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Forest landowner harvest decisions in a new era of conservation stewardship and changing markets in Maine, USA

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ABSTRACT

Forest managers and policymakers across the globe are continually exploring ways to better understand how various socio-economic conditions and shocks can influence timber supply. In this paper, we develop a statistical harvest choice model for the state of Maine, a historically important timber supply region in North America. Landowner-level timber harvest choices were estimated using a multinomial logit model of two products (sawlogs and pulplogs), under varying management intensities (partial harvest, clearcut), and ownership classifications (public, private, conservation) across varying market conditions. Results indicate that stumpage prices have a significant effect on forest landowners' harvest decisions, regardless of the ownership classification or harvest intensity. Timber supply is positive and inelastic with respect to stumpage price, with state-level own-price elasticities ranging from 0.27–0.31 for sawlogs and 0.43–0.73 for pulplogs, with elasticities increasing with harvest intensity. Simulations that increase the proportion of forest designated as private conservation estimated that doing so could reduce Maine's total timber supply by 2%, although the level of sawlog harvests could increase by 0.5% as conservation landowners supplement their non-timber objectives with higher value wood. Our approach to modeling the complex timber harvesting patterns across a diverse array of both private, public, and conservation owners can be leveraged to inform policies focused on sustainable timber flows. Furthermore, it indicates that increases in conservation forestland area does not necessarily lead to large reductions in timber harvests, particularly in a state like Maine where most conservation land is still managed as working forest.

1. Introduction

Forest managers and policymakers across the globe are continually exploring ways to better understand how various socio-economic and biophysical shocks can impact timber supply and associated impacts to the forest sector, especially under changing conditions like species distribution, evolving markets, and ownership classification. This is particularly the case in the state of Maine, USA, which contains over 7 million ha of forest land covering approximately 89% of the land area in the state. From 1997 to 2007, Maine's harvest area was relatively stable at approximately 200,000 ha per year, with the annual harvest volume totaling nearly 6.8 million metric dry tons. Over the past decade though, the harvest area has steadily declined due to changing market conditions. In 2017, only resulting 135,000 ha were harvested, resulting in about 5.6 million metric dry tons of timber (Maine Forest Service, 2018a). About 89% of the state's forestland is currently privately owned, with 59% and 32% controlled by corporate and family owners, respectively (Butler, 2018). Corporate owners harvest about 65% of total volume, while family forests contribute about 29% (Butler, 2017).

The forest product industry comprises a noticeable portion of Maine's economy, accounting for nearly 5% of the state's gross domestic product (MFPC, 2016). Recent changes in the forest products industry, particularly due to advanced technology and changing demand over the past decade, have resulted in the closure of several pulp and paper mills, thereby reducing the total economic impact of the industry by several hundred million dollars, with a concurrent loss of thousands of forest and manufacturing jobs. The aggregate market loss for the sector over recent years poses a challenge to the entire supply chain, raising concerns among landowners and industry stakeholders about the future economic outlook of the forest products industry. Despite this, forest industry leaders and policymakers have recently developed an initiative to grow state's forest products sector by 40% 2025 (FOR/Maine, 2018). However, it is still uncertain whether current and emerging economic and social conditions will adequately incentivize Maine's forestland owners to harvest the amount of timber required to achieve this goal.

Forest policies can have dramatic impacts on the way forests are managed. Regulations and incentives are often applied to motivate

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landowners to manage their woodlands (Wagner et al., 1994; Gregory et al., 2003). After World War II, timber harvesting increased sharply to meet the domestic demand for construction lumber. The widespread use of clearcutting and other environmental concerns associated with logging resulted in several laws to protect forests. Maine's government recognized the necessity for sustained timber yields and to provide incentives for landowners not to sell land for residential or commercial development. In that case, the Maine Tree Growth Tax Law (TGTL) was enacted. This law changed taxation of forestland from an ad valorem tax to current use value. The TGTL successfully achieved its objective of keeping land in forest production: over 4.4 million ha were enrolled in the program and landowners enrolled had a higher harvest intensity than non-enrollees (MFS, 2014). Another key policy implemented in Maine was the 1989 Forest Practices Act (FPA), which put constraints on clearcuts. These constraints resulted in partial cuts comprising about 95% of harvests in the state, down from around 50% in the 1980s (Maine Forest Service, 2018b). The relatively restrictive nature of the policy led to amendments to the FPA that allow qualified landowners to implement outcome based forestry (OBF) that focuses on targeting a wider suite of management objectives. However, only a handful of landowners in Maine have been permitted to adopt OBF to date, and thus the overall outcome of the policy remains to be seen.

Changing public attitudes towards recreation and forest ecosystems, including concerns over habitat and wildlife loss, water quality, and climate change have encouraged forest owners to broaden their management objectives to encompass multiple goals, (i.e., non-timber outputs). Starting in the 1990s, the corporate landowner type in Maine has shifted from the more fully integrated timber product industry companies to private investment firms and conservation groups with a somewhat different objectives (Hagan et al., 2005). Conservation initiatives on state and private land have greatly expanded through the purchase of development rights via conservation easements and simple fee acquisition (Irland, 2018). As of 2018, about 21% of Maine's land is conserved, with a majority of this held privately in the form of fee or easements (MEGIS, 2019). In addition, while land trusts hold approximately 1 million ha of land in Maine, approximately 85% of conserved lands are managed as working forests (MLTN, 2017). Thus, current forest management not only focuses on fiber production, but also has evolved towards non-timber uses including the provision of ecosystem services. Furthermore, both federal and state governments have been subsidizing and encouraging investment in forestry to promote the production of ecosystem services (Kilgore et al., 2018). In the context of this paper, any public and private forestland that is designated as “conserved” is still likely to be harvested, as most conservation land in Maine still retains timber harvest rights.

There is concern that the transfer of industrial forests to Timber Investment Management Organizations (TIMOs) and Real Estate Investment Trusts (REITs) could lead to noticeable changes in harvest regimes that could transform the structure and dynamics of Maine's forests (Daigle et al., 2012; Jin and Sader, 2006; Legaard et al., 2015). Between 1980 and 2005, vertically structured timber or wood products companies divested approximately 4 million ha. Industrial ownership harvested the highest percentage of forest in the 1980s, while TIMOs harvested a higher percentage of forests in the 1990s and early 2000s. Non-Industrial Private Forest (NIPF) landowners have had more stable ownership and more consistent and intermediate harvest rates through time when compared to the commercial landowners (Daigle et al., 2012). Forestland that experienced no ownership change had significantly lower harvest rates than land that changed ownership between 1994 and 2000 (Jin and Sader, 2006). Recently, Kuehne et al. (2019) assessed timber harvest patterns in Maine and suggested that harvesting in the state might be less opportunistic and short-term driven than generally perceived, but they did not include key factors like conservation status and market prices.

The purpose of this paper is to develop and analyze a multi-period, multi-type harvest choice model for Maine that includes mixed characteristics such as stand type, ownership type, site location, stumpage price, and other key factors. To achieve this, we construct a multinomial logit model that is consistent with other harvest analyses conducted at a similar spatial and temporal scale (Beach et al., 2005; Silver et al., 2015), but many of these prior analyses often only focused on a particular landowner type or ignored market factors. Overall, the model developed in this analysis estimates partial and clear-cut harvest probabilities observed at the stand-level with more than 9000 observations across a 15-year period, 2002–2016, which covers a wide array of market conditions and shifts in conservation status not previously addressed in prior analyses. From this model, we were then able to estimate the potential plot-level timber supply response across the state under various economic and land ownership conditions by coupling predicted harvest probabilities with currently available inventory data.

This research expands the existing literature on timber harvest choice modeling in several ways. First, we use regional-level data to control for local effects such as stumpage and demand. Second, we estimate the influences on decisions for both partial and full harvests of both sawlogs and pulplogs. Third, we specifically control for timber harvested from conserved land, which is the most rapidly growing forestland ownership in Maine (Meyer et al., 2014). Fourth, we account for the fair market value of timberland, which along with the designation of conservation land allows us to account for the potential non-timber values and development pressures accrued by the landowner by keeping their timberland as working forest.

This paper is organized as follows. First, we present a review of the literature that outlines the various methods that have been used to assess landowner timber harvest behavior. Next, we describe the methodology and data for our specific harvest choice model. Third, we present the results of our analysis of partial and clear-cut harvest choice in Maine across different product and ownership classes. Fourth, we extend our model to estimate the changes in future harvest supply under varying conditions. We then conclude the paper with a synthesis of our findings and suggestions for future research.

2. Literature review

Extensive research exists on identifying the key drivers of harvest decision making (see Beach et al., 2005; Silver et al., 2015 for detailed reviews of the literature). More recent publications that were not included in previous reviews are summarized in Table 1. Many of the assessments use a utility maximization framework, typically including two-period models (e.g., Prestemon and Wear, 2000; Polyakov et al., 2010). The empirical models used in these studies vary widely. For example, (Dennis, 1989) use a Tobit model to measure the quantity of timber harvested, Prestemon and Wear (2000) applied probit analysis to estimate a probability of harvest model with the dichotomous dependent variable, and Polyakov et al. (2010) built a conditional logit model to estimate landowners' harvest choice with different forest types for seven states. More recently, Zhang et al. (2015) evaluated three harvest choices using a multinomial logit model, while Canham et al. (2013) and Thompson et al. (2017) both used an exponential model to describe regional harvest probability. Biophysical factors such as available timber volume and parcel size have been demonstrated to be reliable predictors of harvest (Silver et al., 2015). However social factors are more complex and harder quantify because they are often mixtures of economic, amenity, and policy influences (Thompson et al., 2017).

Most studies indicate that harvest behaviors are generally consistent with economic theory and can be predicted with some degree of statistical significance (Polyakov et al., 2010), which can be used to explore the direct effects of stumpage price on harvest decisions. For example, Beach et al.'s (2005) meta-analysis expected an increased timber price would incentivize more silvicultural activities, but found that market prices overall are not always statistically significant.

Table 1
Summary of relevant harvest choice studies published since Silver et al. (2015) and Beach et al. (2005) literature summaries.

Study	Study Area	Study population	Methods	Key variables	Key findings
Brown et al. (2018)	Northeast USA	Forestland owners	Logistic regression model	Population density, forest type, basal area, distance to nearest road, land protection status, parcel size.	Distance to the nearest improved road explained the harvest probability. Local population density and parcel size have no effect on harvest frequency, the harvest frequency was predicted to be slightly lower on easement lands.
Thompson et al. (2017)	Northeast USA	Public, corporate, private owners	Logistic regression model	Population density, average household income, forest type, basal area, property size, education, income. Stumpage price, distance from site to road.	Annual harvest probability on privately owned forests double that of publicly owned forests. Population density, household income, and distance to a road help explain harvest intensity but not harvest frequency.
Kittredge (2004)	Massachusetts, USA	Public and private landowners	Exponential model	Median home price, road density, population density, distance to metro center.	Probability of private harvest is most strongly and consistently estimated by affluence and proximity to urban development. Probability of public harvest does not have consistent predictor
Kittredge and Thompson (2016)	Massachusetts, USA	NIPF	Granger causality	Median and maximum stumpage Price.	Harvest decisions primarily influenced by stumpage price under some circumstances.
Zhang et al. (2015)	South USA	NIPF, Industry, TIMOs, REITs	MNL	Stumpage value, distance to road, coastal plain, growth volume.	Harvest frequency increases with stand volume and stumpage price.
Petucco et al. (2015)	France	NIPF	Logistic regression model	Management priorities, demographic, market and policy.	Landowners' management priorities significantly affect the decision of harvesting. Amenities-oriented owners significantly reduced the probability of harvesting. Economic variables were significant predictors of the harvesting decision.
Fortin et al. (2019)	France	Public and private landowners	Conditional probability model	Several economic and social factors.	Stumpage prices positively similarly affect harvesting decision on both private and public lands, but impact is species dependent. Managed private lands exhibited similar harvest occurrences as on public lands.

Kittredge and Thompson (2016) used the notion of Granger causality to analyze the relationship between harvest activity and timber price for NIPFs in Massachusetts, USA, and found that stumpage prices could affected the harvesting decisions of landowners in the red oak (*Quercus rubra* L.) stands located west of the Connecticut River, USA. Dennis (1989) illustrated that the ambiguous effect of stumpage price on timber harvesting may be due to the opposite influences of the substitution and income effect, as well as the variable error problem that the price indices may fail to accurately measure the price offered to a landowner. Recently, Prestemon and Wear (2000) and Zhang et al. (2015) used the timber value to replace the timber price and found that timber harvest probability was positively correlated with present timber value and negatively correlated with future timber value.

Cost factors such as harvesting, transportation, and replanting might also influence landowners' harvest decisions (Beach et al., 2005). The distance from a harvest site to its nearest road is typically used as a cost factor, because it affects the operational logistics and transport costs, and thus may influence the landowners' harvest decision (Kline et al., 2004). For example, Prestemon and Wear (2000) found that the distance of the stand from the road has a negative impact on harvest probabilities. Likewise, Silver et al. (2015) found the distance from residence was negatively correlated with harvest activities. Donahoe et al. (2013) found that forest stand value and ownership were key drivers of stand removals, and the proximity to mills explained some variance, but their overall contributions to the model fitting were relatively minor. Thompson et al. (2017) also found that the distance from roads is a significant predictor of harvest probability. They concluded that ownership class is a powerful predictor of harvest behavior, with harvest intensity increasing with distance to the nearest road, while demographic data about landowners (e.g., age, education attainment, retired status) had a limited relationship on harvest behavior. However, Silver et al. (2015) concluded from a review of 129 NIPF harvest studies that landowners' educational attainment was positively correlated with their intention to harvest, while absentee ownership and age were negatively correlated with the harvest intention.

Landowners' characteristics may also influence their activities. Both Thompson et al. (2017) and Kittredge (2004) found the harvest behavior of private woodland owners were unpredictable, and suggested that family owners were satisfied with the amenity benefits provided by their land until they were influenced by external stimuli or unplanned financial needs. In fact, the harvest probability of privately-owned forest was twice that of publicly-owned forest (except for municipally owned lands), while the harvest probability on corporate-owned land was 25% higher than on private woodlands and about 3.5 times larger than on federal lands (Thompson et al., 2017). Therefore, changes in ownership would likely bring changes in harvest behavior. Few studies have investigated the effect of shifts of privately-owned forestland into "conservation" status. Furthermore, most harvest choice studies focus on clearcutting (i.e., full harvest) decisions as opposed to a mix of harvest options, including partial removal of varying grades of mixed species fiber (e.g., softwood pulplogs vs. sawlogs).

The wide variation in approaches and data reviewed here highlight that there is not a single model framework, sample population, or outcome variable that can be applied to develop a harvest choice model. We build upon this finding to describe our specific methodology in the following section.

3. Materials and methods

3.1. Theoretical model

Forest landowners' objectives comprise a mix of marketable timber products and non-market values such as aesthetic values and other ecosystem services. We hypothesize that Maine landowners are more likely to maximize utility than profitability, which is consistent with state landowner surveys (e.g., Acheson and Doak, 2009; Butler, 2017) and many studies summarized in our literature review. This suggests employing a utility maximization framework to analyze the management decisions of landowners in the state (Dennis, 1989; Hyberg and Holthausen, 1989; Pattanayak et al., 2002; Petucco et al., 2015). As a result, we use a random utility model as the theoretical foundation of the multinomial logit (MNL) model, which allows us to analyze multiple choice behavior. Furthermore, the MNL is an appropriate method to apply to Maine's forest landowners for the following reasons. First, landowners can choose to harvest over a range of intensities, not just no harvest or clearcut. Second, the MNL is a simple extension of binary logistic regression that allows for more than two categories of the dependent or outcome variable. Third, the method has fewer pre-required assumptions than many other statistical models (e.g., normality, linearity, or homoscedasticity).

The general landowners' utility (U_{ist}) can be decomposed into an observable component ($\beta' X_{ist}$, $\beta' Y_{ist}$, $\beta' Z_{ist}$ and an unobservable component or random term (ε_{ist}), which is assumed to be independent and identically distributed by the type 1 extreme value distribution (McFadden, 1973), where βs are parameter estimates, X_{ist} are vectors of market factors, Y_{ist} are vectors of biophysical characteristics, and $Z_{ist}$are vectors of other social factors. A landowner faces a choice set with i alternatives ($i = 1, \ldots, I$; $with I \geq$ 2.Each choice i will lead to a certain level of utility U for decision maker for each plot s and time t:

$$U_{ist} = \beta' X_{ist} + \beta' Y_{ist} + \beta' Z_{ist} + \varepsilon_{ist} \tag{1}$$

Following (Max and Lehman, 1988), we assume that landowners will maximize their present utility of consumption (C) during the current (t) and future ($t + 1$) periods. However, the landowner's consumption is constrained by the total timber revenue plus exogenous income not related to forestry. The landowner's budget constraints can thus be written as:

$$C_t \leq P_t Q_t + E_t - S \tag{2}$$

$$C_{t+1} \leq P_{t+1} Q_{t+1} + E_{t+1} + (1 + r)S \tag{3}$$

where, P_t is stumpage price in period t, $Q_t$is the removal volume of timber, S represents net savings, and E_t is the exogenous income, such as a salaried job, self-employment, or financial investment.

Landowners are assumed to be rational utility maximizing agents, and thus choose to harvest when the net benefits of harvesting their timber surpass the net benefits of delaying harvest where$U_i > U_j$,$where j \neq i$. In this paper, i and j are denoted as the multiple management decisions – i.e., none (0% removal = 0), partial (1–70% = 1) and full (70–100% = 2) – that define the choice probability of a landowner's harvest decision:

$$Pr(i) = Prob(U_i > U_j \; \forall \, j \neq i)$$

$$Prob(\beta' X_i + \beta' Y_i + \beta' Z_i + \varepsilon_i > \beta' X_j + \beta' Y_j + \beta' Z_j + \varepsilon_j)$$

$$Prob(u_i(X, Y, Z) - u_j(X, Y, Z) > \varepsilon_i - \varepsilon_j) \tag{4}$$

The probability of harvest choice i can then be estimated using a MNL, where β is the vector of coefficients and F(.) is the logistic cumulative distribution function (CDF):

$$Pr(i) = F(\beta'(X, Y, Z)) + \varepsilon \tag{5}$$

Following this, let j be an outcome variable that can take on possible decisions i and $j = 0$ (i.e, no harvest) be the reference value, with a collection of independent predictor variables X, Y, Z (e.g., stumpage price, growing stock, site location). The multinomial probabilities of each outcome value are then specified as:

$$Pr(j \mid x, y, z) = \frac{exp(\beta' X_{jst} + \beta' Y_{jst} + \beta' Z_{jst})}{\sum_j^i exp(\beta' X_{ist} + \beta' Y_{ist} + \beta' Z_{ist})} j \in \{0, 1, 2\},\ i = \{0, 1, 2\} \tag{6}$$

$$exp \frac{(u_j(X, Y, Z) \mid)}{\sum_j^i exp} \tag{7}$$

The model parameters β_1', β_2' for partial and fully harvests are then computed using the maximum likelihood estimation with the log likelihood function presented in Eq. (8), where s is the number of observation plots, and i is the harvest choice for each plot.

$$= \sum_{j=1}^{I} \sum_{s=1}^{S} log(pr_{is} \,||) \tag{8}$$

This log-likelihood function ensures that the predicted choice probability is highest for the chosen harvest activity$j$.

3.2. Empirical model

We modify the theoretical utility maximization framework to develop a functional empirical harvest choice model that is parameterized using a combination of plot- and region-specific characteristics. Plot-level measurements are provided by the Forest Inventory and Analysis (FIA) Program of the U.S. Forest Service, which every stand is measured approximately every 5 years (more details in section 3.4). Benefits accrued by the landowner are a function of management decisions, stumpage prices, and observable attributes of the stand such as growing stock biomass and site characteristics that affect growth, non-timber utilities, and management costs. Rewriting the elements of Eq. (1), the benefits of each choice i can be expressed as,

$$maxU = U_{non}(sd) + P_t + V - \varphi(Z) + \varepsilon \tag{9}$$

where non-timber utility (U_{non} is denoted as the standing volume (sd), P is the vector of prices of different timber product (sawlog, pulplog), V is the initial stand volume differentiated by timber product, Z is a group of site variables that affect the growth rate and harvest costs, and ε is the associated error term. Given this, Eq. (6) can be mathematically expressed as:

$$\begin{aligned} maxU_{p,s} = {} & \beta_0 + \beta_1 * PriceSaw_{county} + \beta_2 PricePulp_{county} + \beta_3 * LagBio + \beta_4 \\ & * BioTot \vee Bio_{pulpLD} + \beta_5 PostGrowth_{p,s} + \beta_6 PostGrowth_{p,s}^2 + \beta_7 \\ & * Mills_{p,s} + \beta_8 LandValue + \beta_9 * County + \beta_{10} \\ & * HighwayDist + \beta_{11} * Conservation + \beta_{12} * Elevation + \beta_{13} \\ & * Year + \varepsilon \end{aligned} \tag{10}$$

where *PriceSaw* and *PricePulp* are sawlog and pulplog stumpage prices, LagBio is the amount of standing biomass on the stand in the previous period, *BioTot* is the total standing biomass on the stand in the current period (t ha^{-1}), Bio_{pulpLD} is the standing biomass on the stand except sawlogs (t ha^{-1}), *PostGrowth* is biomass growth between periods (t ha^{-1} yr^{-1}), *Mills* is the number of mills within a specific buffer around the plot, *LandValue* is the assessed forestland value ($ ha^{-1}), *County* is the respective Maine county, *HighwayDist* is the distance from the plot to a primary highway (km), *Conservation* is an indicator variable described the category of plot ownership status (0 = non-conservation; 1 = public conservation;, 2 = private conservation), *Elevation* is the elevation of the plot (m), and *Year* is the period that the plot was sampled.

The coefficients of the empirical multinomial logit model cannot be directly interpreted as the marginal effects of the independent variables on harvest decisions. Thus, we estimated average marginal effects to quantify explanatory variables' impacts on the harvesting decision, which are interpreted as the effect of a one unit change in an explanatory variable on the probability of a landowner selecting a particular harvest choice using standard statistical methods. The estimated coefficients can also be used to compute response elasticities, measured as the percentage change in one variable that is associated with a one percentage change in another.

According to (Train, 2009), the elasticity of $Pr(i)$ with respect to x_i is calculated as:

$$E_{ix} = \beta_x x \tag{11}$$

where $x$is an explanatory variable of the utility derived from harvest activity i, β_x is the parameter estimate of x_i, $Pr()$ is the predicted choice probabilities for alternative harvest activities, and n is denoted as n$^{\text{th}}$ observation. The elasticities are then aggregated across all N observations following Ben-Akiva and Lerman (1985):

$$E_{ix_i} = \sum_1^N \tag{12}$$

The harvest, stand volume, and plot location probability estimates are then used to quantify the expected annual harvest volume of pulplogs and sawlogs under a range of conditions. Plot-level harvests are extended across the landscape using a Thiessen polygon method that combines the volume and spatial attributes of sampled plots to estimate the potential timber supply $Q_{kt,}$for k timber products in time period t. We then use a bootstrap procedure to randomly draw a sample size M from total N observations to calculate the various elasticities of interest.

State- and county-level harvest volumes were estimated via interpolation of the predicted individual stand harvest decisions and corresponding harvest intensities to account for all ~7 million ha of forested area in Maine. For stands with no harvest and fully harvested estimates, the harvest intensity is equal to 0 and 1, respectively. However, for stands that are partially harvested, the corresponding harvest intensity distribution is rightly skewed and censored. Thus, partially harvested stand intensities – which can range from 1 to 70% of total growing stock – are estimated using a Tobit model of initial stand volume, growing stock volume, stumpage price, and other site variables. The total harvest is then estimated by scaling up the individual plot-level estimates based on the area that each of the approximately 3000 plots represent, which is roughly 2400 ha/plot.

3.3. Model validation

We assess the validity of our model specification using a range of criteria. First, we compare the log likelihood value for the intercept only model to that of the final model with all independent variables using a likelihood ratio (LR) test. A greater amount of change between the two models suggests a greater improvement in model fit. The LR statistic was then transformed to McFadden's pseudo R^2 (McFadden, 1973), where estimates of 0.2 or higher are considered highly satisfactory (McFadden, 1977). Next, we use variance inflation factors (VIF) to test the multi-collinearity among the independent variables. In general, VIFs exceeding a value of 4 warrant further investigation, while those exceeding 10 indicate serious multicollinearity (Menard, 2002; Marquaridt, 1970). The correct classification rate (CCR) represents the percentage of correct predictions in our analysis. We thus use CCR and the Akaike Information Criterion (AIC) to further evaluate the model fit.

3.4. Data

Sawlog and pulplog growing stock and harvests are estimated on a green ton per hectare (t ha^{-1}) level using data from the U.S. Forest Service FIA program USDA Forest Service (2019), which consistently measures a spatially distributed base grid of forest inventory plots across the United States. Harvest activities are estimated at the plot-level, controlling for Maine's 16 counties that encompass four forest sector megaregions (Fig. 1). Approximately 20% of FIA plots are randomly re-measured in a given year such that the entire sample is measured within a 5-year cycle. As a result, we cluster our analysis into three periods: 2002–2006, 2007–2011, and 2012–2016. Each FIA plot is sampled three times over the 2002–2016 period for a total of nearly 9000 observations, although harvests did not necessarily occur at each of those plots over the study period (Table 2).

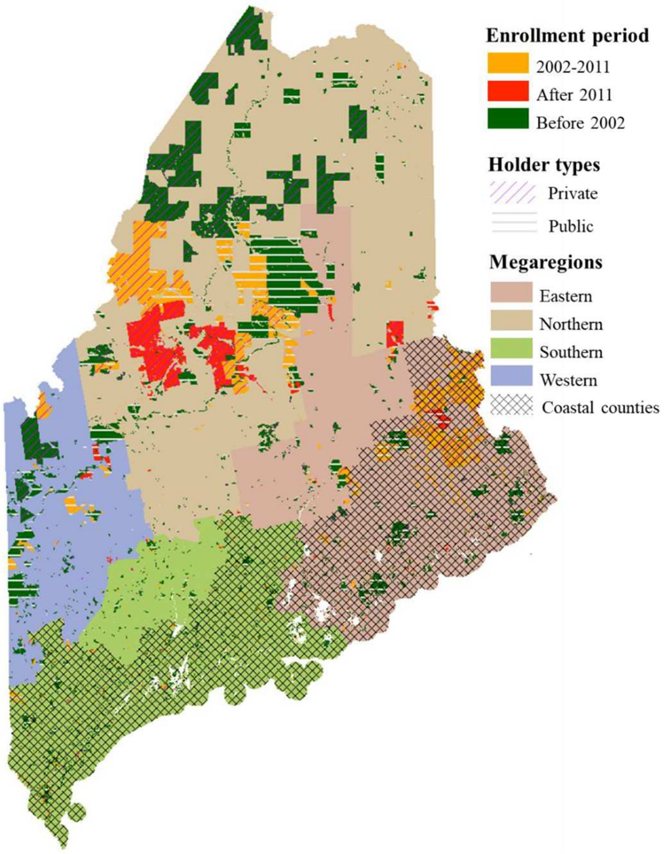

Fig. 1. Spatial location of Maine conservation lands as of 2018 by ownership type and enrollment period. Sources: FIA (2018) and Maine Office of GIS (2018).

The location and type of conservation (i.e., public, private) forestland and year of acquisition was accounted for using the Maine Conservation Land GIS database that is regularly updated (ME Office GIS, 2018). In 2018, this represented 21% of Maine's total forest area, with about half of that area enrolled as conservation since 2002 (Fig. 1). The conservation land ownership layer what then combined with the FIA plot data to establish that a total of 1621 observations in our dataset were designated as either public or private conserved forestland.

We estimated the harvest intensity of each plot by calculating the net removal of a given timber type relative to the total growing stock. In this analysis, we define a "full" harvest as the removal of 70% or more of merchantable timber on the site and a "partial" harvest as between 1% and 69%, which would include commercial thinning and multi-stage shelterwood harvests. We estimated both harvest choices separately for sawlogs and pulplogs. Data were compiled on removals by timber type, location, elevation, and other site characteristics for matched plots for each period, t. Growing stock volume functions were calculated by regression analysis of no-harvest activity plot records. The number of saw and pulp mills within a 50 km radius circle buffer served as a proxy for local demand (Anderson et al., 2011). Logging and transport costs was calculated as the minimum Euclidian distance from a state or national highway (Kline et al., 2004).

Stumpage prices were obtained from Maine Forest Service, 2018a, where annual prices vary by county, product, and species. We constructed county-level annual stumpage price indices for both sawlogs and pulplogs by calculating the weighted average price for each period included in the model. Real stumpage prices for every sampled stand were taken as the mean stumpage prices with deflated producer price index (setting the average producer price index of 2016 equal to 100). We also included prices of both timber types in each regression to

Table 2
Summary of Maine harvest choice model variables.

Variable	Description	Units	Source/Description	Mean/Number	Median	St Dev
$Choice_{saw}$	Harvest choices of sawlogs	–	FIA, change in sawlog biomass over 2 measurement periods	7732	n/a	n/a
	No harvest	–		5979	n/a	n/a
	Partial harvested	–		1404	n/a	n/a
	Full harvest	–		349	n/a	n/a
$Choice_{pulp}$	Harvest choices of pulplogs	–	FIA, change in pulplog biomass over 2 measurement periods	8051	n/a	n/a
	No harvest	–		6056	n/a	n/a
	Partial harvested	–		1685	n/a	n/a
	Full harvest	–		310	n/a	n/a
$PriceSaw_{County}$	Mean 5-year county-level price of sawlogs	$\$\ t^{-1}$	Maine Forest Service, 2018c	26	25	1
$PricePulp_{County}$	Mean 5-year county-level price of pulplogs	$\$\ t^{-1}$	Maine Forest Service, 2018c	9	9	0
$BioTot$	Aboveground biomass	$t\ ha^{-1}$	FIA, all aboveground biomass	122	116	7
Bio_{pulpLD}	Biomass of pulplogs and low-diameter wood	$t\ ha^{-1}$	FIA, all aboveground biomass except sawlogs	81	78	6
$PostGrowth_{saw}$	Growth volume of sawlogs after harvest	$t\ ha^{-1}\ yr^{-1}$	FIA, calculated from non-harvest plots	4	4	2
$PostGrowth_{pulp}$	Growth volume of pulplogs after harvest	$t\ ha^{-1}\ yr^{-1}$	FIA, calculated from non-harvest plots	7	8	2
$Mill_{saw}$	Number of saw mills within 50 km radius buffer	#	University of Maine	6	4	6
$Mill_{pulp}$	Number of pulp mills within 50 km radius buffer	#	University of Maine	0	1	1
$LandValue$	Average ad valorem value of forestland by municipality	$\$\ ha^{-1}$	Maine Revenue Service	10,362	1692	34,580
$Conservation$	Non-conserved	–	Maine Office of GIS	6430	n/a	n/a
	Private conservation lands	–		935	n/a	n/a
	Public conservation lands	–		686	n/a	n/a
$Elevation$	Elevation (meters)	m	Maine Office of GIS	239	204	170
$Coastal$	Coastal county = 1	–	Maine Office of GIS	1952	n/a	n/a
$HighwayDist$	Distance to national highway	km	U.S. Geological Survey, 2017	10	2	16

n/a = not applicable.

explore the potential complementary and substitution effects between the two products.

The appraised forest value for a given municipality or territory was tracked for each plot, which essentially estimates the fair market value of the land (Maine Revenue Service, 2018). This metric was included a both a proxy for landowners attitudes to both timber and non-timber values as well as the value of alternative land uses. In addition, we used county-level data to control for other local effects. All data and

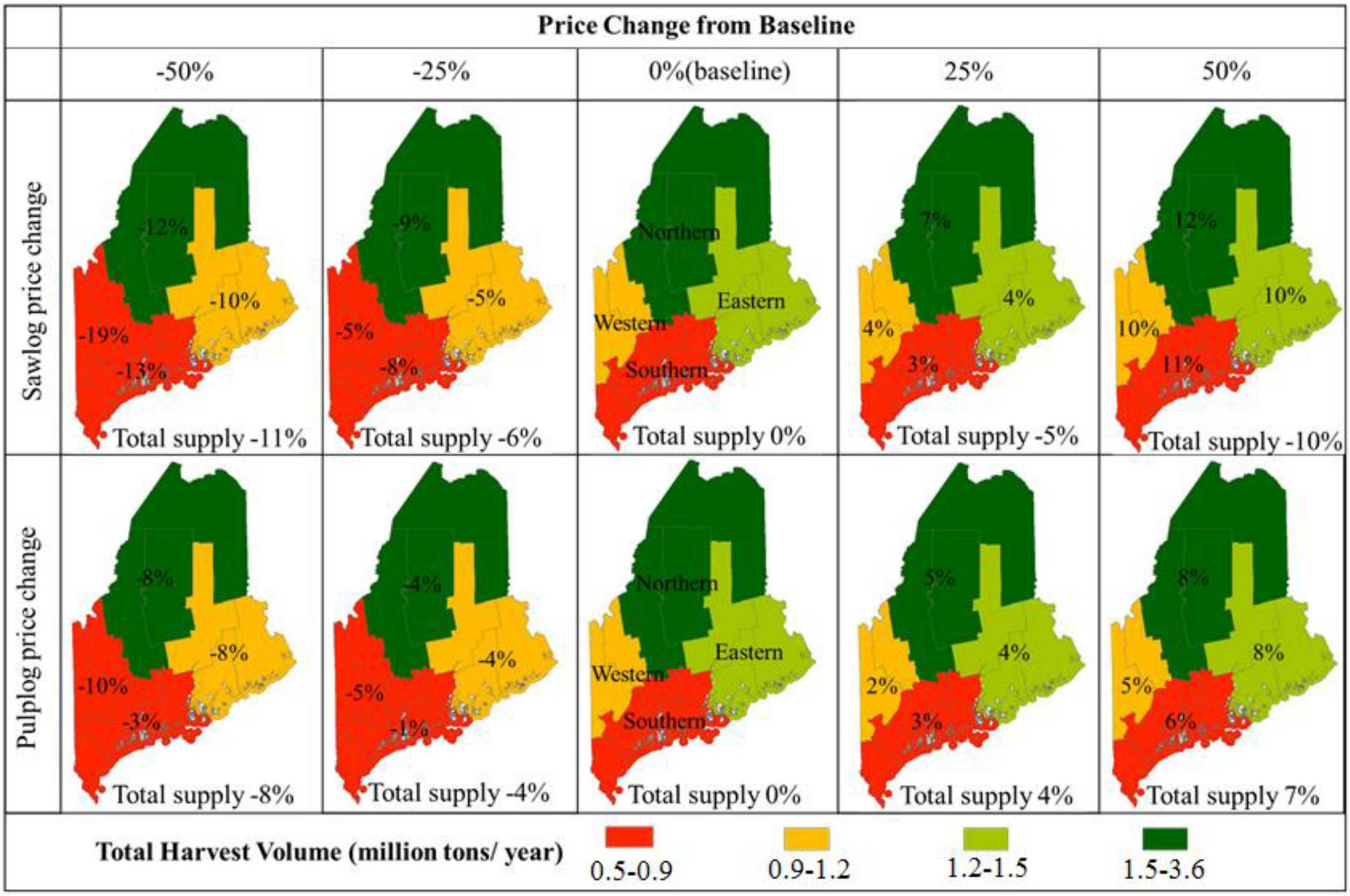

Fig. 2. Simulated total (sawlogs and pulplogs) annual supply responses for sawlogs and pulplogs price changes, by megaregion.

Table 3
Estimation results of harvest choices for sawlogs and pulplogs.

Variable	Sawlogs		Pulplogs	
	Partial Harvest	Full Harvest	Partial Harvest	Full Harvest
	Coefficients (Standard error)			
$PriceSaw_{County}$	0.018***	0.029***	0.030***	0.064***
	(0.006)	(0.006)	(0.005)	(0.008)
$PricePulp_{County}$	0.020*	0.221***	0.029**	0.231***
	(0.014)	(0.003)	(0.013)	(0.003)
$LagBio$	0.060***	0.090***	0.060***	0.096***
	(0.002)	(0.002)	(0.002)	(0.003)
$BioTot$	−0.065***	−0.107***		
	(0.002)	(0.004)		
Bio_{pulpLD}			−0.069***	−0.130***
			(0.002)	(0.005)
$PostGrowth$	0.534***	1.349***	−0.383***	1.555***
	(0.002)	(0.000)	(0.002)	(0.001)
$PostGrowth^2$	−0.036***	−0.413***	0.071***	−0.205***
	(0.003)	(0.001)	(0.002)	(0.008)
$Mill_{saw}$	−0.009***	−0.015***		
	(0.001)	(0.002)		
$Mill_{pulp}$			−0.048***	0.232***
			(0.001)	(0.001)
$LandValue$	−0.001***	0.001***	0.002***	−0.0001***
	(0.000)	(0.000)	(0.000)	(0.000)
$Conservation_{private}$	0.014***	0.113***	−0.040***	−0.296***
	(0.000)	(0.000)	(0.000)	(0.000)
$Conservation_{public}$	−0.292***	−0.281***	−0.212***	−0.049***
	(0.000)	(0.000)	(0.000)	(0.000)
$Elevation$	0.0004	0.002***	0.001***	0.003***
	(0.0002)	(0.001)	(0.0002)	(0.0005)
$HighwayDist$	−0.001	0.005	0.003	0.003
	(0.002)	(0.005)	(0.002)	(0.005)
$Year_{2011}$	0.013***	−0.224***	0.124***	0.190***
	(0.001)	(0.000)	(0.001)	(0.000)
$Year_{2016}$	−0.525***	−0.892***	−0.288***	−0.147***
	(0.001)	(0.000)	(0.001)	(0.000)
$Coastal$	14.225***	−18.068***	−12.519***	0.082***
	(0.000)	(0.000)	(0.000)	(0.000)
$Constant$	−0.977***	−7.508***	−2.309***	−7.535***
	(0.00)	(0.00)	−0.001	0
Number of observations	1404	349	1654	232
LR $\chi^2(60)$	4202.5		3828.5	
Prob > Chi^2 ($\chi 2$)	0.000		0.000	
Akaike Inf. Crit.	5945.1		6285.2	
Log likelihood at convergence	−2912.5		−3084.6	
Log likelihood at 0	−5013.8		−4998.8	
McFadden R^2	0.424		0.383	
Correct classification rate	85.24%		83.44%	

Note: $*p < .1$; $**p < .05$; $***p < .01$.

variables included in the analysis are described in Table 2.

4. Results

4.1. Harvest choice

The maximum likelihood estimates for select variables associated with various sawlog and pulplog harvest decisions in Maine are reported in Table 3, and the full set of estimates are listed in the appendix (Table A.1). The likelihood ratio test statistics, McFadden R^2 and percent correct predictions all indicate that the model had a high goodness of fit. Furthermore, we reject the null hypothesis that the equations have no explanatory power. Nearly all coefficients were statistically significant and had the expected signs. Table 4 presents the relevant elasticity response estimates, while the marginal effects of the key coefficients are listed in Table A.2.

Results indicated that all prices were positive and significant for both the partial and fully harvested decisions. That is, higher prices yield a higher harvest probability. To a certain extent, a high timber

Table 4
Estimated state-level elasticities for sawlogs and pulplogs.

Elasticity (%)	Sawlogs		Pulplogs	
	Partial Harvest	Full Harvest	Partial Harvest	Full Harvest
$PriceSaw_{County}$	0.269***	0.309***	0.432***	0.731***
$PricePulp_{County}$	0.085***	0.856***	0.144***	0.960***
$LagBio$	4.207***	3.773***	3.155***	3.395***
$BioTot$	−4.239***	−2.466***	−3.615***	−4.594***
$PostGrowth$	1.380***	1.494***	−1.562***	3.342***
$PostGrowth^2$	−0.479***	−1.416***	2.316***	−2.293***
$Mill_{saw}$	−0.029***	−0.030***		
$Mill_{pulp}$			−0.017***	0.059***
$LandValue$	−3.154***	2.050***	4.306***	−0.075***
$Elevation$	0.051	0.229**	0.084**	0.284***
$HighwayDist$	−0.007	0.026	0.018	0.016
$Constant$	–	–	–	–

Note: Elasticities can be interpreted as the percentage change in choice probability for harvest activities in response to a 1% change in an explanatory variable. E.g., 1% increase in sawlogs price will increase the probability of partial harvest by 0.269%.

price indicates the tight supply conditions and increased demand, so the landowners might harvest more wood to reach the potential balance between the supply of and demand for timber. Harvest decisions are driven by timber price, but responses are relatively inelastic. In particular, the stumpage price of sawlogs has an elasticity of 0.27 for partial harvests and 0.31 for full harvests, while pulplogs had respective values of 0.43 and 0.73 (Table 4). The elasticity estimates indicate that if the price of sawlogs increased by 1%, then the probability of a partial harvest of sawlogs increases by 0.27% and that of a full harvest increases of sawlogs by 0.31%. The prices elasticities for full harvests of sawlog and pulplog probabilities were estimated to be higher than those for partial harvests, indicating the harvest decision of clear-cutting (or full removal of a given timber class) was more sensitive to stumpage price than partial removals. Thus, a small reduction in the market stumpage prices could lead to less clear-cutting. However, the probability that landowners adjust their partial harvest decisions are less affected by timber prices, especially for pulplogs (Table 4).

The parameter estimates for harvests from public lands were negative and statistically significant for all harvest intensities and timber types (Table 3). Negative signs indicate that public land managers may tradeoff between economic maximization and other benefits and thus harvest with longer rotations and retain old trees. Compared to non-conservation lands, public lands have a 2.6% and 2.4% lower probability of choosing to partially harvest sawlogs and pulplogs, respectively. They also have a 0.2% and 0.1% lower probability of choosing to fully harvest sawlogs and pulplogs, respectively. The private conservation land estimates were different from public lands. A key difference was that full sawlog harvests are estimated to increase by 0.3% compared to non-conservation forestland.

Estimates showed that landowners in the coastal counties were 1.38 times more likely to choose the partially harvested for sawlogs than inland counties. Pulplog harvests demonstrated the opposite effect; landowners in the coastal region being 1.46 times less likely to conduct partial harvests of the less valuable timber on their land than inland counties (Table A.2). Forest management in coastal counties may be driven less by timber revenue when compared to other objectives such as aesthetics, urban and community design, and constraints associated with owning and harvesting smaller tracts of land. As a result, they have more active management for sawlogs than pulplogs, particularly for partial harvests.

The initial (i.e., pre-harvest) stand volumes were significant and positively related to the harvest probabilities, while the retained stand volume negatively influenced the harvest probabilities (Table 3). The average marginal effect and elasticity estimates also demonstrate that a high initial stand volume may stimulate harvest activities, while a large retained stand volume indicates that landowners who are focused on non-market values are less likely to harvest.

The megaregion-level elasticities and standard errors of timber supply response with respect to stumpage prices are reported in Table 5. The estimates indicate that Maine's timber supply is inelastic with respect to stumpage price throughout the state, although only the elasticities related to pulplog prices were statistically significant. Estimates were also relatively consistent across megaregions. In particular, own-price elasticities ranged from 0.078 to 0.106 for sawlogs and 0.326 to 0.434 pulplogs. With respect to cross-price elasticities of timber supply estimates ranged from 0.162 to 0.218 for sawlog supply and from 0.020 to 0.053 for pulplog supply, indicating that the two products are complementary.

4.2. Timber supply

The estimates from the empirical harvest choice model can be used to estimate how Maine's timber supply could respond to various socioeconomic conditions such as changes in prices and ownership type. We set the inventory plots and harvest volume during 2012–2016 as the baseline. Fig. 2 indicates how supply could change under varying sawlog and pulplog stumpage prices (+/− 50% compared to baseline means). As the prices of either sawlogs or pulplogs increase, supply for both timber types increase as well, indicating that the two products are complements. If sawlog and pulplog prices simultaneously increase by 50% at the same time – a value that is within the bounds of historical price fluctuations – their complementary effects could increase Maine's total wood supply by 17.8%. On the contrary, simultaneously reducing sawlog and pulplog prices by 50%, could reduce Maine's supply by 18.6%.

Table 5
Maine stumpage price-elasticity of supply estimates.

Supply	Megaregion	Sawlog price	Pulplog price
Elasticity (Std. Err.) Sawlogs	Eastern	0.106	0.218^{**}
		(0.148)	(0.094)
	Northern	0.093	0.173^{*}
		(0.120)	(0.086)
	Southern	0.078	0.162^{*}
		(0.167)	(0.084)
	Western	0.098	0.170^{*}
		(0.164)	(0.094)
Pulplogs	Eastern	0.020	0.434^{***}
		(0.157)	(0.137)
	Northern	0.031	0.326^{***}
		(0.128)	(0.119)
	Southern	0.047	0.399^{***}
		(0.150)	(0.133)
	Western	0.053	0.361^{***}
		(0.157)	(0.131)

Note: $^{*}p < .1$; $^{**}p < .05$; $^{***}p < .01$.

Overall, total harvests respond more to sawlog price changes than pulplog price changes, indicating that prices for sawlogs have a dominant influence on Maine's timber supply. However, this finding does not necessarily hold for all regions of the state. For example, the eastern region of the state is estimated to have a relatively equal response to price changes for both products. On the contrary, Maine's southern region is at least two times more responsive to changes to sawlogs than pulplogs. This finding highlights the heterogeneity in Maine's timber markets and suggests developing more regionally-focused policies may be more effective than those created at the state-level.

As expected, there are less impacts to timber supply if there is only a price change for either sawlogs or pulplogs (Fig. A.1). For example, a 50% increase in sawlog prices would lead to a 14.7% increase in pulplog supply, but only a 5.1% increase in sawlog supply, further highlighting the complementarity effect of the two products. However, a 50% increase in pulplog prices would increase Maine's pulplog and sawlog supply by 6.8% and 8.1%, respectively. Declines are estimated to be of similar scale when prices decline by 50%.

Approximately 21% of Maine's forestland is currently designated as conserved land, with most of that area located the northern megaregion (61%) and followed by the east (24%). The west and south megaregions comprise the remaining 15%, where a majority of the conservation land is fragmented (Fig. 1). To assess the potential effects on the state timber supply if the recent trend in the conversion of Maine's forests to private conservation land continues, we estimated the effects of increasing the total area of Maine's forestland designated as private conservation in 25% increments (Fig. 3). Overall, we estimate that converting all remaining private forestland to conservation would reduce Maine's total annual timber supply by about 140,000 t $\text{yr}^{`}$, or 2% below current harvest levels. The entire decline is expected to be in pulplog harvests (−2.3 to −4.3%), while total sawlog harvests are estimated to increase (0.1 to 0.5%). Regionally, most of the changes are estimated to occur in the northern region of the state, which currently provides a bulk of the Maine's wood supply (Fig. 3). Large sections of this region are also already designated as conservation land though, and thus have already started to transition away from primarily focusing on pulplog-based harvesting and manufacturing. Thus, we estimate that a continued

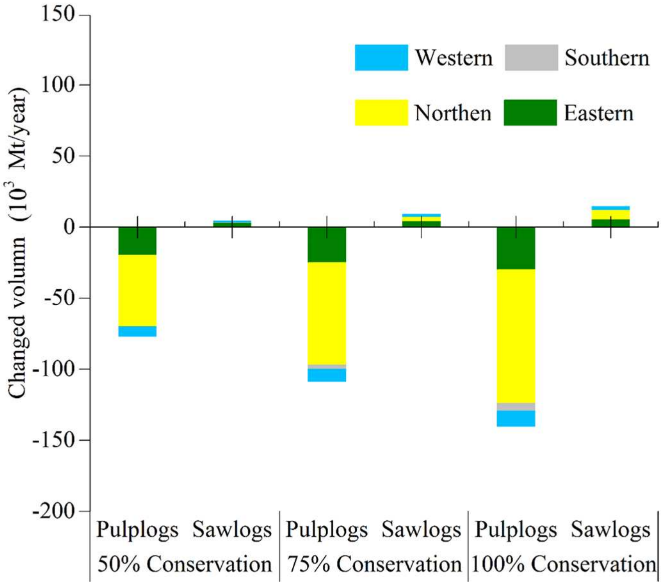

Fig. 3. Estimated change in timber harvest from baseline for conversion to private conservation forestland.

trend of shifting forestland ownership into conservation land will have a minor effect on Maine's timber supply, when all else is held equal.

4.3. Model validation

As a validation step, the total supply of sawlogs and pulplogs in Maine were predicted and compared with published reports, as shown in Fig. 4. Our estimates of sawlogs and pulplogs were similar to historical data, often estimating harvests within 10% of the actual amount. The largest difference in model and historical harvests occurred in the 2007–2011 period, in which there was a global economic recession that had a major impact on housing demand and resulted in some structural change to the U.S. forest product industry. As we described above, the effects of stumpage price for different product supply are complementary. Thus, our approach to lag pulplog prices could overestimate the harvest volume for both sawlogs and pulplogs. However, in aggregate, the verification indicates that the model is relatively robust and adequately specified despite the wide range of conditions and underlying variability in the data available. The relatively consistent estimates show that the empirical model presented in this paper is a useful decision support tool for estimating both regional- and state-level impacts on Maine's timber supply under a wide range of conditions and constraints.

5. Discussion and conclusion

Our analysis found that stand volume and site location are both important aspects of the harvest decisions of Maine's forestland owners' despite existing differences in landowner types and their primary objectives. It also illustrated that the landowners' decisions are driven by stumpage prices, regardless of product type or harvest intensity. That is, higher prices induce landowners to be more likely to harvest their stand. In addition, the choice to harvest the stand more intensively (i.e., full harvest or clear-cut) is more sensitive to stumpage price changes than less intensive (i.e., partial) harvests. Model estimates identified that the supply of all timber types were relatively inelastic with respect to stumpage price, in addition, positive coefficients of cross-price elasticities in timber supply between sawlogs and pulplog further-indicated these two products are complements. In aggregate, we estimated Maine's total timber supply was more responsive to changes in sawlog prices than pulplog prices. That is, a 50% increase in sawlogs could increase Maine's timber supply by 10.4%, while the same increase in pulplog prices would result in a 7.4% increase.

The analysis also found there some variation in harvest response across the state. Coastal areas are 1.38 times more likely than inland areas to selectively cut sawlogs, but also 1.46 times less likely to selectively harvest pulplogs. This finding supports the general perception that landowners in the coastal counties often have less reliance on timber revenue than those in the interior of the state. As a result, those living on the coast are more likely to actively manage their land for sawlogs than elsewhere. This suggests that the structure of Maine's large but geographically spread forest products industry has already been factored into various decisions. In addition, this highlights the high variability in landowner behavior even for a given type such as NIPF.

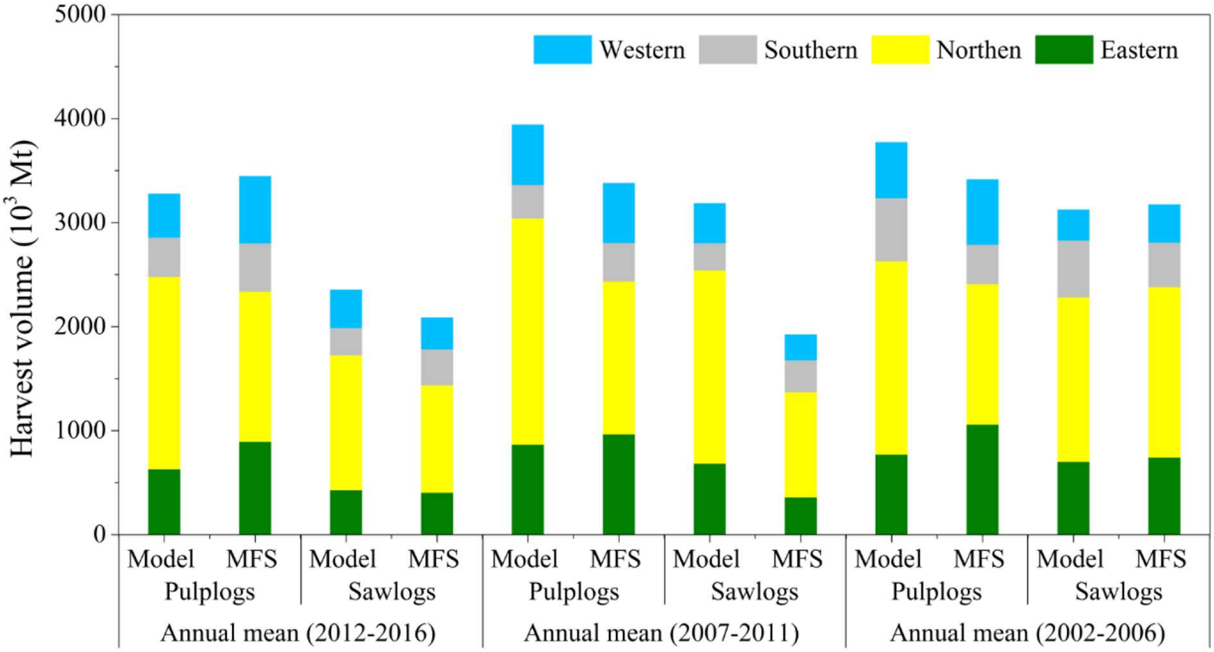

Fig. 4. Maine's historical and predicted average annual harvest volume (dry t yr^{-1}).

Our findings that forest landowners have a positive but inelastic response to price signals are primarily aligned with previous studies, although the findings are highly variable. For example, Bolkesj et al. (2010) reported the elasticity of 0.91 of sawlogs supply and 0.53 of pulplogs supply. In contrast Tian et al. (2017) conducted a meta-analysis of studies involving elasticities of timber supply and found the elasticity of 0.39 of sawlogs supply and 0.13 of pulplogs supply, while Prestemon and Wear (2000) found that elasticity of sawlogs in the United States was 4.57. With respect to cross-price elasticites, some studies found the pulplogs and sawlogs products were substitutes (e.g., Bolkesj et al., 2010), while most studies report that they are complements (e.g., Polyakov et al., 2010; Prestemon and Wear, 2000), as was the case for this study.

We estimated that public conservation of forestlands had a slightly negative and statistically significant impact on harvest decisions and timber supply. However, privately designated conservation landowners responded rather similarly than their non-conservation neighbors, only reducing average annual harvests by 2%. This suggests that private conservation land management might emphasize more commercial activities compared to public lands. In addition, these landowners may harvest more high-quality sawlogs to offset the diminution in income and/or fund their multi-use objectives. Fully converting all remaining non-conservation lands to privately managed conservation could decrease pulplog harvests by 4%, but then increase sawlog supply by about 0.5%. These results are similar to previous findings that conversion to conservation makes landowners less likely to harvest pulplogs and more likely to harvest sawlogs. For example, Owley and Rissman (2016) estimated that 24% of forest conservation easements opened their land to harvest, and suggested that although their management objectives are often more complex than those on standard private land, timber harvests were generally less restrictive. Furthermore, MLTN (2017) indicated that approximately 85% of conserved lands are managed as working forests. Related to this, Sims et al. (2019), found that designating areas in New England as large protected private timberland could have a positive impact on regional employment, particularly in areas far from major cities, as in the case of Maine.

The finding that private conservation forestland owners respond similarly to their private neighbors, suggests that there is still large potential to increase conservation area from its current levels of 21% of total forest area in the state, particularly as Maine's residents continue to place more emphasis on the recreation and ecosystem services that its forests can provide, and industry continues to divest their forestland holdings. With improved management, Maine's forests have the potential to produce considerably more high-quality timber per land area, while maintaining other forest values, particularly carbon. This could also ensure that the stumpage prices remain high in globally competitive market. Furthermore, as more emphasis could be placed on diversifying Maine's forest products industry in the future, landowners may have more opportunities to supply timber for a wider range of products, including wood pellets, liquid biofuels, mass timber, composite wood products, and other bio-based products. Collectively, these emerging wood products could stimulate market demand, further encouraging sustainable harvesting and healthy forest management in the state. Further research should consider the expectation that global change will alter rates and patterns of tree growth and mortality as well as how a wider array of socio-economic drivers may influence regional supply and demand for harvested wood products. Research that also explores the impacts of non-timber markets and land use policies such as forest carbon offset programs that are also expected to be part of the emerging change in how Maine's forests are utilized in the upcoming decades would also be useful extensions of this model and related timber supply projections.

Like Kuehne et al. (2019), we would generally conclude that harvesting trends across a diverse set of forest and market conditions in Maine would suggest that it might be less opportunistic and short-term driven than generally perceived. However, we acknowledge that our analysis has some limitations, particularly because econometric modeling is only as robust as the data available. First, the mean annual county-level stumpage price data does not necessarily represent the exact price that landowners received for their harvest nor the variability in prices across species. Second, FIA plots are relatively small (1/60 ha) and are only sampled once every five-years, limiting our simulations to 5-year averages. Third, public FIA data do not differentiate across private landowner type (e.g., corporate, non-industrial, etc.), so we are unable to assess the potential impact that this might have on harvest levels. Fourth, the state's megaregions are primarily defined by political boundaries, not necessarily ecological or socioeconomic similarities, thereby restricting some broader model inference. Fifth, we do not assess harvests at the species level, which has been found to be important (e.g. Kuehne et al., 2019) and would have implications on the timber demand side of the market (i.e., pulpmills and sawmills only process certain species). Other model and data limitations that could be explored in future research include improving the estimation of harvest costs, land values, and proxies that represent non-timber and amenity values that landowners take into consideration. Despite these limitations, we believe that our approach to modeling the complex timber harvesting patterns across a diverse array of both private, public, and conservation owners can be leveraged to inform policies focused on sustainable timber flows under a wide range of socioeconomic conditions.

Declaration of Competing Interest

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

Acknowledgements

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Appendix

Table A.1
Full model estimates of Maine sawlogs and pulplogs harvest choices.

Variable	Sawlogs		Pulplogs	
	Partial Harvest	Full Harvest	Partial Harvest	Full Harvest
Coefficients (Standard errors)				
$PriceSaw_{County}$	0.018***	0.029***	0.030***	0.064***
	(0.006)	(0.006)	(0.005)	(0.008)
$PricePulp_{County}$	0.02*	0.221***	0.029**	0.231***
	(0.014)	(0.003)	(0.013)	(0.003)
LagBio	0.060***	0.090***	0.060***	0.096***
	(0.002)	(0.002)	(0.002)	(0.003)
BioTot	−0.065***	−0.107***	−0.069***	−0.130***
	(0.002)	(0.004)	(0.002)	(0.005)
PostGrowth	0.534***	1.349***	−0.383***	1.555***
	(0.002)	(0.000)	(0.002)	(0.001)
PostGrowth_sqr	−0.036***	−0.413***	0.071***	−0.205***
	(0.003)	(0.001)	(0.002)	(0.008)
$Mill_{saw}$	−0.009	0.000		
	(0.008)	(0.002)		
$Mill_{pulp}$			−0.048***	0.232***
			(0.001)	(0.001)
LandValue	−0.004***	0.004***	0.002***	−0.0001***
	(0.000)	(0.000)	(0.000)	(0.000)
$Conservation_{private}$	0.014***	0.113***	−0.040***	−0.296***
	(0.000)	(0.000)	(0.000)	(0.000)
$Conservation_{public}$	−0.292***	−0.281***	−0.212***	−0.049***
	(0.000)	(0.000)	(0.000)	(0.000)
Elevation	0.0001	0.001***	0.0002***	0.001***
	(0.0001)	(0.0002)	(0.0001)	(0.0001)
$Year_{2011}$	0.013***	−0.224***	0.124***	0.190***
	(0.001)	(0.000)	(0.001)	(0.000)
$Year_{2016}$	−0.525***	−0.892***	−0.288***	−0.147***
	(0.001)	(0.000)	(0.001)	(0.000)
Coastal	14.225***	−18.068***	−12.519***	0.082***
	(0.000)	(0.000)	(0.000)	(0.000)
CountyAroostook	−1.232***	0.152***	0.586***	−0.352***
	(0.001)	(0.000)	(0.001)	(0.000)
CountyCumberland	−7.024***	16.956***	9.208***	3.595***
	(0.000)	(0.000)	(0.000)	(0.000)
CountyFranklin	−0.269***	−1.091***	−0.623***	−0.574***
	(0.000)	(0.000)	(0.000)	(0.000)
CountyHancock	92.526***	−104.153***	−119.821***	5.553***
	(0.000)	0.000	(0.000)	0.000
CountyKennebec	0.404***	−1.977***	−1.063***	−4.252***
	(0.000)	(0.000)	(0.000)	0.000
CountyKnox	−11.437***	22.225***	15.984***	2.677***
	(0.000)	0.000	(0.000)	(0.000)
CountyLincoln	−12.910***	23.840***	16.798***	3.519***
	(0.000)	(0.000)	(0.000)	(0.000)
CountyOxford	−0.290***	−0.779***	−0.238***	−0.645***
	(0.000)	(0.000)	(0.000)	(0.000)
CountyPenobscot	−0.704***	0.047***	0.220***	−0.571***
	(0.000)	(0.000)	(0.000)	(0.000)
CountyPiscataquis	−0.735***	−0.186***	0.373***	−0.373***
	(0.000)	(0.000)	(0.000)	(0.000)
CountySagadahoc	−7.757***	−55.059***	9.264***	−24.032***
	(0.000)	0.000	(0.000)	0.000
CountySomerset	−0.977***	−0.065***	0.410***	−0.531***
	(0.000)	(0.000)	(0.000)	(0.000)
CountyWaldo	−13.329***	24.059***	16.828***	1.809***
	(0.000)	(0.000)	(0.000)	(0.000)
CountyWashington	−14.671***	24.803***	18.233***	2.022***
	(0.000)	(0.000)	(0.000)	(0.000)
CountyYork	−11.671***	22.451***	15.213***	3.075***
	(0.000)	(0.000)	(0.000)	(0.000)
HighwayDist	−0.00001	0.00005	0.00003	0.00003
	(0.00002)	(0.00004)	(0.00002)	(0.00005)
Constant	−0.977***	−7.508***	−2.309***	−7.535***
	(0.00)	(0.00)	−0.001	0
Number of observations	1404	349	1654	232
LR $\chi^2(56)$	4202.5		3828.5	
Prob > Chi^2 ($\chi2$)	0.000		0.000	
Akaike Inf. Crit.	5945		6285	

(*continued on next page*)

Table A.1 (*continued*)

Variable	Sawlogs		Pulplogs	
	Partial Harvest	Full Harvest	Partial Harvest	Full Harvest
Log likelihood at convergence	−2913		−3085	
Log likelihood at 0	−5014		−4999	
McFadden R^2	0.423		0.383	
Correct classification rate (CCR)	85.24%		83.44%	

Note: *p < .1; **p < .05; ***p < .01

Table A.2

Estimated marginal effects of Maine sawlogs and pulplogs harvest choices.

Average Marginal Effect	Sawlogs		Pulplogs	
	Partial Harvest	Full Harvest	Partial Harvest	Full Harvest
$PriceSaw_{County}$	0.002***	0.000***	0.003***	0.001***
$PricePulp_{County}$	−0.001**	0.004***	0.001***	0.003***
$LagBio$	0.005***	0.001***	0.006***	0.001***
$BioTot$	−0.006***	−0.001***		
Bio_{pulpLD}			−0.007***	−0.001***
$PostGrowth$	–	–	–	–
$PostGrowth^2$	–	–	–	–
$Mill_{saw}$	−0.0007***	−0.0002***		
$Mill_{pulp}$			−0.008***	0.004***
$LandValue$	−0.00008***	0.00003***	0.00009***	−0.000008***
$Conservation_{private}$	−0.002***	0.003***	−0.002***	−0.004***
$Conservation_{public}$	−0.026***	−0.002***	−0.024***	−0.001***
$Elevation$	0.00001	0.00004***	0.00005**	0.00004***
$HighwayDist$	−0.0002	0.0001*	0.0003	0.00002
$Year_{2011}$	0.004***	−0.004***	0.013***	0.001***
$Year_{2016}$	−0.044***	−0.011***	−0.032***	0.001***
$Coastal$	1.381**	−0.420**	−1.458***	0.110***
$Constant$	–	–	–	–

Notes:*p < .1; **p < .05; ***p < .01.

The average marginal effects are interpreted as the percentage change in choice probability for partial or full harvest activities in response to a one unit change in the respective explanatory variable (keeping all other independent variables constant at their mean values) in the row. e.g., one dollar increased in sawlogs price will drive up the probability of partial harvest in sawlogs by 0.2% and transfer the non-conservation land to privately conservation land will drive down the probability of partial harvest in sawlogs by 0.2%.

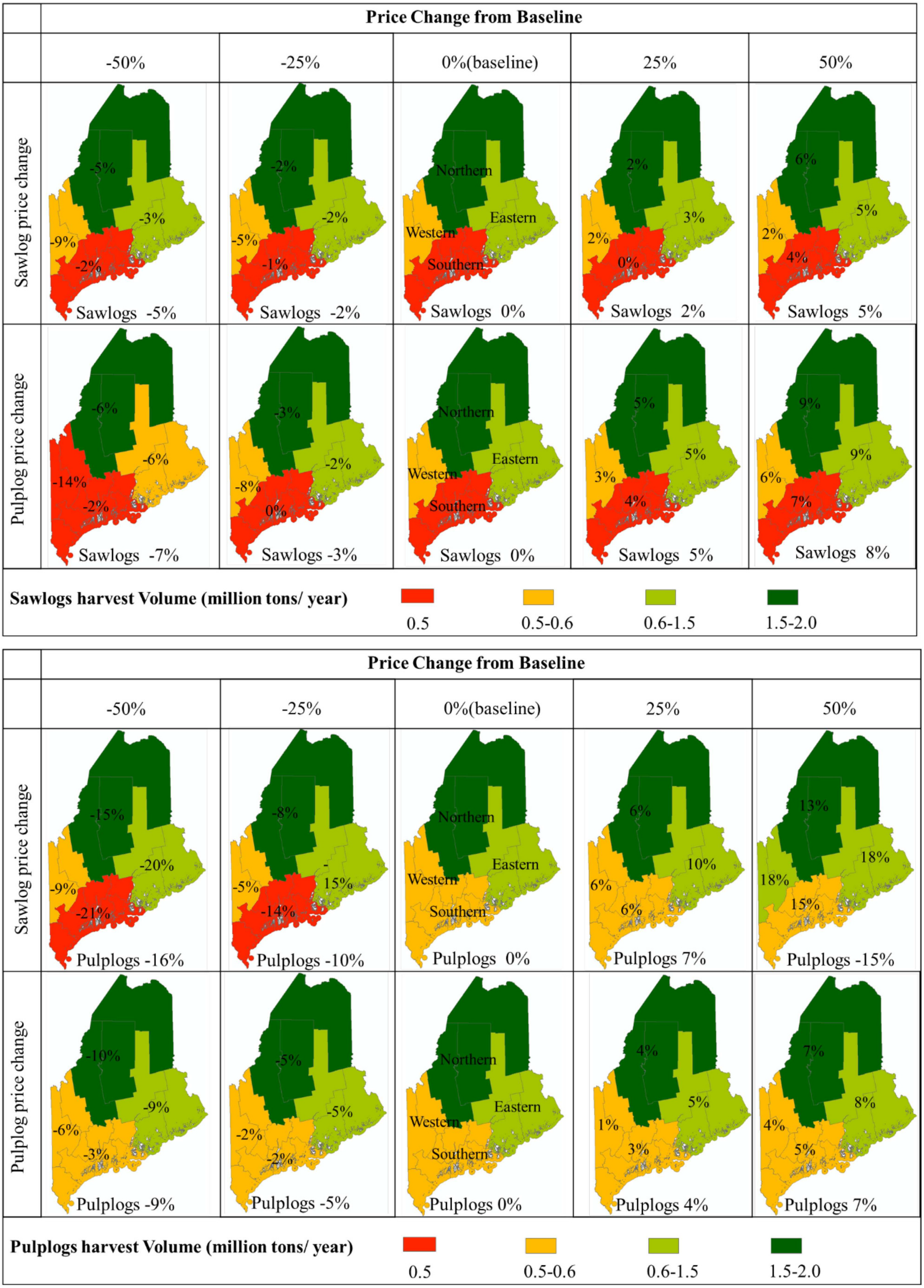

Fig. A.1. Simulated annual (a) sawlog and (b) pulplog supply responses by megaregion.

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