used for estimating starting and ending standing values, as well as revenue from harvesting. Several states provide average annual stumpage prices by species groups and product classes (e.g., sawtimber and pulpwood) based on recorded timber sales.

However, these data have inconsistencies in terms of reporting intervals, units of measure, and point of valuation. Methods for compiling and reporting data vary across states (e.g., different unit measures and points of valuation), but a comparison of adjacent state records indicates some regularity for relative prices. For each region of the eastern United States, we construct average species-level prices using multiple state reports by defining species price indices relative to a reference species (red oak, *Quercus rubra*), averaging the relative prices across observations, and then multiplying the indices by the average price for red oak for the region. Hardwood prices are generally recorded for species groups (e.g., white oak, hard maple, soft maple), and we constructed a crosswalk between these groups and individual tree species recorded in the FIA inventory (e.g., ash sawlog prices apply to blue, green, white, and black ash species). For species without a sawlog value, we assign pulpwood prices to the sawlog component of the inventory. Most states in the eastern United States have approximately 100 tree species, some marketable only as pulpwood, and others without any markets.

4. Results

4.1. Inventory Estimates

Our queries of the US FIA database provide records for 115,643 remeasured forested plot conditions for the 48 conterminous United States. After we exclude plots in a reserved condition (e.g., national parks and wilderness areas), these account for 245 million hectares (ha) of nonreserved forests, which is generally consistent with the national FIA reports (Oswalt et al. 2019).[2] Between remeasurements, expanded plot records estimate .35 billion cubic meters of harvest removals per year, with substantial variation across regions. The South, divided into the Southeast (SE) and South-Central (SC), had 61 percent of removals; the Pacific region, comprising the Pacific Northwest (PNW) and Pacific Coast (PC), had 17 percent (PNW alone had 12 percent); and the North, consisting of the Northeast (NE) and North-Central (NC), had 19 percent. The Plains (PL) and Rocky Mountains North (RMN) and South (RMS) together represent about 3 percent of removals. The percentages match national reporting for the United States for 2016 (Oswalt et al. 2019). Harvests also vary strongly by ownership (Figures 2 and 3). Commercial owners, with 21 percent of the nonreserved forest area, contribute about 48 percent of timber harvests. Family forest owners hold 48 percent of the forest area and produced about 41 percent of harvests, while public forests (31 percent of the area) contributed the remaining 11 percent.

About 10.1 percent of the forest area, 25 million ha, is recorded as being planted at the beginning of the remeasurement period. The South contains 17.9 million ha of planted

[2] Remeasured inventory plots are limited in the Rocky Mountain region, and we created a set of removal plots from available data that were comparable to the other regions. These constructed plots included only plots that were in forest land use at the beginning and end of the evaluation period.

forests (72 percent of the total), the PNW 3.2 million ha (12 percent), and the North 2.3 million ha (9 percent). Planted forests provided 32 percent of harvests in the United States, with variation across regions (Figure 4). Planted forests provided 52 and 46 percent of harvests in the SE and SC, respectively, and 39 percent in the PNW. Among the remaining regions, only the NC has more than 5 percent harvest area from planted

forests (8.4 percent). Harvest shares for planted forests are highest for commercial forests in the SE (69 percent) and SC (61 percent) and for all private owners in the PNW (40 percent).

The average harvest frequency (based on portion of plots with recorded harvest) in US nonreserved forests is 1.4 percent/year and ranges from near zero to 3.8 percent of forest area across regions and ownerships (Figure 3). Except for the PL, harvest frequency is highest on the forests with commercial ownership, followed by family ownership and then public ownership. The highest harvest frequencies are more than twice the average and are found in the South on commercial land (3.8 and 3.6 percent for the SC and SE, respectively).

Harvest removal intensities, measured as the proportion of beginning volume removed by harvests for a forest condition, vary by region as well as by ownership within a region. Figures 5 and 6 show the distribution and average of harvest removal intensity by region and subregion. Note that harvest intensity can exceed 1.0 because harvest removals may include volume accumulated through growth during the remeasurement period. In all regions except the NC, harvest intensity is highest for commercial ownership (in the NC, public and commercial ownerships have comparable intensities). Highest harvest intensities are found for commercial owners in the PNW, SC, and SE, at 0.95, 0.85, and 0.83, respectively. Overall, average harvest intensities are highest in the SE and SC regions (ranging 0.65 to 0.85 across all ownerships) and lowest in the Rocky Mountains (ranging from 0.25 to 0.57 across ownerships). The greatest variation in harvest intensity across ownership groups is found in the PNW, with a harvest intensity of 0.57 for public ownership and 0.95 for commercial. Harvest patterns (Figure 7) are consistent with lower-intensity uneven-aged management in the NE and NC subregions and with even-aged management only in the SE, SC, and PNW, the regions with the highest volume of removals.

4.2. Harvest Choice Models

Estimates of the harvest choice models are generally consistent with expectations regarding economic choice logic. For all subregions and ownerships in the East, we universally reject the hypothesis of no influence of timber value (*dVAL*) on harvest choices at the p = 0.05 value and in all but one case (NC-commercial) at the p = 0.01 level. *dVAL* coefficient estimates for commercial owners are generally higher than for other ownership groups, indicating a higher degree of responsiveness to price changes (the only exception is the NC region, where other private is somewhat higher). Within regions, the greatest difference in *dVAL* coefficient estimates is between planted and nonplanted forests in the South (both the SE and SC), where the coefficient value for planted forests is between 2.6 and 4.5 times larger. As expected, the coefficient on the slope variable is negative in all equations. In the South, it is significant only for equations for nonplanted forests (planted forests tend to be on sites with lower slopes). In the North, the coefficient is significant in four of six equations. *Var*(*ba*) is significant on planted forests. In all cases, *var*(*ba*) coefficients are positive but with limited significance. The variance in the basal area across species classes is positively correlated with harvest occurrence, which runs counter to expectations that variance would be correlated with more costly harvesting operations. However, this finding could be consistent with the emergence of an understory within a maturing planted forest.

For western regions, all *dVAL* coefficients are positive, and seven of nine are significant at the 5 percent level. The two subregions with the highest levels of timber harvesting in the West, the PNW and RMN, have significant *dVAL* coefficients for both public and private ownerships, indicating some level of market-responsive harvesting even for public forests (consistent with Adams et al. 1991). In the PNW region, planted forest conditions are associated with larger harvest probabilities ($p = 0.05$) on both public and private forests, and in the RMN, commercial ownership is associated with larger harvest probability on private forest land ($p = 0.05$). In the West, all slope coefficients are negative and significant for public land. On private forests, slope coefficients are significant in three of five equations. The coefficients for the *var*(*ba*) are insignificant for all but one equation in the West (PNW-private).

4.3. Tree-Planting Models

Tree-planting models were initially evaluated for significant explanatory power with a chi-squared test against a null model with only ecological province and intercept values ($p = 0.05$). Estimated models had no explanatory power in the PL, PC, and RMS subregions, areas with very little tree-planting activity. We also accept the null of no explanatory power for models applied to public forests in all regions except the NC. The coefficient on having been planted in the previous period is significant (p = 0.05) for all regions and ownerships except for the RMN and PNW (Table 2). One revenue variable is significant in six of the nine estimated models, with pulpwood revenue significant in the East (SE-commercial, SC-other private and commercial, and NE-private) and sawtimber revenue significant in the West (NRM-private and PNW-private). Regions-ownership combinations with significant revenue coefficients represent more than 90 percent of all planted forests in the United States.

Predicted probabilities of planting depend on whether the harvested stand had originally been planted. In the South, average planting probabilities are at least 50 percent and significantly greater for previously planted forests (Figure 7). In contrast, in the PNW, there is no significant difference. Planting rates are also influenced by ownership group. In the South, where private ownership is split into commercial and other private categories, planting rates are significantly greater on commercial forests (regardless of previous planted condition). In the PNW, however, public and private owners have comparable planting probabilities.

The predicted area of planting for harvested forests in the historical period (based on models in Table 2) is 0.78 million hectares per year (ha/yr). Comparing this with previous planted condition defines gains in planted area (from nonplanted to planted) and losses (from planted to nonplanted). Total changes in planted forest area over the historical period (Figure 8) show net loss of planted forests in the East (–7.3 thousand ha/yr in the South and –1.5 thousand ha/yr in the North). Gains exceed losses in the West (+16.2 thousand ha/yr).

4.4. Timber Supply

To estimate timber supply relationships, we simulate harvest choice and tree-planting models within a stochastic forest inventory plot imputation framework. Resulting shifts in supply over time account for harvesting and planting decisions, as well as other factors influencing forest growth and mortality. For each time step in our simulation, we generate harvest and planting outcomes across 1,000 realizations of timber price changes to produce the supply curves shown in Figure 9. Supply curves at each time step assume that all previous prices were set to historical values ($p = 1.0$). Future supply curves at 10-year intervals (Figure 9) indicate a steady outward shift in timber supply in the SC and SE through 2050, reflecting the maturation of existing young forests and patterns of investment. At constant prices, the SC supply curve shifts out by ~20 percent and the SE shifts out by ~12 percent. Supply also expands in the NE and NC but at lower rates (10 and 8 percent, respectively). Western regions show no discernible expansion in supply, reflecting their older forests and generally slower growth rates.

Arc elasticities of timber supply with respect to prices were calculated for shifts along supply curves in Figure 9 to define short-run elasticities (Table 3). We also calculate implied elasticities of supply between adjacent periods to define long-run elasticities. We generate variance estimates using the variance of outcomes across Monte Carlo realizations in a Taylor series expansion of the elasticity formula (Newman and Wear 1993). All short-run elasticities, except those for the PL and NE, are significant and positive ($p = 0.01$), ranging from 0.18 in the South to 0.55 in the RMN. In eastern regions and the Rockies, long-run elasticities are larger than short-run elasticities, while there is no significant difference between short- and long-run elasticities in the Pacific regions. The latter reflects the stability of supply curves over time in these regions. Results indicate the greatest investment-driven supply response in the South (long-run elasticities are 3–4.8 times higher than short-run elasticities).

5. Discussion and Conclusions

Timber supply derives from an economic choice calculus applied to forest conditions that vary widely by species, productivity, and ownership. While previous studies have used detailed forest inventory data to evaluate supply potential in the US South, where production is concentrated and tends toward even-aged management, these data have limited application to other regions where harvest choices are more nuanced within uneven-aged forests. For the first time, consistently remeasured forest plots across a full forest inventory are available for all regions of the United States. We have used these measurements to fit generalized harvest choice models and evaluate timber supply relationships both in the short run and across multiple decades. We have also estimated economic models for tree-planting choices.

Overall, the results of these models indicate a regularity in timber choice models across the regions of the United States. Harvest choice models in all regions and most ownership-region subsets indicate that revenues—more precisely, rates of revenue growth—are a significant determinant of harvest outcomes. This is consistent with the capital-theoretic formulation of choice where growth is allowed to proceed until it declines to some threshold determined by the time preference of owners. Importantly, this means that timber supply outcomes can be built from the ground up by aggregating price-responsive harvesting across plots within an inventory. Unlike traditional supply models that proxy for inventory change by linking supply shifts to the amount of standing inventory (i.e., increasing inventory defines an outward shift in the supply curve), our approach captures how changes in the structure of the inventory would alter timber supplies over time.

Tree-planting models capture the long-run feedback between scarcity indicators (stumpage prices) and investment in future production. In the major timber-producing regions of the United States (the South and Pacific Northwest), our findings show that planting is responsive to price terms consistent with scarcity-mitigating investments in the timber sector. Results indicate a higher propensity to replant existing planted forests than to plant naturally regenerated forests following harvests. Applied to the existing inventory and current prices, planting models indicate net expansion in planted area for the SC and PNW but net shrinkage in the SE—an area that has experienced considerable urbanization in recent decades.

We faced some data issues in making our unified timber supply assessment of the United States. A challenge in valuing timber harvests is the need to account for forest conditions and relevant prices when more than 10 species may be present and species composition changes over time. Valuation requires an uncertain “merchandizing” of measured trees to translate biomass removals into product categories. Price data for hardwood species are a weak link in the analysis. We have developed methods for aggregating disparate data sources to generate prices across the region, but the data are highly variable in quality. Still, we know of no better source of price data and doubt their quality can be substantially improved in the immediate future.

Combining harvest and tree-planting models within an inventory projection system allows us to project future timber supplies based on these models—and here we project supply for constant prices. The projected supply of timber in western regions shows little change over time, including the PNW, where supply shrinks slightly by 2050. Timber supply in the South is projected to grow strongly, especially in the SC, where it is expected to increase by 20 percent by 2040. In the North, timber supply should expand but at rates much lower than for the South. At the national level, a combination of these supply relationships with a stable demand implies downward pressure on prices. The combination of harvest and planting outcomes is consistent with a well-organized timber sector, where investments are expected to mitigate resource scarcity over time.

References

Adams, Darius M., Clark S. Binkley, and Peter A. Cardellichio. 1991. “Is the Level of National Forest Timber Harvest Sensitive to Price?” *Land Economics* 67 (1): 74–84. **https://doi.org/10.2307/3146487**.

Adams, Darius M., and Richard W. Haynes. 1980. “The 1980 Softwood Timber Assessment Market Model: Structure, Projections, and Policy Simulations.” *Forest Science* 26 (suppl. 1): a0001–z0001. **https://doi.org/10.1093/forestscience/26.s1.a0001**.

Baker, Justin S., George Van Houtven, Jennifer Phelan, Gregory Latta, Christopher M. Clark, Kemen G. Austin, Olakunle E. Sodiya, et al. 2023. “Projecting U.S. Forest Management, Market, and Carbon Sequestration Responses to a High-Impact Climate Scenario.” *Forest Policy and Economics* 147 (February): 102898. **https://doi.org/10.1016/j.forpol.2022.102898**.

Coulston, John W, Grant M Domke, David M Walker, Evan B Brooks, and Claire B O’Dea. 2023. “Near-Term Investments in Forest Management Support Long-Term Carbon Sequestration Capacity in Forests of the United States.” *PNAS Nexus* 2 (11): pgad345. **https://doi.org/10.1093/pnasnexus/pgad345**.

Dennis, Donald F. 1990. “A Probit Analysis of the Harvest Decision Using Pooled Time-Series and Cross-Sectional Data.” Journal of Environmental Economics and Management 18 (2, pt. 1): 176–87. **https://doi.org/10.1016/0095-0696(90)90047-3**.

Max, Wendy, and Dale E Lehman. 1988. “A Behavioral Model of Timber Supply.” *Journal of Environmental Economics and Management* 15 (1): 71–86. **https://doi.org/10.1016/0095-0696(88)90029-0**.

Miles, Patrick D., Gary J. Brand, Carol L. Alerich, Larry F. Bednar, Sharon W. Woudenberg, Joseph F. Glover, and Edward N. Ezell. 2001. *The Forest Inventory and Analysis Database Description and Users Manual Version 1.0*. General Technical Report NC-218. St. Paul: US Dept. of Agriculture, Forest Service, North Central Research Station. **https://doi.org/10.2737/NC-GTR-218**.

Newman, David H., and David N. Wear. 1993. “Production Economics of Private Forestry: A Comparison of Industrial and Nonindustrial Forest Owners.” *American Journal of Agricultural Economics* 75 (3): 674–84. **https://doi.org/10.2307/1243574**.

Oswalt, Sonja N., W. Brad Smith, Patrick D. Miles, and Scott A. Pugh. 2019. *Forest Resources of the United States*, 2017. General Technical Report WO-97. Washington, DC: US Department of Agriculture, Forest Service. **https://doi.org/10.2737/wo-gtr-97**.

Polyakov, Maksym, and David N. Wear. 2010. "Harvest Choice and Timber Supply Models for Forest Forecasting." *Forest Science* 56 (4): 344–55.

Prestemon, Jeffrey P., and David N. Wear. 2000. "Linking Harvest Choices to Timber Supply." *Forest Science* 46 (3): 377–89. **https://www.fs.usda.gov/research/treesearch/1795**.

Provencher, Bill. 1997. "Structural versus Reduced-Form Estimation of Optimal Stopping Problems." *American Journal of Agricultural Economics* 79 (2): 357–68. **https://doi.org/10.2307/1244135**.

Sohngen, Brent, Marwa E. Salem, Justin S. Baker, Michael J. Shell, and Sei Jin Kim. 2019. "The Influence of Parametric Uncertainty on Projections of Forest Land Use, Carbon, and Markets." *Journal of Forest Economics* 34 (1–2): 129–58. **https://doi.org/10.1561/112.00000445**.

Westfall, Jim A., John W. Coulston, Gretchen G. Moisen, and Hans-Erik Andersen. 2022. *Sampling and Estimation Documentation for the Enhanced Forest Inventory and Analysis Program: 2022*. General Technical Report NRS-GTR-207. Madison, WI: US Department of Agriculture, Forest Service, Northern Research Station. **https://doi.org/10.2737/NRS-GTR-207**.

Tables

Table 1A. Coefficient Estimates and Standard Errors for Harvest Choice Models by Owner Group, Subregion, and Stand Origin in the East

			Explanatory variables				
Region	**Strata Owner**	**Origin**	**Intercept**	***dVal***	***var(ba)***	**Slope**	**Softshare**
Southeast	not comm	planted	−1.6551	0.0018	0.0000	−0.0273	
			(0.2390)*	(0.0002)*	(0.0000)*	(1.0041)	
Southeast	not comm	not	−3.1530	0.0006	0.0000	−0.9788	
			(0.3258)*	(0.0001)*	(0.0000)	(0.2057)*	
Southeast	comm	planted	−0.4205	0.0022	0.0000	−0.4777	
			(0.1591)*	(0.0002)*	(0.0000)*	(0.9863)	
Southeast	comm	not	−1.7671	0.0005	0.0000	−0.9622	
			(0.2375)*	(0.0002)*	(0.0000)	(0.3530)*	
South-Central	not comm	planted	−0.5269	0.0015	0.0000	−1.2541	
			(0.3122)	(0.0002)*	(0.0000)*	(0.8107)	
South-Central	not comm	not	−1.5456	0.0006	0.0000	−0.1272	
			(0.2002)*	(0.0001)*	(0.0000)	(0.1169)	
South-Central	comm	planted	−0.7031	0.0025	0.0000	−0.6251	
			(0.2755)	(0.0002)*	(0.4517)*	(0.4517)	
South-Central	comm	not	−1.5711	0.0008	0.0000	−0.5294	
			(0.2613)*	(0.0001)*	(0.0000)	(0.2271)	
Northeast	public		−19.7336	0.0026	0.0000	−1.5440	−0.4488
			(4805.5260)	(0.0007)*	(0.0000)	(0.5391)*	(0.5625)
Northeast	otherpr		−1.7846	0.0017	0.0000	−0.4024	0.0362
			(0.4640)*	(0.0003)*	(0.0000)	(0.1417)*	(0.1728)

Northeast	comm	−1.5762	0.0033	0.0000	−0.5855	−0.2252
		(0.3573)*	(0.0005)*	(0.0000)	(0.2186)*	(0.2272)
North-Central	public	−3.1664	0.0015	0.0000	−0.2935	0.2703
		(0.7563)*	(0.0005)*	(0.0000)	(0.3474)	(0.1504)
North-Central	otherpr	−2.5115	0.0023	0.0000	−0.5452	0.6674
		(0.3221)*	(0.0003)*	(0.0000)*	(0.1895)*	(0.1582)*
North-Central	comm	−17.8416	0.0018	0.0000	−0.5245	0.0692
		(1,127.3399)	(0.0008)*	(0.0000)	(0.4465)	(0.3460)

* Indicates significance $p = 0.05$.

Table 1B. Coefficient Estimates and Standard Errors for Harvest Choice Models by Owner Group and Subregion in the West

Region	Owner	Intercept	*dVal*	*var(ba)*	Slope	Commercial	Planted
Rockies North	private	−2.4540	0.0002	0.0000	−0.5267	0.6700	
		(0.3810)*	(0.0001)*	(0.0000)	(0.2452)	(0.2444)*	
Rockies North	public	−3.4596	0.0003	0.0000	−1.3216		
		(0.2997)*	(0.0001)*	(0.0000)	(0.2583)*		
Rockies South	private	−3.7930	0.0008		−27.5624		
		(0.7964)*	(0.0005)*		(5598.9)		
Rockies South	public	−2.8705	0.0001		−2.1545		
		(0.3248)*	(0.0003)*		(1.0538)*		
Pacific NW	public	−2.9211	0.0001	0.0000	−0.7307		0.9137
		(0.4489)	(0.0001)	(0.000)	(0.2194)*		(0.2575)*
Pacific NW	private	−4.1572	0.0004	0.0000	−0.1063		−0.4562
		(0.5408)*	(0.0001)*	(0.000)*	(0.2137)		(0.2059)*
Pacific Coast	public	−2.2533	0.0000				
		(0.2307)*	(0.0000)				
Pacific Coast	private	−2.1305	0.0001		−0.8818		
		(0.2615)*	(0.0000)*		(0.2312)*		
Plains	public	−19.4865			−2.5028		
		(2661.1)			(1.0379)*		
Plains	private	−4.3209	0.0012		−0.9596		

* Indicates significance p = 0.05.

Table 2. Coefficient Estimates and Standard Errors for the Tree-Planting Equations

Region	Owner	Intercept	Planted (*t*–1)	Sawtimber revenue	Pulpwood revenue	Slope dummy
Southeast	other private	–1.9175	0.9397	0.0001	0.0007	–1.1991
		(0.5632)*	(0.2156)*	(0.0001)	(0.0007)	(1.1493)
Southeast	commercial	–2.1686	1.4296	0.0000	0.0016	–2.1242
		(0.8687)*	(0.2203)*	(0.0001)	(0.0007)*	(2.0025)
South-Central	commercial	–2.2270	1.7500	0.0001	0.0033	–1.3109
		(0.6268)*	(0.1307)*	(0.0001)	(0.0007)*	(0.4459)*
South-Central	other private	–4.0452	2.6245	0.0001	0.0018	–0.6934
		(0.7488)*	(0.1405)*	(0.0001)	(0.0007)*	(0.4902)
Northeast	private	–7.5636	8.4280	–0.0003	0.0671	–5.0689
		(1.2836)*	(1.3576)*	(0.0005)	(0.0274)*	(2.3573)*
North-Central	private	–5.2160	7.8224	0.0006	0.0012	–76.7128
		(0.8297)*	(0.8903)*	(0.0005)	(0.0102)	(11895.7)
North-Central	public	–3.6793	8.9212	–0.0019	0.0081	2.1365
		(0.8762)*	(1.2958)*	(0.0010)	(0.0086)	(1.6056)
Rockies North	private	–22.1588	—	0.0007	0.0191	–1.5981
		(4062.87)	—	(0.0003)*	(0.0310)	(1.6091)
Pacific NW	private	–2.8472	0.1923	0.0002	–0.0006	1.3224
		(1.3625)*	(0.5946)	(0.0001)*	(0.0066)	(0.6956)*

* Indicates significance $p = 0.05$.

Table 3. Estimated Supply Price Elasticities Based on Application of Harvest Choices and Tree-Planting Models within an Inventory Plot Imputation Framework

Region	North-Central	Northeast	Pacific Coast	Pacific Northwest	Plains	Rockies North	Rockies South	South-Central	Southeast
					Short-run elasticities				
Elasticity	0.2685	−0.0165	0.2816	0.2737	0.3495	0.5520	0.3773	0.1768	0.1862
Standard error	0.0440	0.0387	0.0506	0.0754	0.2558	0.0807	0.2328	0.0304	0.0286
					Long-run elasticities				
Elasticity	0.5700	0.2630	0.2266	0.2151	1.2068	0.6199	1.0484	0.8431	0.5613
Standard error	0.0429	0.0377	0.0508	0.0758	0.2365	0.0802	0.2190	0.0286	0.0277

Figures

Figure 1. Map of RPA Subregions

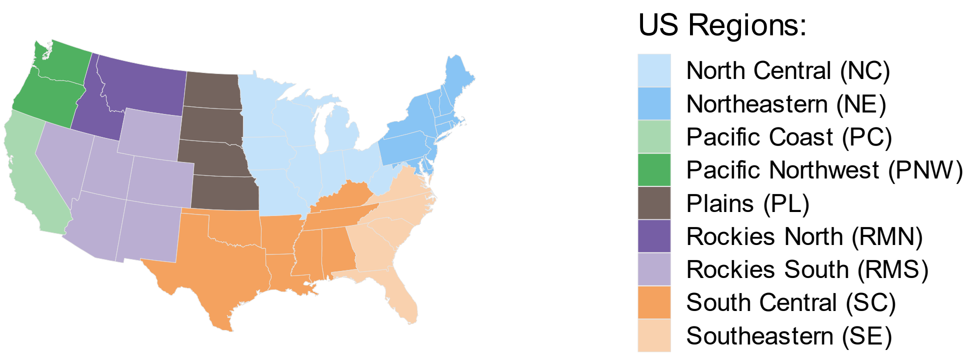


Figure 2. Average Annual Harvest Removals from Nonreserved Forest Plots in the Conterminous 48 United States by (A) Subregion and (B) Subregion and Ownership

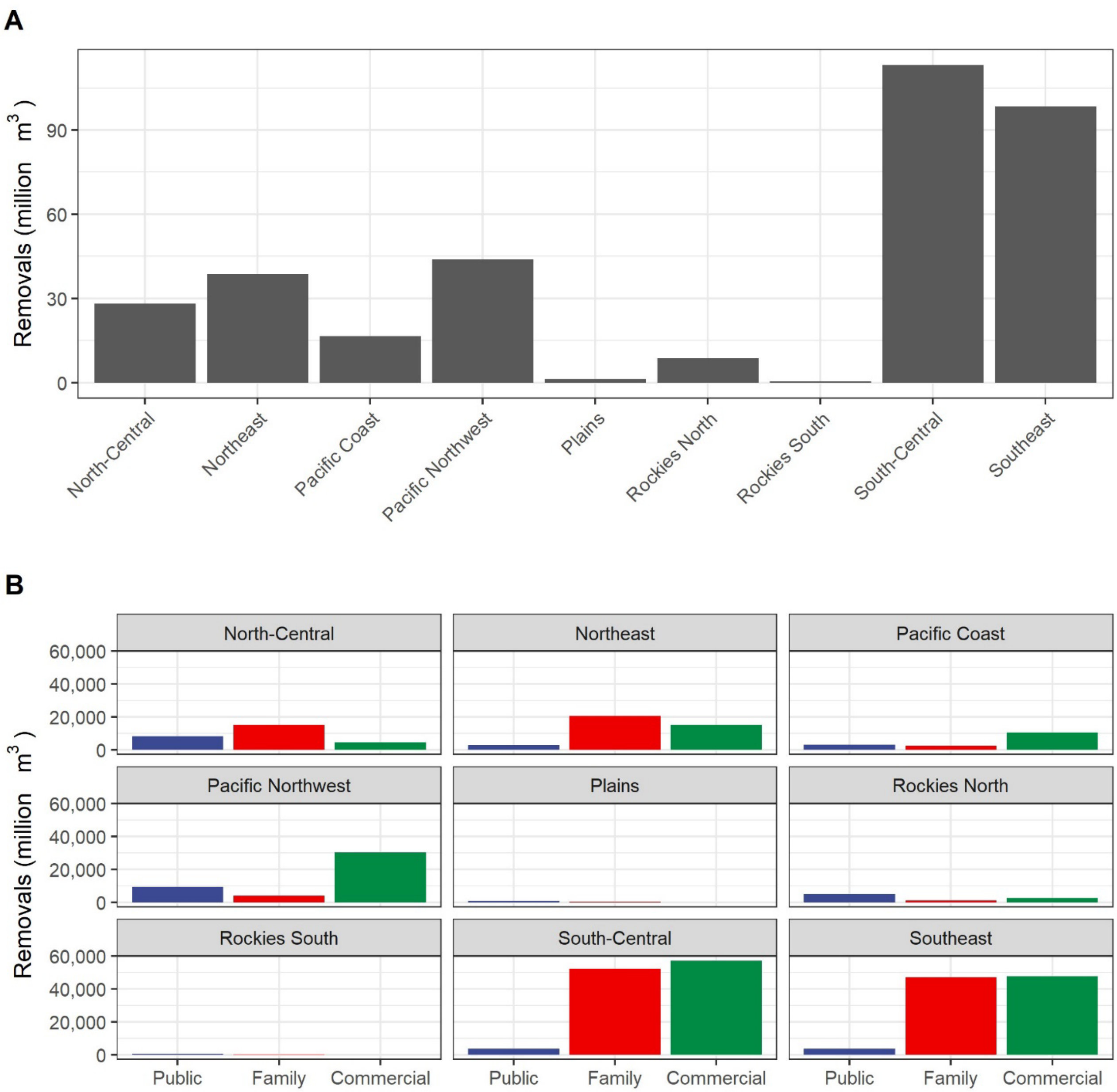


Figure 3. Annual Harvest Frequency (Portion of Plot Conditions with a Harvest Record) by Subregion and Ownership Group for Remeasured Plots, 2019

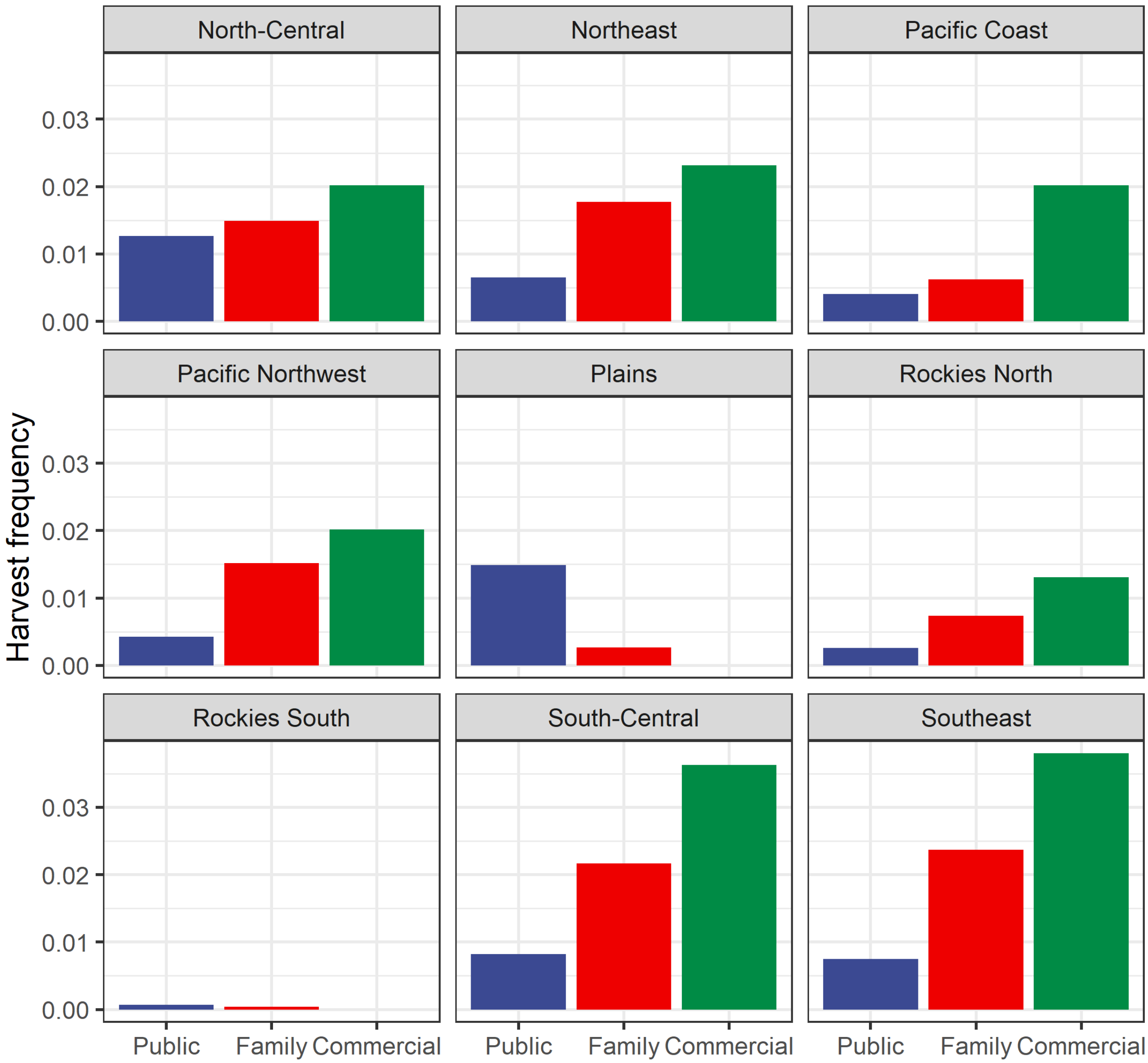


Figure 4. Portion of Harvested Area from Planted Forests by Region and Broad Ownership Group

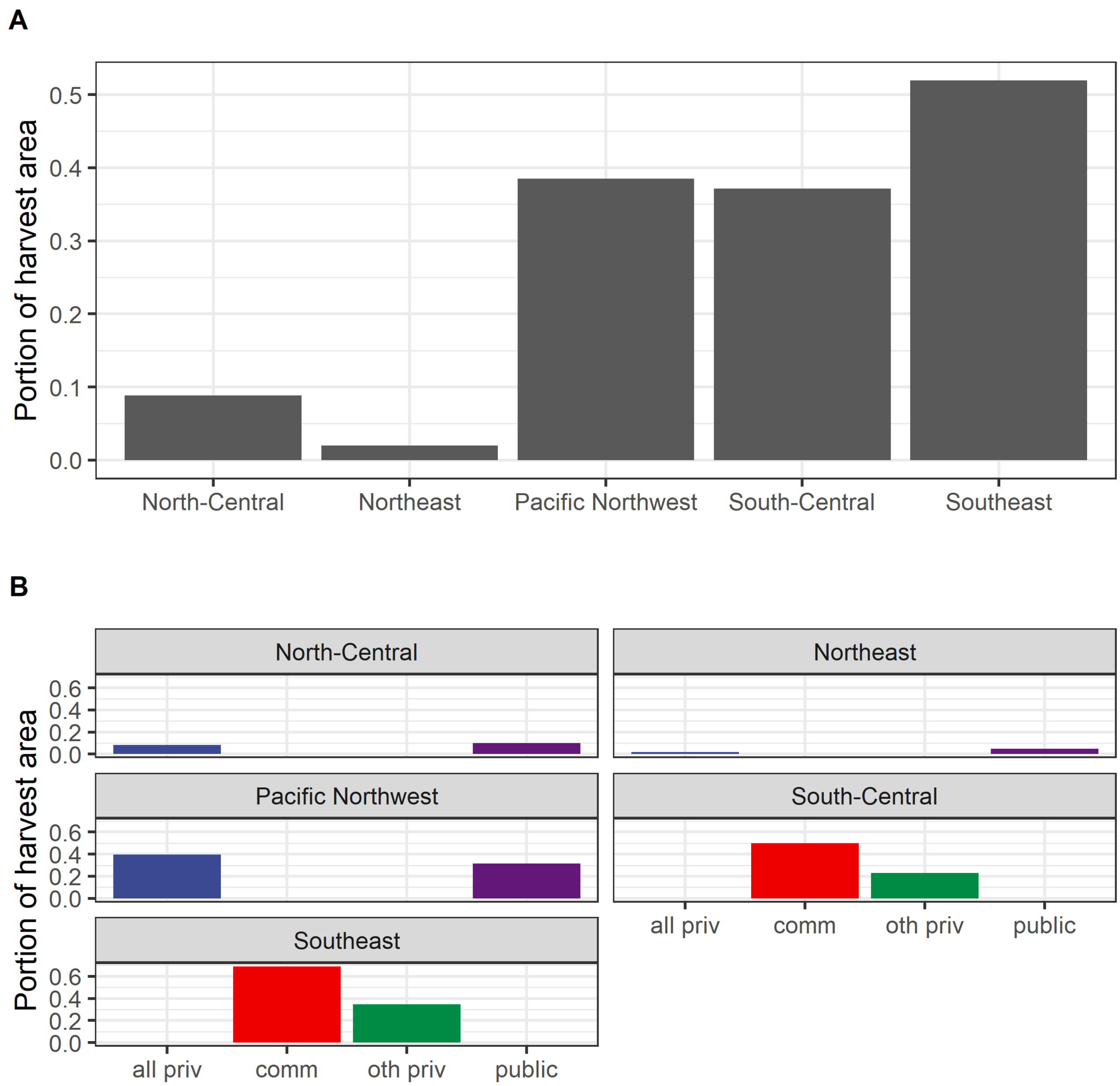
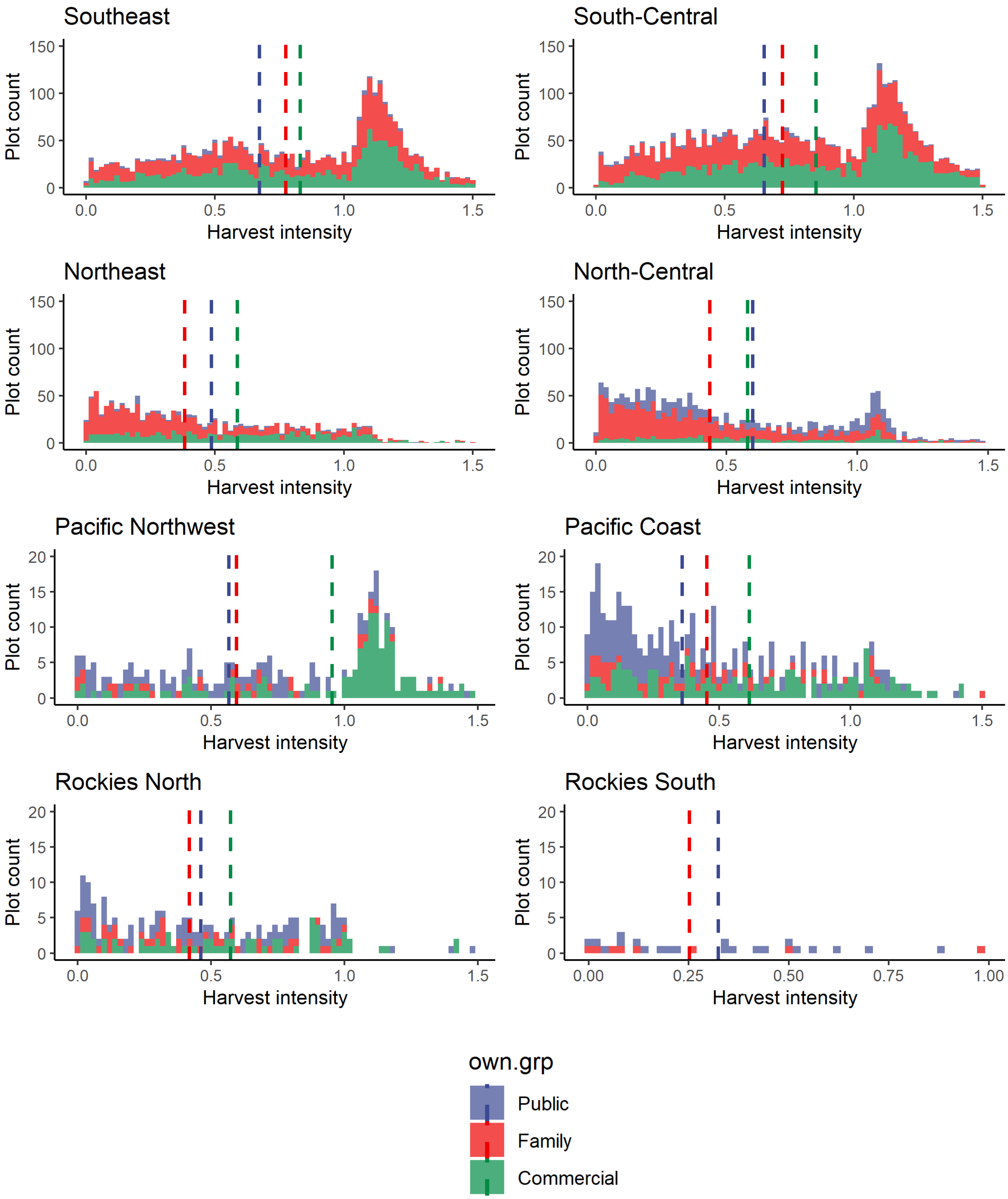
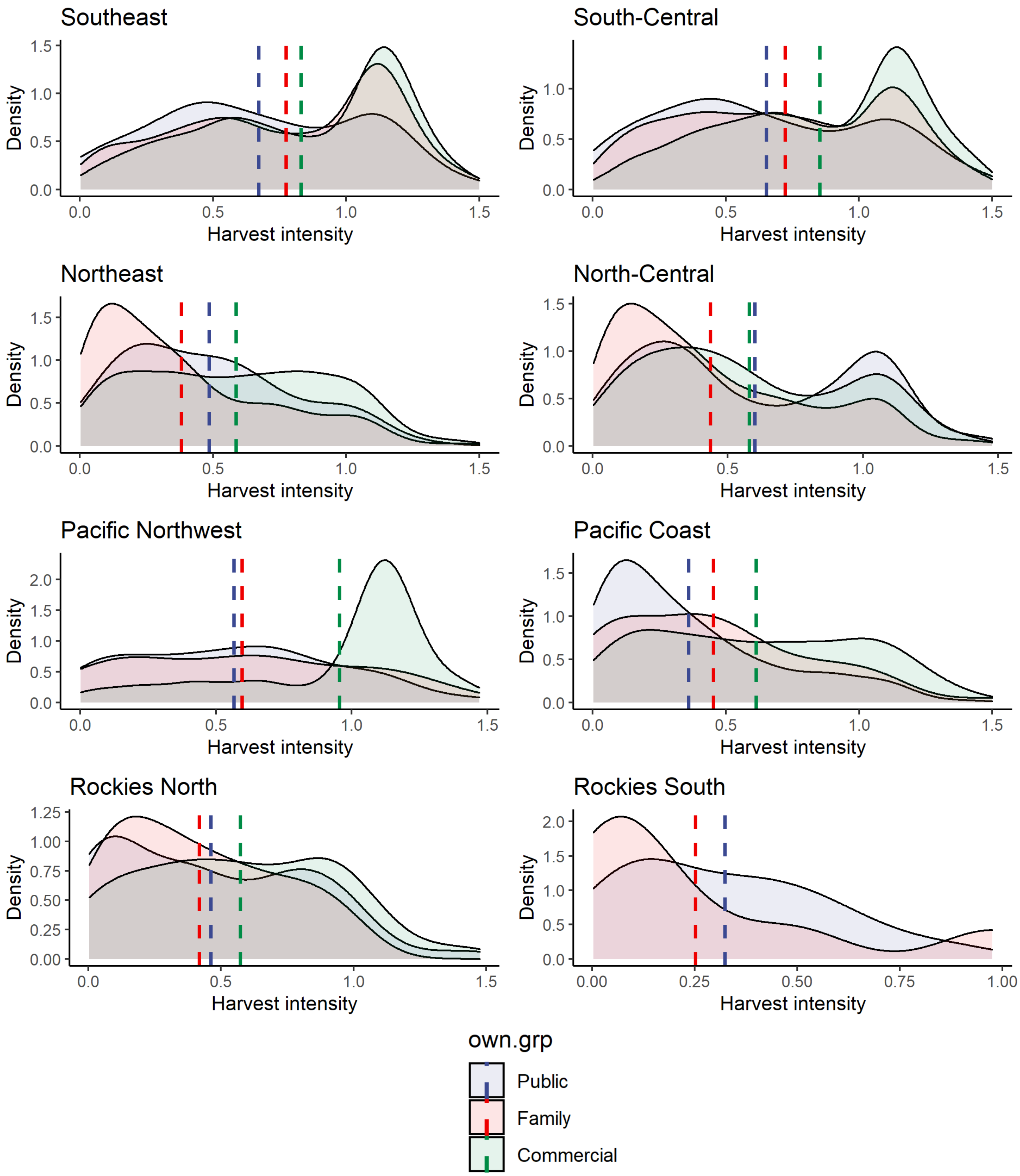


Figure 5. Distribution of Harvest Intensity (Volume Removed / Standing Volume at Beginning of Measurement Period) for Harvested Plots by Subregion and Ownership



Note: Dashed lines indicate average harvest intensity by owner type group.

Figure 6. Density of Harvest Intensity (Volume Removed / Standing Volume at Beginning of Measurement Period) for Harvested Plots by Subregion and Ownership



Note: This is a smoothed histogram by owner type group. Dashed lines indicate average harvest intensity by owner type group.

Figure 7. Predicted Probabilities of Tree Planting Following Harvest by Region and Ownership Groups for (A) Naturally Regenerated Forests and (B) Previously Planted Forests

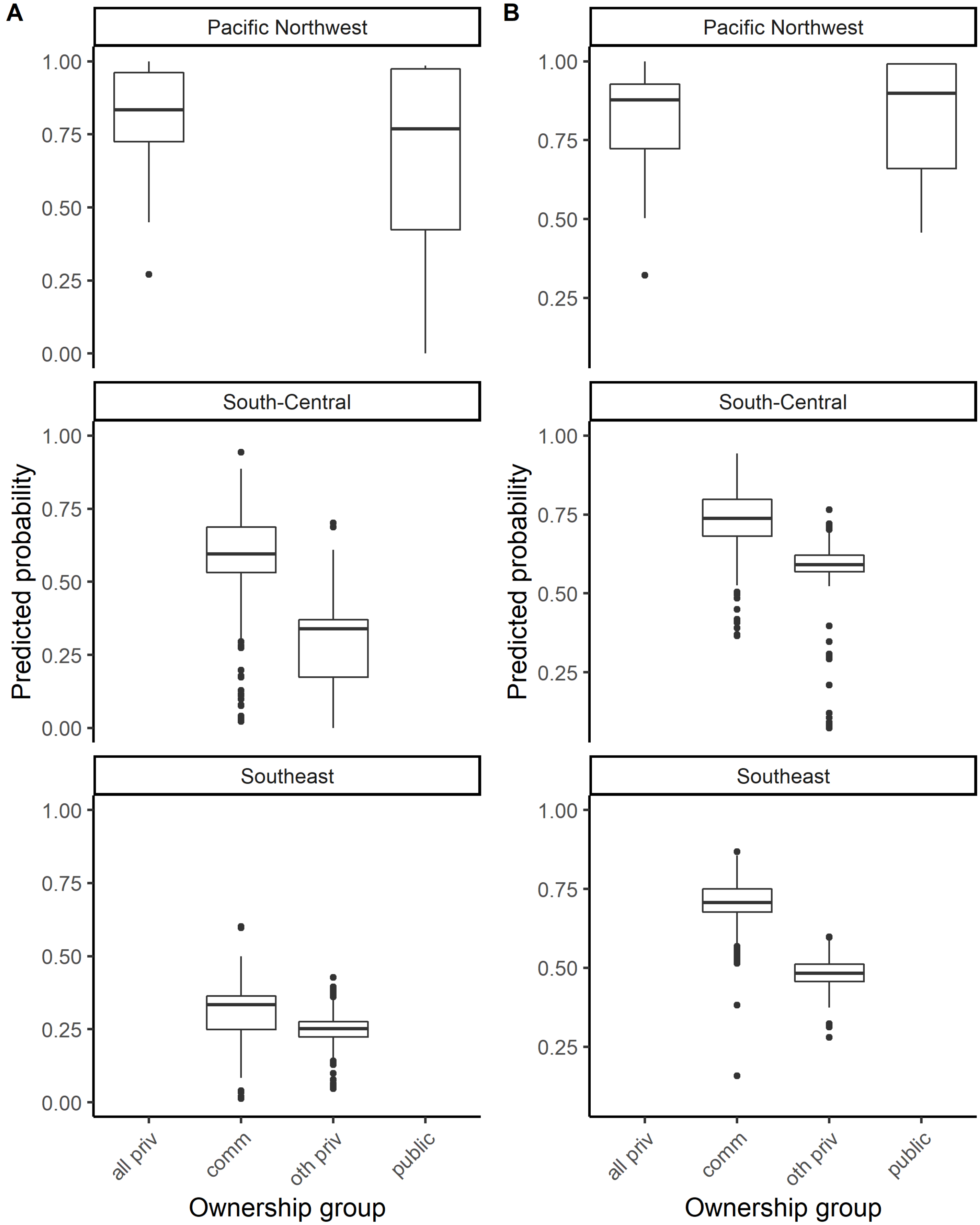


Figure 8. Annualized Gain, Loss, and Net Change in Planted Forest Area Following a Harvest, by Region

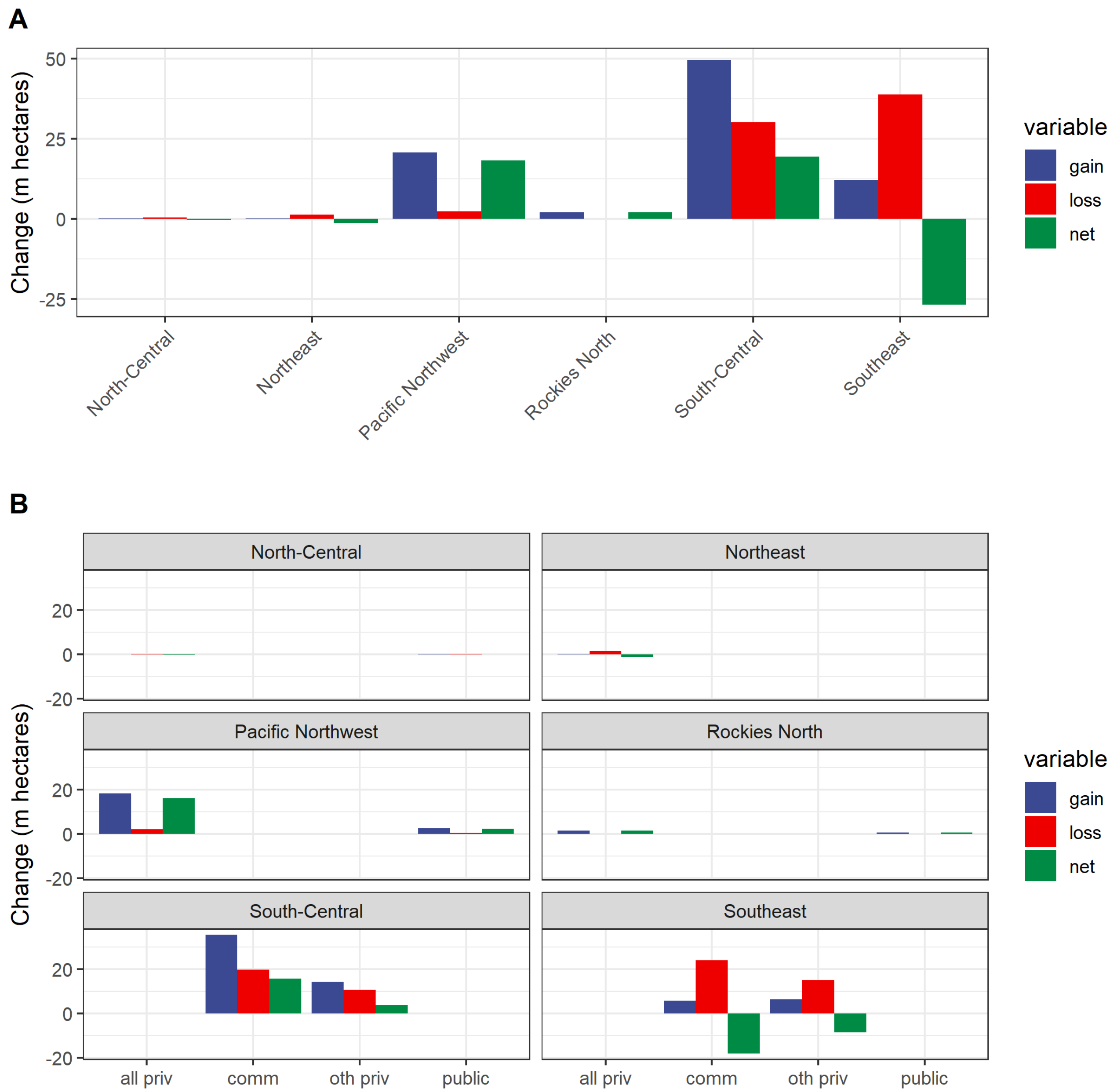
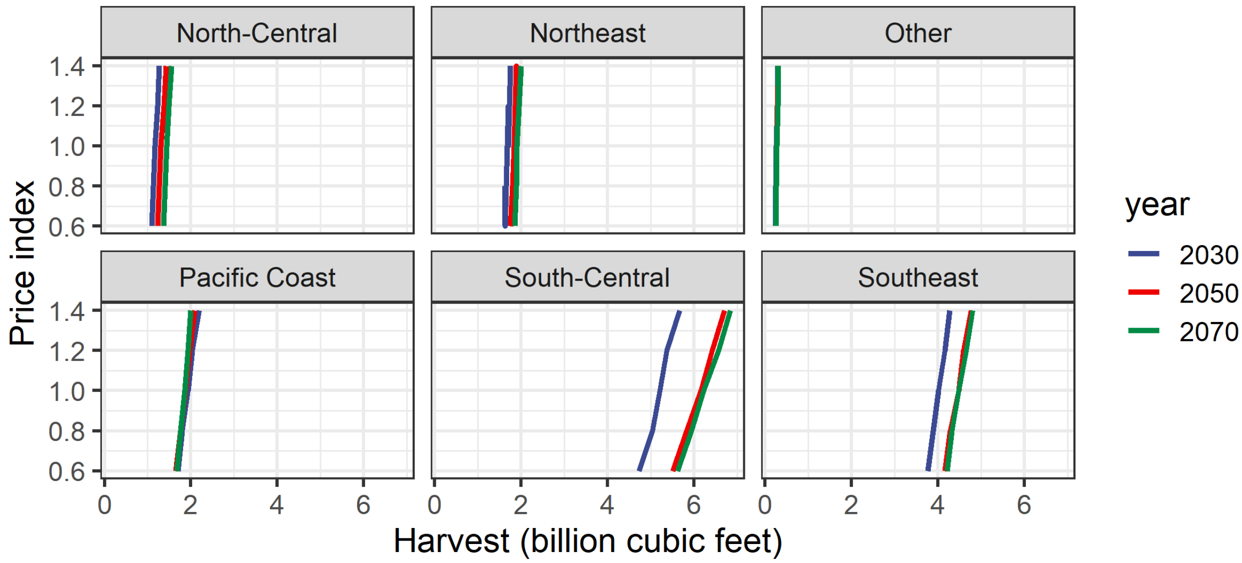


Figure 9. Simulated Timber Supply (Annual Removals as a Function of Price) by Region and Years (2030, 2050, and 2070)



Note: These projections are based on a model of Shared Socioeconomic Pathway (ssp) 2 along with moderate climate change (Radiative Concentration Pathway 4.5) and averaged across climate projections from several Global Circulation Models (see Langner et al for a definition of scenarios).