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Research Article

Economics

Wood Supply from Family Forests of the United States: Biophysical, Social, and Economic Factors

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Abstract

Wood products are an essential provisioning ecosystem service with US forests providing nearly one-fifth of global wood supply. As of 2018, an estimated 46% of the annual wood harvested came from corporate forests, 42% came from family forests, and the remainder came from other private, public, and Tribal forests. The supply of wood from corporate forests is well described by traditional economic models, but the supply from family forests is much less well understood. This article combines data from three components of the USDA Forest Service's Forest Inventory and Analysis program—plots, landowner surveys, and mill surveys—with other data to model the wood supply from family forests in the United States. Results are summarized in terms of bivariate relationships and a logistic regression model. The model results show that basal area, stand origin, forest type, having timber as an ownership objective, the amount of annual income derived from their forestland, proximity to a mill, management advice, and region are significantly associated with family forest timber harvesting. The results should be useful for forest industry analysts and others interested in understanding the current and potential future supply of wood from family forests.

Study Implications: Family forests provide an estimated 42% of the annual timber harvested in the United States. It is important to understand the factors affecting their harvesting behaviors to design effective policies and programs to ensure a continual supply and sustainable management of this critical resource. This article shows that timber harvesting by family forest owners is influenced by a combination of biophysical, social, and economic factors, including basal area, stand origin, forest type, having timber as an ownership objective, the amount of annual income derived from their forestland, proximity to a mill, management advice, and region. These results suggest that programs aimed at increasing the area covered by planted stands, the area covered by softwood stands, and the number of owners receiving forest management advice may be particularly influential in maintaining and increasing the amount of wood harvested from family forests.

Keywords: timber harvesting, nonindustrial private forest owners, Forest Inventory and Analysis, National Woodland Owner Survey, timber products output

There are countless ecosystem services that are provided by forests, but one of the most recognizable and financially important is wood. The United States is the largest global producer of industrial roundwood (19% of global production), the second largest producer of sawn wood (17% of global production), and the largest producer of pulp for paper (26% of global production) (FAO 2021). Forests, including paper products, durable wood products, and forestry-related activities, contributed US$400 billion to the US gross domestic product in 2021 (BEA 2022).

United States timber removals peaked in 1996 at 455 million m^3yr^{-1}, and decreased to 369 million m^3yr^{-1} as of 2016 (Oswalt et al. 2019). Timber is a potentially renewable natural resource, and current estimates suggest that most major species in the United States are being sustainably harvested, at least in terms of growth-to-removal ratios (Butler et al. 2022b). The continued sustainability depends on both supply and demand dynamics. There was a 111% increase in US housing starts between 2010 and 2019 (Brandeis et al. 2021), and this has led to increased demand for associated wood products. Over the same period, US consumption of paper decreased and demand for paperboard slightly increased (Brandeis et al. 2021). There has been increasing demand for wood as an energy source, including industrial (1.4×10^{18} J or 1.4 EJ in 2021), residential (0.5 EJ), electric power (0.2 EJ), and commercial (0.1 EJ) sectors (EIA 2022). Trends in global demand, such as wood pellets for heating in Europe (Rodriguez Franco 2022), also affect US forests. These shifts in demand have led to the closing, opening, and reconfiguring of primary wood processing facilities across the United States, which has led to changes in opportunities for marketing harvested wood.

Harvesting wood is the primary disturbance agent in many parts of the United States and therefore has important ecological consequences (Thompson et al. 2017) and implications for forest carbon sequestration and storage (Duveneck and Thompson 2019). The locations, methods, and intensities of harvesting affect the quality and distribution of habitat for forest-dependent fauna and flora (Berger et al. 2013; Fredericksen et al. 2000). There are also interactions between timber harvesting and ecological processes such as fire, which

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can lead to mutual benefits or tradeoffs among management goals (Ager et al. 2019). Any study examining harvesting patterns also has implications for ecological patterns and processes.

The differences among the factors influencing different ownership groups have been implicitly or explicitly addressed. Layered on top of these differences are inherent ownership dynamics. For example, changes in ownership and management structure of the forest products industry over the past several decades have diminished the vertical integration of primary wood processors and timberland ownership (Clutter et al. 2005), although harvesting continues to be an important objective for large corporate owners (Sass et al. 2021). Over the past 40 years, there has been a large decrease in harvesting on public forestlands, particularly on federal forestlands in the western United States (USDA Forest Service 2022), due to management decisions related to policies such as the Northwest Forest Plan and the Endangered Species Act (Spies et al. 2019). Anthropogenic factors influencing many US forests, and family forests in particular, include development pressures, invasive species, low management intensity, and increased importance of nontimber ownership objectives (Shifley et al. 2014).

Wood production is an important financial asset for many landowners, with virtually all large corporate forest owners (Sass et al. 2021) and 8% of family forest owners in the United States harvesting timber in the previous 5 years (Butler et al. 2021). These financial rewards are the reasons why some owners own their land, and for many it is a means for covering the expenses of forest management practices and holding costs, such as property taxes. For many family forest owners, the decision to harvest may be triggered when an opportunity or need arises, rather than from an intentional plan (Kittredge 2004). Although the timber harvesting behavior of corporate forest owners has been well modeled using economic models that assume profit maximization, modeling the behavior of family forest owners has proven more challenging (Newman and Wear 1993).

Across the United States, 58% of the forestland is privately owned, and collectively, these private forestlands provide 89% of the nation's annual timber removals (Oswalt et al. 2019). Furthermore, nonindustrial private forest owners (i.e., private forests ownerships that do not own primary wood processing facilities) have provided roughly 50%–60% of the annual timber removals in the United States since at least the 1950s (Adams et al. 2006). Although previous studies have reported acreage in finer details (e.g., 39% of forestland in the United States is owned by families, individuals, trusts, and estates, collectively referred to as family forest owners [Butler et al. 2021]), timber removals have only been reported by coarser groupings (e.g., national forests, other public, and private [Oswalt et al. 2019]). So, whereas it is clear that family forest owners are a dominant part of the forested landscape, their contributions to timber removals, although presumably substantial, have not been quantified at the national level.

Public ownerships generally harvesting proportionately less than private forests (Thompson et al. 2017) is in alignment with their general focus on amenity, recreation, and environmental resources, although this varies depending on the priority of the agency (Polyakov et al. 2010) and on stand characteristics (Prestemon and Wear 2000). Among private ownerships in the northeastern United States, corporate forest ownerships were more likely to harvest than family forest ownerships (Thompson et al. 2017), which is in line with their respective ownership and management objectives. Where harvests occurred, the intensity of the harvests also varied by ownership type, ranging from a median of 40% of the basal area being removed on state- or corporate-owned harvested plots to a median of 20% of the basal area being removed on nonindustrial private-owned harvested plots (Thompson et al. 2017). Newman and Wear (1993) attributed lower harvesting rates by nonindustrial private forest ownerships to the higher values they placed on "nonmarket benefits" and amenity values.

A meta-analysis of studies of the harvesting behavior of family forest owners, sometimes referred to as nonindustrial private forest owners or private woodland owners, found several factors related to the likelihood of harvesting; these included positive associations with size of holdings, stumpage price, distance to residence, education level, and owner age, and mixed results for income and being a farmer (Silver et al. 2015) (Table 1). Silver et al. found that most studies measure landowners' intentions to harvest rather than actual harvesting behavior and concluded that more research is needed that measures actual harvesting behavior and connects it to the intentions to harvest. There have also been several studies that have highlighted the importance of peer networks in regards to timber harvesting and other forest management activities (e.g., Knoot and Rickenbach 2011; Lind-Riehl et al. 2015).

A meta-analysis of family forest ownerships' actions also found that size of holdings was consistently related to likelihood of action across studies, but that only five out of seventeen objectives and four out of twelve policy tools were significantly related to actions (Floress et al. 2019). Thompson et al. (2017) found that the probability of harvesting was best described using site variables, including basal area, owner class, and forest type. For plots that were harvested, the intensity of harvest was best described using a combination of site and ownership variables (Table 1).

Although supply of wood from family forests has been the focus of many studies, the overall predictive power of the models has been low. Given their importance for timber supply in the United States and elsewhere in the world, there is a need for greater understanding of factors influencing family forest owner harvesting behavior. In this study, we examine the supply of wood from family forests across the United States using data from the USDA Forest Service's Forest Inventory and Analysis program (FIA). We assess biological, social, and economic factors potentially associated with this wood supply using data from the FIA forest inventory plots, national landowner survey, and survey of primary wood processing facilities, in addition to other data sources. We present bivariate analyses of harvest removals by selected variables and then results from a logistic regression model. We conclude with a discussion of the implications and limitations of these results and potential next steps.

This article contributes to the published literature by addressing a perennially important topic, generating population-level estimates of removals by key attributes, novel linking of data sources, and expanding on previous work both in terms of geographic scope and variables tested. This work has direct implications for wood supply procurement, the programs and policies aimed at increasing wood supply, and the activities that are affected by harvesting.

Table 1. Summary of variables discussed in selected papers examining family forest owner timber harvesting (Silver et al. 2015; Thompson et al. 2017) and other actions (Floress et al. 2019) in the United States.

Category/variable	Silver et al. (2015)	Thompson et al. (2017) Harvest	Thompson et al. (2017) Harvest intensity	Floress et al. (2019)
Demographics				
Age	-	NS	NS	
Debt to income ratio	+			
Education	+	NS	NS	
Income	+/-	NS	NS	
Occupation	S			
Retired		NS	NS	
Economics				
Distance to road		-	+	
Stumpage price	+			
Land characteristics				
Basal area		+	+	
Forest group		S	S	
Site value	+			
Timber stock	+			
Management practices				
Advice	+			
Extension involvement	+			
Management plan	+			
Owner/ownership characteristics				
Proximity to home	+			
Size of forest holding	+	NS	+	+
Tenure	+	NS	NS	
Woodland owner association membership	+			
Owner objectives				
Any				+/-/NS
Nontimber	-			
Timber	+			
Programs & policies				
Any				+/NS
Certification		NS	NS	
Easement		NS	NS	

+ = significant, positive association; - = significant, negative association; NS = not significant; S = significant (indeterminant direction).

Methods

After quantifying wood supply by ownership group (Table 2), the factors associated with the supply of wood from family forests in the United States were analyzed using bivariate summaries and a logistic regression model. The primary removals/harvesting data were derived from remeasurements taken on USDA Forest Service FIA inventory plots. The FIA program is the national forest inventory for the United States and consists of a network of permanent inventory plots that are randomly distributed across the country (Bechtold and Patterson 2005). For the inventory cycles used in this analysis, there were a total of 309,723 remeasured plots, of which 130,095 were classified as completely or partially forested during the most recent measurement and 54,013 classified as completely or partially family forest during the most recent measurement. Forest was defined as land with "at least 10 percent canopy cover by live tally trees of any size or has had at least 10 percent canopy cover of live tally species in the past … [and] at least 1.0 acre [0.4 ha] in size and 120.0 feet [37 m] wide" (Burrill et al. 2021, 2–38). Family forest was defined as forest owned by "individual and family, including trusts, estates, and family partnerships" (Burrill et al. 2021, 2–40).

Based on data availability, the nominal year for the FIA inventories used was 2018, with specific inventory years varying by state. The inventory sample design used an annualized implementation with 10% to 20% of plots in a cycle inventoried per year; the "current" (t_1) data were collected between 2009 and 2018 and the "previous" (t_0) data were collected between 2001 and 2015, with an average remeasurement period of 5.8 years (SE = 1.3) for the model data. Alaska, Hawaii, Idaho, Nevada, New Mexico, and Wyoming, all in the western United States, where forestland ownership is dominated by public agencies (74% of the forestland across these six states is publicly owned [Oswalt et al. 2019]), were

Table 2. Descriptions of ownership groups used to analyze wood supply in the United States

Ownership Group	Description	Area* owned/managed	
		million ha	percentage
Private			
Corporate	Corporations, including Native Corporations in Alaska and private universities	64.3	23.8
Family	Individuals and families, including trusts, estates, and family partnerships	135.0	50.0
Other private	Non-governmental conservation/natural resources organizations and unincorporated local partnerships, associations, and clubs	4.9	1.8
Public			
Federal	US National Forests, National Grasslands, and other Forest Service lands, National Park Service, Bureau of Land Management, Fish and Wildlife Service, Departments of Defense/Energy, and other federal	36.7	13.6
State	State including State public universities	7.8	2.9
Local	Local (county, municipality, etc.) including water authorities and other non-federal public	19.2	7.1
Tribal			
Tribal	Native American	2.1	0.8

*Excluding Alaska, Hawaii, Idaho, Nevada, New Mexico, and Wyoming due to unavailability of removals data. Categories and descriptions are based on USDA Forest Service, Forest Inventory and Analysis definitions (Burrill et al. 2021).

excluded from all results and analyses due to a lack of sufficient data to estimate removals.

Harvesting estimates were based on "average annual harvest removals of sound bole volume of trees (at least 5 inches [12.7 cm] d.b.h./d.r.c. [diameter at breast height for forestland species/ diameter at root collar for woodland species]), in cubic feet [converted to cubic meters; 1.0 ft^3 = 0.028 m^3], on forest land" (FIA database attribute number 237; Pugh et al. 2018, A-11). The harvest variable (HRV) used in the logistic regression model was a binary variable coded as "Yes" if trees were removed from the plot during the remeasurement period and the primary treatment recorded was "cutting," and was coded as "No" otherwise (Table 3). Cutting was defined by FIA as the "removal of one or more trees from a stand" since the last measurement with a minimum affected area of 0.4 ha (Burrill et al. 2021), but there was no explicit information recorded to indicate the reason for the removals (e.g., whether it was a commercial harvest).

Data explored for associations with wood removals came from additional variables measured as part of the FIA plot inventory (USDA Forest Service 2022a), the FIA landowner survey (National Woodland Owner Survey; USDA Forest Service 2022b), the FIA mill survey (Timber Products Output survey [TPO]; USDA Forest Service 2022c), the National Land Cover Database (NLCD; U.S. Geological Survey 2021), and the American Community Survey (U.S. Census Bureau 2018). Additional plot attributes included basal area at t_0 and planting/stand origin status at t_0 (Table 3). Region was assigned based on plot location (Table 3) and was based on the state groupings used by the Renewable Resource Plan Act Assessment (e.g., Oswalt et al. 2019).

The family-owned forested FIA plots were the basis for the FIA landowner survey data used in this analysis. This survey collects information on landowners' attitudes, behaviors, and other characteristics (Butler et al. 2021). The most recently completed survey collection cycle, implemented in 2017 and 2018, was used. Information from the survey included in the analyses were related to general ownership characteristics, management practices, program participation, ownership objectives, and demographics (Table 3). For the variables that went into the program participation variable (OWN_PROG), "Don't know" responses were recoded as No. "Not applicable" responses for the variable indicating if their primary residence was associated with their forestland (OWN_HOME) were recoded as No.

The FIA mill survey collects information on the volume and types of wood used by primary processing facilities across the United States (Coulston et al. 2018). Data from the 2018 TPO survey were used. The mill survey data were incorporated using an index based on distance and volume to sawmills:

$$MILL\_SAW_P = \left(\sum_{i=1}^{3} \frac{V}{d^2} \right) /3 \tag{1}$$

where V was the mill capacity (measured in m^3), divided by the distance (d, measured in km) from the mill to the plot, and the final value was the mean of the three mills with the greatest values for each plot, P. TPO mill data were missing for Texas and Washington and these states were consequently excluded from the sawmill index (MILL_SAW) bivariate analysis and the logistic regression model.

Landscape context was measured using data from the 2019 National Landcover Database (NLCD; U.S. Geological Survey 2021). At each sample point location, the proportion of the area within 1 km classified as forest was calculated (Table 3).

Population density, measured as people per km^2, was taken from data corresponding to the 2014–2018 American Community Survey (U.S. Census Bureau 2018). Sample point locations were intersected with tract-level polygon data to extract the values (Table 3).

Bivariate Analyses

Bivariate analyses consisted of numeric and graphical summaries and associated statistical tests of wood removals on family forests by each of the variables of interest listed

Table 3. Descriptions of variables used to model the supply of wood from family forests in the United States*

Variable	Description	Summary[a]	Source[b]
HRV	A harvest occurred on the plot/condition during the remeasurement period	Yes = 11%; No = 89%	FIA
LC_FOREST	Proportion of area within 1 km of the sample point that was classified as forest cover	Q_0 = 0.0; Q_1 = 0.5; Q_2 = 0.7; Q_3 = 0.8; Q_4 = 1.0	NLCD
MILL_SAW	Sawmill index (see equation 1)	Q_0 = 1.1; Q_1 = 34.5 Q_2 = 95.5; Q_3 = 258.7; Q_4 = 154,715.4	TPO
OWN_AGE	Age of primary decision-maker in years	Q_0 = 21; Q_1 = 59; Q_2 = 66; Q_3 = 74; Q_4 = 106	NWOS
OWN_HOME	Owner had a primary residence within 1.6 km of their forestland	Yes = 59%; No = 41%	NWOS
OWN_INC	Owner earned at least 5% of their annual income from their forestland	Yes = 22%; No = 78%	NWOS
OWN_MAN_ADV	Owner had received forest management advice in the previous 5 years	Yes = 34%; No = 66%	NWOS
OWN_OBJ_TIM	Owner rated "for timber products, such as logs or pulpwood" as an important or very important ownership objective on a 5-point Likert scale	Yes = 41%; No = 59%	NWOS
OWN_PROG	Forestland was green certified, owner participated in a cost-share program in the previous 5 years, or forestland was enrolled in a preferential property tax program	Yes = 35%; No = 65%	NWOS
OWN_SIZE	Size of forest holding (ha). A logged version of this variable was used in the models.	Q_0 = 4.5; Q_1 = 18.2; Q_2 = 40.5; Q_3 = 111.6 Q_4 = 14,625.3	NWOS
PLOT_REMPER	Years between plot measurements	Q_0 = 3.9; Q_1 = 5.0; Q_2 = 5.4; Q_3 = 6.1; Q_4 = 11.3	FIA
POP_DENS	Number of people per km^2 for the Census tract where the plot was located	Q_0 = 0.1; Q_1 = 6.7 Q_2 = 13.1; Q_3 = 25.4; Q_4 = 617.6	ACS
REGION	Region where the plot was located[c]	North = 56%; South = 39%; West = 5%	FIA
STAND_BA	Basal area (m^{2}ha^{-1}) at t_0	Q_0 = 0.0; Q_1 = 14.9; Q_2 = 22.3; Q_3 = 29.9; Q_4 = 103.9	FIA
STAND_FORTYPE	Forest type group was softwood (vs. hardwood) at t_0	Yes = 22%; No = 78%	FIA
STAND_ORIGIN	Stand was planted at t_0	Yes = 10%; No = 90%	FIA

*Excluding Alaska, Hawaii, Idaho, Nevada, New Mexico, Texas, Washington, and Wyoming due to unavailability of removals or mill data.
[a]For binary and categorical variables, percentage of respondents in the final model dataset (n = 3,182) in each category are shown. For numeric and proportion variables, zeroth (Q_0; minimum), first (Q_1), second (Q_2; median), third (Q_3), and fourth (Q_4; maximum) quartiles are shown.
[b]ACS = American Community Survey (U.S. Census Bureau 2018); FIA = Forest Inventory and Analysis (U.S. Forest Service 2022a); NLCD = National Landcover Database (U.S. Geological Survey 2021); NWOS = National Woodland Owner Survey (U.S. Forest Service 2022b); TPO = Timber Products Output survey (U.S. Forest Service 2022c).
[c]North includes Connecticut, Delaware, Illinois, Indiana, Iowa, Maine, Maryland, Massachusetts, Michigan, Minnesota, Missouri, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, Vermont, West Virginia, and Wisconsin; South includes Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, and Virginia; and West includes Arizona, Colorado, California, Kansas, Montana, Nebraska, North Dakota, Oregon, South Dakota, and Utah.

in Table 3. The FIA sample design facilitates the generation of population-level estimates and associated standard errors, and estimation procedures relied on custom data retrievals that followed the procedures outlined in Burrill et al. (2021) and Pugh et al. (2018). Data were summarized in terms of total wood removals and the average wood removed per hectare (i.e., total wood removals divided by total forest area for the variable/level of interest).

Significance tests were performed on the average wood removed per hectare using two-sample t-tests; for variables with more than two levels, the tests were run on the levels with the greatest differences for each variable. An alpha value of 0.05 was used to define significant differences with a Bonferroni adjustment applied to account for multiple comparisons ($\alpha_{adj} = 0.05/17 = 0.003$; the denominator is based on sixteen variables/levels in the bivariate analyses + the logistic regression model). Those t-tests with p-values of ≤ 0.003 were considered statistically significant.

Logistic Regression Model

Logistic regression is a common approach used to model binary outcomes that uses a logit transformation of the dependent variable and subsequently has many attributes of linear, ordinary least squares regression (Hosmer et al. 2013). A logistic regression model was generated with the binary HRV variable as the dependent variable (Table 3). The full set of independent variables is listed in Table 3. All data were associated with remeasured FIA plots where the plot center was classified as family forest at t_1. The final dataset (n = 3,182) was filtered to exclude records with missing data and ownerships with forest holdings of less than 4 ha (~10 ac). Ownerships with forest holdings less than 4 ha in size have been found to have different attitudes and behaviors towards their forestland than larger ownerships, particularly related to timber harvesting (Snyder et al. 2019).

To avoid potential overparameterization, a model was identified a priori with the maximum number of variables based on 343 events (i.e., observed harvests) in the dataset and the rule-of-thumb of a minimum of 20 events per variable (Austin and Steyerberg 2017). This implied that a maximum of 16 variables (or more precisely degrees of freedom) could be included in the model, which are listed in Table 4.

The results of the logistic regression model are presented in terms of odds ratios and associated confidence intervals, which is a common approach for this model type (Hosmer et al. 2013). Odds ratios are equal to the probability of an event occurring given the presence of a specific attribute divided by the probability of an event occurring given the absence of a specific attribute. This is derived by exponentiating the logistic regression coefficients. This transformation allows for more straightforward interpretations of how much each variable, given all other variables in the model, affects the likelihood of an event occurring.

Goodness-of-fit of the logistic regression model was assessed using the Hosmer-Lemeshow goodness-of-fit test (Hosmer et al. 2013), through examination of the receiver operating characteristic curve (ROC curve; Hosmer et al. 2013), and by calculating the ROC area under the curve (AUC; Hosmer et al. 2013) and Tjur's R^2 (Tjur 2009). Multicollinearity was assessed by examining variance inflation factors (Fox and Weisberg 2019). All of the variables had variation inflation factor values less than 2, implying no issues with multicollinearity in the model.

Statistical summaries and other analyses, apart from the calculation of the land cover variable, were conducted using the R Computing Environment (R Core Team 2022). In addition to the core R packages, specific R packages used included the *tidycensus* package (Walker and Herman 2022) for accessing the ACS data, the *BSDA* package (Arnholt and Evans 2021) for testing differences between groups, the *car* package (Fox and Weisberg 2019) for calculating variance inflation factors, the *pROC* package (Robin et al. 2011) for plotting the ROC curve and calculating the AUC, the *ResourceSelection* package (Lele et al. 2019) for calculating the Hosmer-Lemeshow goodness-of-fit test, and the *performance* package (Lüdecke et al. 2021) for calculating Tjur's R^2. The land cover data were processed in ArcGIS (Esri 2021) using a combination of reclassification, buffer, and zonal statistic functions.

The primary raw data (i.e., USDA Forest Service FIA plot inventory, landowner survey, and mill survey data) cannot be made publicly available because they contain confidential information that were collected under agreements for anonymity and protected from data disclosure under US law (7 U.S.C. 2276 as amended by P.L.106-850). The scripts used to query, summarize, and analyze the data are available at https://github.com/familyforestresearchcenter/WOOD_SUPPLY.

Results

The wood supply in the United States comes predominantly from private forestlands and, in particular, corporate and family forestlands (figure 1). Corporate forestlands account for 47% of the annual removals in the United States, and family forestlands account for 41% (Forest Service FIA 2022a). The average per hectare removals across all forested acreage in the ownership category is highest for corporate forestlands (3.4 $m^3ha^{-1}yr^{-1}$) followed by family forestlands (1.5 $m^3ha^{-1}yr^{-1}$), lowest for federal and Tribal forestlands (0.3 and 0.7 $m^3ha^{-1}yr^{-1}$, respectively), and other ownership groups have values between 1.0 and 1.1 $m^3ha^{-1}yr^{-1}$ (Forest Service FIA 2022a). Due to data limitations, these statistics, and all results presented in this article, exclude data from Alaska, Hawaii, Idaho, Nevada, New Mexico, and Wyoming.

The proportion of wood removals by different ownership groups varies across the country (figure 2). For thirty-seven of the forty-four states where removals data are available, a

Table 4. Odds ratios and associated 95% confidence intervals for a logistic regression model of family forest timber harvesting in the United States,* 2018.

	Odds Ratio	CI 2.5	CI 97.5	*p*-value
(Intercept)	0.008	0.003	0.023	<0.001
LC_FOREST	0.709	0.383	1.324	0.276
MILL_SAW	1.019	1.001	1.038	0.033
OWN_AGE	1.003	0.993	1.014	0.561
OWN_HOME - Yes	0.807	0.632	1.031	0.085
OWN_INC	1.459	1.073	1.979	0.016
OWN_ MAN_ADV - Yes	1.506	1.139	1.990	0.040
OWN_OBJ_TIM - Yes	1.591	1.189	2.128	0.020
OWN_PROG - Yes	0.927	0.702	1.221	0.591
OWN_SIZE_LOG	1.025	0.929	1.130	0.623
PLOT_REMPER	1.150	1.037	1.273	0.008
POP_DENSITY	0.998	0.995	1.001	0.222
REGION—South	1.308	0.973	1.754	0.074
REGION—West	0.220	0.080	0.533	0.002
STAND_BA	1.040	1.030	1.050	<0.001
STAND_FORTYPE - Softwood	2.359	1.759	3.151	<0.001
STAND_ORIGIN - Planted	2.043	1.440	2.896	<0.001

*Excluding Alaska, Hawaii, Idaho, Nevada, New Mexico, Texas, Washington, and Wyoming due to unavailability of removals or mill data.

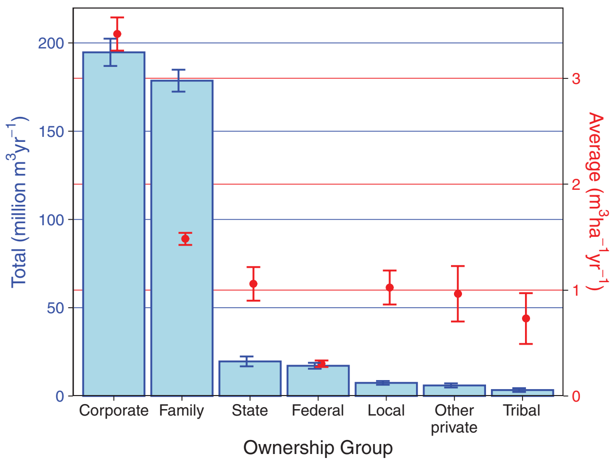

Figure 1. Total (bars) and average per hectare (points) wood removals by ownership group, United States,* 2018. Error bars represent 95% confidence intervals. Data source: Forest Service FIA 2022a.*Excluding Alaska, Hawaii, Idaho, Nevada, New Mexico, and Wyoming due to unavailability of removals data.

plurality of the timber harvested comes from private forestlands. Across these forty-four states, corporate forestlands account for a majority of the removals volume in the west coast states (California, Oregon, and Washington), a number of southern states (Arkansas, Florida, Louisiana, Oklahoma, and Texas), and two northern states (Maine and West Virginia). Across the forty-four states, family forests account for a plurality of the removals in most of the northern states (Delaware, Illinois, Indiana, Iowa, Maryland, Massachusetts, Michigan, Missouri, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, Vermont, and Wisconsin), a number of southern states (Alabama, Georgia, Kentucky, Mississippi, North Carolina, Tennessee, and Virginia), and two western states (Kansas and Nebraska). Removals from federal forestlands dominate across most of the Intermountain West states including, among the forty-four states analyzed, Arizona, Colorado, Montana, and Utah, as well as South Dakota; in Montana, removals from corporate and family forestlands are only slightly lower than federal removals. Removals from state forestlands dominate in Connecticut. Removals from Tribal forestlands dominate in North Dakota.

Bivariate Analyses

The bivariate analyses are presented for harvest removals from family forestlands across forty-four states in terms of totals and averages (figure 3). Due to harvesting patterns and underlying distributions of forestland, the two metrics can show substantial differences. The total and average volumes of wood harvested from family forests vary substantially across many of the levels within each of the variables tested, and the values are statistically different among two or more of the levels for all of the variables tested.

In terms of land cover (figure 3A), most family forest harvest removals come from areas that are moderately forested (50%–74%) followed by areas that are well forested (75+%). The average removals per hectare are substantially lower for areas with low forest cover (≤25%).

The sawmill index represents the average influence of the top three sawmills weighted in terms of volume and distance (1). Family forestlands with moderate sawmill influences (indices of 50–249) account for 42% of the harvest removals from family forests followed by forestlands with low (≤50) or slightly higher (250–499) indices with 19% and 20%, respectively (figure 3B). The average removals by sawmill index show a substantial increase up to 250, at which point an asymptote of around 2.2 m^{3}ha^{-1}yr^{-1} is reached.

In terms of owner age (figure 3C), most harvest removals come from family forests with primary decisionmakers between 65 and 74 years of age followed by decisionmakers who are 55–64 and 75+ years of age. When examined in terms of average removals, primary decisionmakers between 65 and 74 years of age are still the highest (1.8 m^{3}ha^{-1}yr^{-1}), but primary decisionmakers between 18 and 44 of years age have the second highest values (1.6 m^{3}ha^{-1}yr^{-1}) with values then increasing to the 65–74 category and dropping for the 75+ years of age category.

Owner income derived from their forestland (figure 3E), the importance of timber as an ownership objective (figure 3G), and size of forest holdings (figure 3I) show similar patterns in terms of average harvest removals from family forests. For these three variables, the average removals increase substantially in relation to increases in income, importance of timber production, and size of holdings. But the totals have very different patterns. Whereas the amounts of removals increase in relation to the importance of timber production, the greatest amount of removals in terms of income is for ownerships who receive no income from their forestland in a typical year and in terms of size of holdings, the totals are dominated by ownership with holdings of 4–199 ha.

The patterns for harvest removals from family forests for management advice (figure 3F) and program participation (figure 3H) are largely analogous to those for income, ownership objective, and size of holdings patterns. The average removals from family forests owned by people who either received management advice or participated in a program are higher than for owners who have not. But greater total removals come from forestlands where owners have not received management advice or have not participated in a program, 46% and 41%, respectively.

A higher percentage of the annual timber removals come from forestland associated with a primary residence, 57% (figure 3D), but the average removals are not substantively different for ownerships with and without primary residences associated with their forestland, 1.4 and 1.6 m^{3}ha^{-1}yr^{-1}, respectively.

Population density has a nonlinear relationship with harvest removals from family forests, particularly in terms of totals (figure 3J). The majority of removals, 29%, come from forests located in areas with population densities between 10 and 19 people km^{-2} with lower shares in areas with higher and lower densities. Averages show a similar but more muted pattern with the highest values, 1.6 m^{3}ha^{-1}yr^{-1}, for forests located in areas with 5–49 people km^{-2} and lower elsewhere, 1.1 m^{3}ha^{-1}yr^{-1} in areas with fewer than 5 people km^{-2} and 1.3 m^{3}ha^{-1}yr^{-1} in areas with at least 50 people km^{-2}.

The harvest removal totals and averages vary substantially across regions (figure 3K). An estimated 68% of the annual harvest removals from family forests come from the southern United States with an average of 1.8 m^{3}ha^{-1}yr^{-1}. Family forests in the northern United States account for 26% of the removals with an average of 1.1 m^{3}ha^{-1}yr^{-1}. The remaining 5% of the family forest harvest removals come from the western United States, with an average of 0.9 m^{3}ha^{-1}yr^{-1}; all of the missing

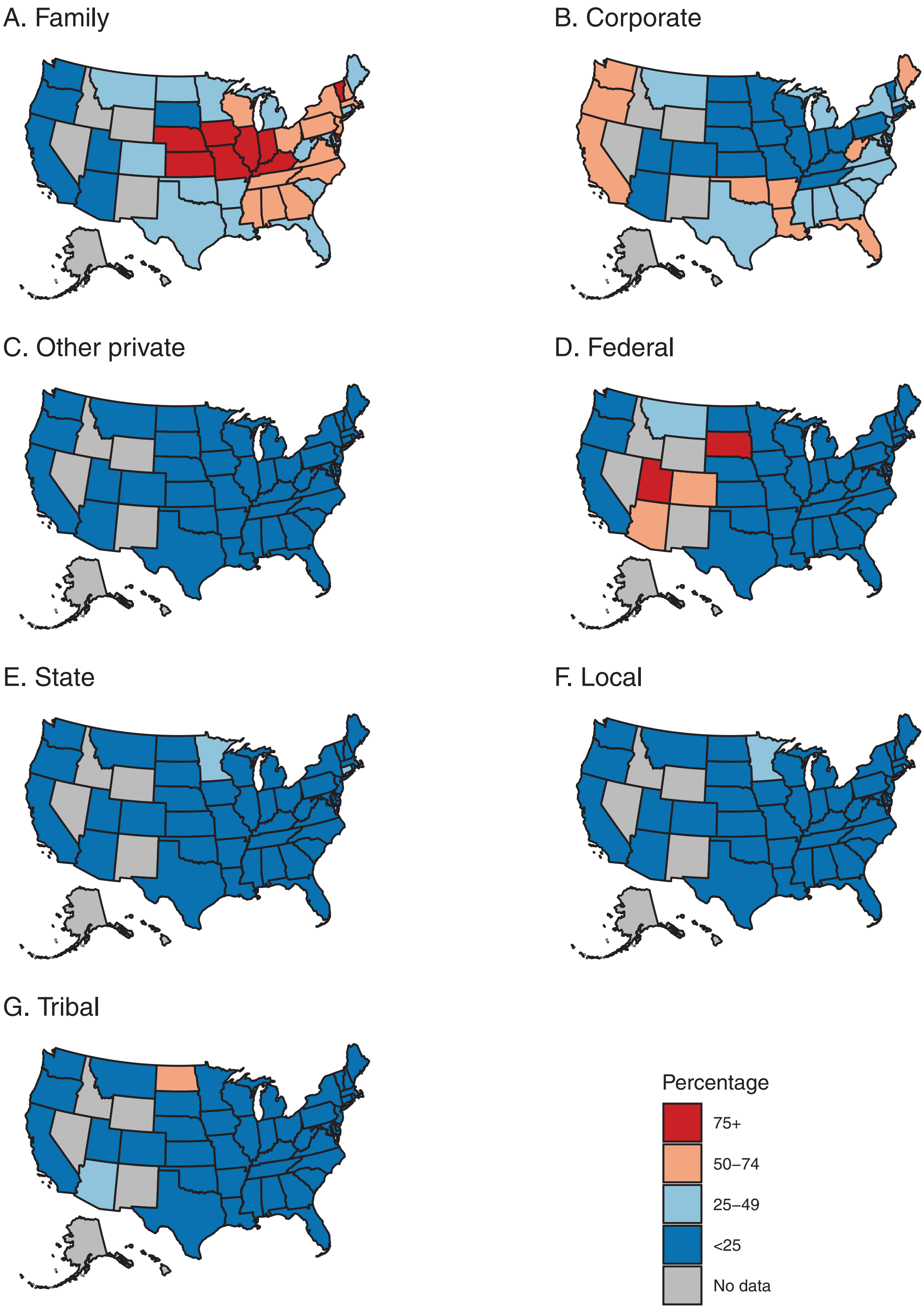

Figure 2. Wood removals by ownership group by state, 2018. Data source: Forest Service FIA 2022a.

states are from this region; thus, this is an underestimate of this region's contributions.

Planted versus natural stands (figure 3M) and softwood versus hardwood stands (figure 3N) show similar relationships to harvest removals from family forests, but the pattern is stronger for stand origin. Planted stands have average removals of 3.6 $m^3ha^{-1}yr^{-1}$ versus 1.3 $m^3ha^{-1}yr^{-1}$ for natural stands but account for only 24% of the removals. Softwood stands account for 47% of the total removals and average removals of 3.1 $m^3ha^{-1}yr^{-1}$ compared with 1.0 $m^3ha^{-1}yr^{-1}$ for hardwood stands. Stand basal area has a very pronounced positive relationship to average removals, but the total volumes harvested are predominately from stands with moderate basal areas between 20 and 40 m^2ha^{-1} (figure 3L).

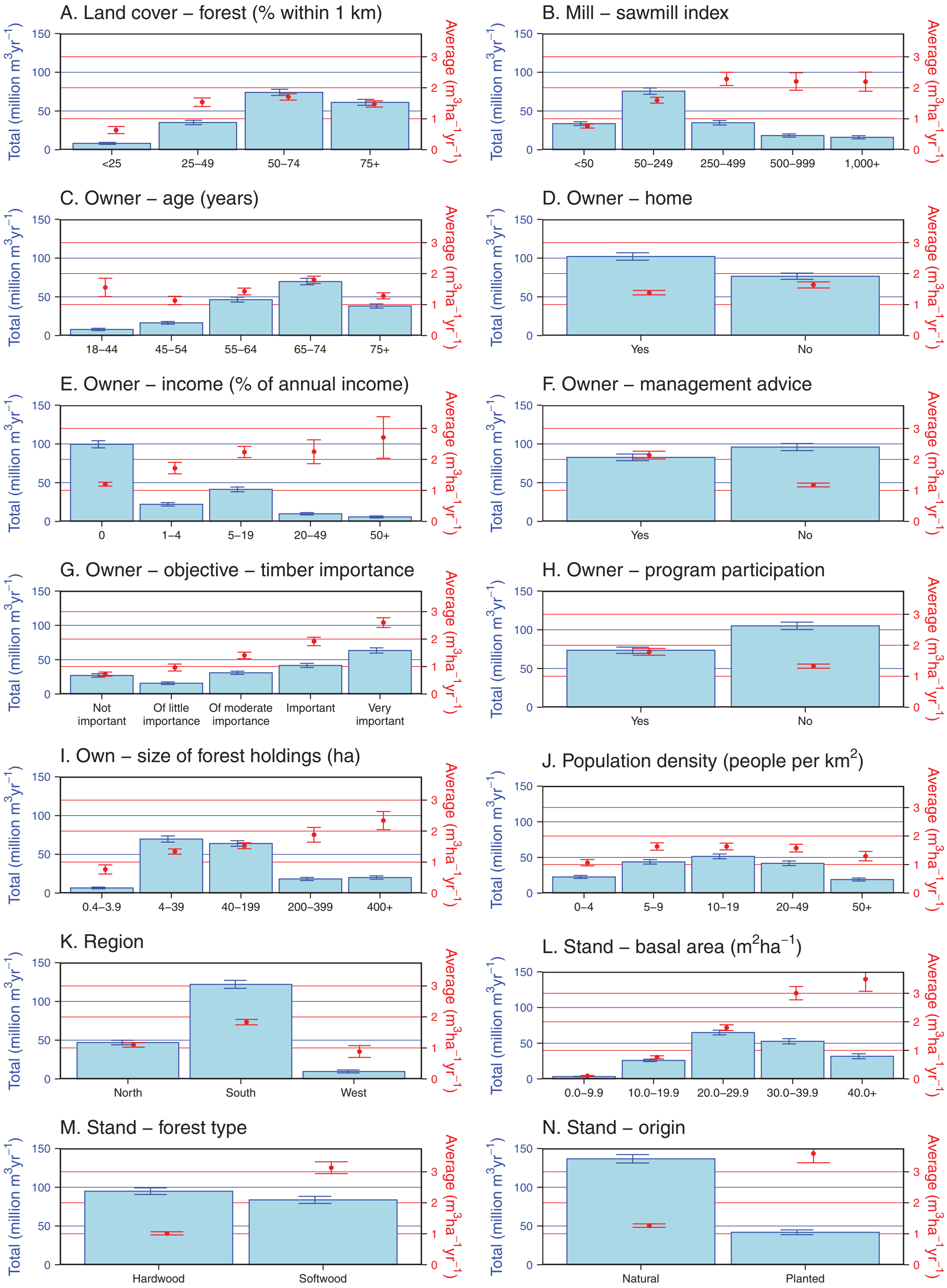

Figure 3. Volume (bars) and average per hectare (points) wood removals from family forests by selected variables, United States,* 2018. Error bars represent 95% confidence intervals. Variable descriptions and data sources are listed in Table 3.* Excluding Alaska, Hawaii, Idaho, Nevada, New Mexico, Texas, Washington, and Wyoming due to unavailability of removals or mill data.

Logistic Regression Model

There are 3,182 records in the final model dataset used for the logistic regression family forest harvesting model. The reduction in number of records is due to a limited number of landowner survey responses associated with the plots and, to a lesser extent, missing data for other variables. Of the records in the final model dataset, 343 (11%) are identified as harvested (HRV = 1) and 2,839 (89%) are identified as nonharvested (HRV = 0).

The logistic regression model has adequate fit according to the Hosmer-Lemeshow test and has a Tjur's R^2 of 0.14. Examination of the ROC curve and AUC

(0.76) suggest that the model has adequate discrimination power.

Of the sixteen variables included in the model, nine variables plus the intercept are significant at the 0.05 level and two additional variables are significant at the 0.10 level (Table 4). The sawmill index variable, MILL_SAW, is divided by 1,000 to make the odds ratio easier to interpret. Significant ($p \leq 0.05$) variables positively associated with family forest timber harvesting include the stand type being softwood, the stand origin being planted, stand basal area, remeasurement period, forestland income, having timber as an ownership objective, greater sawmill influence, and having received forest management advice. The plot being located in the West (with the North as the reference level) is the only variable that is significant and negatively associated with timber harvesting. In addition, the plot being located in the southern United States is marginally ($p = 0.07$) and positively associated with harvesting, and having their home near their forestland is marginally significant ($p = 0.09$) and negatively associated.

Owner age, population density, forest land cover, being enrolled in a program, and size of forest holding are, *ceteris paribus*, not significant ($p \geq 0.10$) in the model.

The effect sizes are challenging to compare due to the mix of continuous and categorical variables. Although the odds ratio of 1.04 for basal area is quite close to 1.0, this is a continuous variable, and the odds ratio is for every unit (m^2ha^{-1}) increase in basal area, so for every one unit increase in basal area the probability of harvesting increases by 4%, *ceteris paribus*, or for a basal area increase of 10 m^2ha^{-1}, the probability of harvesting increases by 40%. Stand forest type and origin also have substantial influences in the model with odds ratios of 2.4 and 2.0, respectively, meaning that softwood stands are 2.4 times more likely to be harvested than hardwood stands and planted stands are 2.0 times more likely to be harvested than naturally regenerated stands. A plot being in the West is a significant negative factor, with these plots being 80% less likely to be harvested than those in the reference region, the North.

Discussion

Wood removals differ substantially across ownership groups (figure 2) related to differences in ownership/management objectives, applicable policies and other legal constraints, and the underlying conditions created by biophysical and economic environments. Most wood removals in the United States (88% across the forty-four states included in this analysis) come from private forests. In general, corporate forest owners have a strong focus on profit maximization and consequently tend to most intensively manage their forestland and concentrate their land holdings in regions that are most conducive for industrial wood production (e.g., the southern and Pacific Coast regions of the United States).

Despite the importance of family forests for wood supply, collectively they contribute 42% of the harvest removals across the forty-four states included in this analysis, and many studies looking at their attitudes and behaviors related to it (Silver et al. 2015), there is still much that is not understood, or at least much that is not captured in the published models. One shortcoming of many studies has been a focus on harvesting intentions instead of observed harvesting behavior (Silver et al. 2015). The combination of biophysical and social data, as in this study, helps to overcome this issue.

As in all analyses, how variables are defined is important and the definition of a "timber harvest" can be surprisingly difficult to capture. For empirical studies, remeasurement data, such as the FIA plot data used here, offer some of the best opportunities to identify removals. When properly implemented and analyzed, these data can unequivocally assess what has been removed, but ultimately the reasons for why a tree was removed cannot be discerned by looking only at biophysical evidence. The observed removals can be for firewood (for personal use or sale), sale to a sawmill, sale to a pulp or pellet mill, or a combination thereof and indeed the owner, forester, or logger may never know the ultimate destination. Although not a panacea, a mixed methods approach explicitly examining timber harvesting can help to disambiguate the reasons for removals by combining plot inventories with surveys of owners/managers.

Given the data, definitions, and analyses used in this article, biophysical, social, and economic factors are shown to have substantial associations with timber harvesting by family forest owners in the United States. Many of the most powerful variables are biophysical, but it is important to note what influences these variables; for example, stand origin is the result of owner decisions, and it is similarly difficult to completely disentangle any of the variables. Basal area being an important predictor, as was shown in Thompson et al. (2017) and other studies, is related to the fact that as there is more wood in a stand, there is more potential for harvest. Biophysical factors, such as stand age and species composition, are at least in part also the result of ownership decisions. For example, nonindustrial private forest owners in North Carolina were found to harvest more than their corporate counterparts because they owned older stands that had more harvestable timber at the time (Prestemon and Wear 2000). There are also effects on the forest from legal structures (e.g., logging being largely prohibited in national parks [Miller et al. 2016]) and historical context that has allowed different ownership groups to hold forestland across varying geographies with varying site productivities (e.g., land dispossession of Tribal groups [Indian Forest Management Assessment Team 2013] and the dominance of federal ownership in the West [Vincent and Hanson 2020]).

The results from the bivariate analyses are not identical to those from the logistic regression model but they are largely mutually supporting. The most direct comparisons of the variables used in the analyses presented here are between the average removals per hectare statistics reported in the bivariate analyses and the logistic regression coefficients/odds ratios, because the logistic regression model data are for behaviors and other attributes associated with specific points on the ground. This convergence between the results is due in part to the same underlying data being used. The fact that not all of the significant bivariate relationships are significant in the logistic regression model is evidence of underlying relationships among many of the variables and part of the reasoning for conducting multivariable analyses. For example, the size of forest holdings, which has been found to be positively associated with timber harvesting across many studies (Silver et al. 2015), is not significant in the logistic regression model presented here, but it does show the expected relationships in the bivariate analysis.

Although the list of variables included in this analysis is relatively extensive (Table 3), there are many variables that are missing or could be quantified in different manners but were not due to data limitations or other reasons. One of the most obvious variables that is missing is stumpage price, which has been shown to be positively associated with harvesting in previous studies (Silver et al. 2015), because there are no national datasets available for these data in the United States. A mill index is included, but capacity and distance are only rough approximations for demand and do not include information about species suitability or other supply requirements (Anderson et al. 2011). Other than a positive relationship between stumpage prices and harvesting, it is difficult to predict the impact of including this variable on the results reported here. The model would most likely improve in terms of predictive power and the relationships for the other variables should hold, given the results from previous studies, but this would need to be empirically tested. Relatedly, incorporating more information about species and characteristics of trees at t_0 and trees removed could be useful.

Two potentially important concepts that are not incorporated in this analysis nor, to our knowledge, in previous studies, are direct measures of knowledge or information levels related to harvesting and the proximal causes for harvesting. The large influence of forest management advice, with an odds ratio of 1.5 in the model presented here (Table 4), is strong support for the importance of knowledge, be it direct or indirect, and there are likely differences depending on the source of the information that was not tested here. Even if stumpage prices were incorporated, what likely matters more is what the owners are offered or know about the value of their timber and how this amount fulfills their needs and desires. Conceivably, there are information imbalances between professionals (e.g., loggers and foresters) and lay people (e.g., landowners) that can influence how decisions are made and where benefits accrue. Likewise, a given amount of money may mean different things to different people and even different things to the same person at different times. There have been few, if any, studies looking at the specific reasons why harvests occur, although there is substantive anecdotal information related to life events, be they retirement, health care expenses, college payments, or large purchases, such as a new vehicle.

The impacts of policies and programs on family forest owner behaviors has been extensively studied (e.g., Kilgore et al. 2015), but the actual impacts have often been difficult to discern (Andrejczyk et al. 2016), and the impact on timber harvesting has not been extensively studied. To address this issue, the tasks would be to identify those programs and policies that are directly (or indirectly) aimed at encouraging timber harvesting (e.g., Wisconsin's Managed Forest Law), identify/generalize program attributes, and implement appropriate assessment approaches. The long-term coupled plot and survey data collected by the FIA program could prove a very beneficial data source for these analyses, but there is a disconnect in that the survey data are for all of an owner's land and not specific for the given sample point. The long-term, in-depth approaches used by US National Science Foundation's Long-term Ecological Research sites and the Forest Service's Experimental Forests to study ecological processes are potential analogs for what could be done with the human dimensions of forestry. Although these approaches can be expensive and may take decades to prove their full worth, the long-term data should provide a wealth of unprecedented insights into the attitudes and behaviors of landowners. Indeed, there may be possibilities for coupling long-term ownership research with existing long-term ecological research networks.

A more immediate next step could be the development of regional models that incorporate more of a theoretical approach and more in terms of potential financial returns. Financial returns could bring in stumpage price data that are not nationally available, and additional work could be done to differentiate product mixes and mill requirements. This may also be an appropriate place to further explore the potential of segmentation analyses. Also, given the relatively low explanatory power of many individual choice harvesting models, there may be advantages, at least in terms of predictive power, of modeling aggregate timber supply. Aggregate behavior will be challenging to examine due to currently available data sources and harvesting being relatively rare detection events, but new data sources related to harvesting (e.g., Healey et al. 2022) and ownership distributions (e.g., Harris et al. 2021) will help to address this challenge.

The results of this and other wood supply studies have important implications for policies, programs, and services that affect family forests and the benefits derived from these forests. In terms of industrial timber supply, the results help explain where the wood is coming from and provide insights into future supplies with results potentially incorporated into projection models, such as those used by the Renewable Resource Planning Act Assessment (Wear et al. 2013). The results can also lead to more informed policies that are aimed at changing or maintaining harvesting levels. This could be in terms of the more traditional goals of maintaining a flow of timber or related to the deferred harvests or other harvest-related activities associated with the proliferation of carbon sequestration programs (Sharma and Kreye 2022). Of the variables that can be most directly influenced by policy, the relationship between increased harvesting and softwood stands, planted stands, and management advice may be of most interest. Policies that encourage these activities would likely increase harvesting rates. In addition, harvesting is often necessary to meet other objectives, such as wildfire hazard reduction or wildlife habitat creation, and these too should be considered when designing programs aimed at influenced harvesting or other forest management practices.

Although the focus of this article is on the United States, there are potential implications and comparisons with other countries, particularly those that have similar ownership patterns and substantial proportions of family forest ownership. This includes many European, especially Nordic, countries, and the Canadian Maritime Provinces. Indeed cross-fertilization is occurring; for example, comparisons between the United States and Sweden (Fischer et al. 2010) and comparisons across approaches being used to segment owners (Ficko et al. 2017). Although the specific policy environments differ, many of the psychological and demographic factors appear to be similar, and all of the models still struggle to capture a majority of the variance. Accountancy networks pioneered in German and Austria (e.g., Toscani and Sekot 2018) provide detailed information on labor and other costs and profits associated with forest ownership. The potential pairing of the financial details accruing from an accountancy network paired with inventory data and attitudinal information could prove very powerful.

An innovation of this article is the novel merging of biophysical, social, and economic data sources, namely the USDA Forest Service FIA plot, survey, and mill data. Although these data sources are all collected under the auspices of the FIA program, they have been largely siloed. By combining these data, issues related to timber harvesting can be addressed, as can myriad other questions, such as the efficacy of landowner assistance programs. One downside of linking these data sources is the reduction in sample sizes, specifically due to the limited number of responses for the ownership survey. This could be addressed by increasing the sample size for the ownership survey, working on efforts to increase response rates, or developing data interpolation approaches. Another limitation is the confidentiality of information that disallows public sharing of full datasets; however, the datasets are available to analysts within the FIA program and summaries or models can be generated for those outside the program. It may also be possible to create publicly accessible, linkable versions of the data that are securely available via future tools that can facilitate data exploration without the need for exposing confidential or sensitive data.

Family forests of the United States provide copious ecosystem services, including an immense amount of wood, which accounts for 42% of the harvest removals from the forty-four states analyzed. The demand for this wood is high and will likely increase, especially as wood-based engineered products, such as cross-laminated timber, gain acceptance as substitutes for more energy-intensive materials (Kuzmanovska et al. 2018), but there are also increasing demands for additional sequestration of forest carbon (Richards and Huebner 2012). The United States has relatively strong environmental regulations regarding forestland and forestry operations (Cubbage et al. 2020) and wood that is not harvested within the country may come from areas with fewer protections (Berlik et al. 2002). This means that US family forests will continue to play a critical role in wood supply and the countless other ecosystems services these forests provide.

The forestry sector has long been concerned with the flow of timber from America's family forests (Straka 2011). Indeed, there have been historical shifts in where wood has come from both in terms of geography and ownership. The southern United States has long been the major timber supplier in the country, and most of these lands are privately owned, with a substantial percentage being family forests. The reduction in timber harvesting from federal forests, particularly in the Pacific Northwest after the Northwest Forest Plan, places additional importance on private lands. The southern United States has a number of biophysical advantages, including longer growing seasons, that allow for shorter harvest rotations and, coupled with improved growing stock and management practices (Fox et al. 2007), increased potential for profits. The ultimate profit an owner earns is a function of market conditions, location of the land, forest management practices, knowledge, and other factors.

Conclusions

Overall, the results of this study are consistent with past research (e.g., Floress et al. 2019; Silver 2015; Thompson et al. 2017), but we were able to produce population-level estimates and empirically examine harvesting behavior while covering a wider geography and incorporating a broader set of variables from a novel combination of data, including biophysical, social, and economics elements. However, there is still much that is unknown in terms of understanding (and predicting) family forest owner behavior. There is need for a theoretical framework that can be operationalized to better understand these behavioral dynamics. Issues related to imperfect information (and constrained rationality), how nonforest-related needs (e.g., paying for education, health care, and other expenses) influence decisions, the perceptions related to the "maturity" of timber, and other factors should be considered. Many of these factors may need different investigation approaches than have been traditionally used, for example, qualitative or mixed methods approaches.

The dynamics of wood production are relevant economically and ecologically, both currently and regarding future sustainability. Family forests have proven to be a reliable timber source despite, or maybe because of, their diversity. Consequently, a logical goal of policies aimed at maintaining the supply of wood and other ecosystem services from family forests could be to keep family forests as family forests through conservation easements (Vizek and Nielsen-Pincus 2017), efforts that facilitate the intergenerational transfer of land (Bell et al. 2019), and other conservation-oriented programs (Mitani and Lindhjem 2022). Although many of the indicators of sustainability for family forests are positive, the metrics related to keeping forests as forests are negative (Butler et al. 2022a); this is disheartening and deserves further attention in terms of policies, programs, and research.

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Author Contributions

BJB: Conceptualization, methodology, formal analysis, writing, supervision, and funding acquisition; EMS: methodology and writing.

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Conflict of Interest

The authors have no conflicts of interest to declare.

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