Meta-Analysis of Price Responsiveness of Timber Supply

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Abstract

Modeling and projecting timber supply requires a good understanding of how supply responds to price. The price elasticity of supply (PELS) reported in the literature varies greatly, indicating that conclusions regarding price signaling in the timber market are mixed. Therefore, we conducted a meta-analysis to determine the key factors associated with the heterogeneity of PELS of primary timber product supply by examining data from numerous studies conducted around the world. Twelve ''moderator'' variables were examined to explore differences in PELS. Moderators with significant impacts on variation of PELS included forest products, geographic regions, econometric models, and data type. Furthermore, two-level categorical variables contained within the econometric models including standing stock were found to have significant influence on the heterogeneity of PELS. Variation in PELS also depended on whether or not the supply models accounted for price inflation, and the time period when the study was conducted. These findings may improve the understanding of the dynamics of price signaling in timber markets, and further improve the efficiency of timber supply and forecasting models for market participants and policy makers.

Wood remains the primary good in the forest product market, making timber supply essential to sustaining forest industries. Annual timber harvests in the United States currently total approximately 1.9 billion m^3, which represents 20 percent of global timber harvests (Sedjo and Sohngen 2015). Demand for timber products is often driven by low price for building materials and paper, relative to other materials. It is also popular for other products, e.g., furniture, biofuels, and in the United States alone, annual timber demand per capita is estimated at 816.47 kg (1,800 lbs; Haynes 2003). This suggests that total timber demand is likely to increase as a function of population growth. Therefore, understanding the market dynamics of timber supply with respect to price and other factors is an important issue. Timber supply refers to the volume of harvested timber within a region made available to the market (Prestemon and Wear 1999). It has been found to be influenced by several market and nonmarket factors, including net prices, merchantable stock of standing timber, and the interest rate.

Specifically, timber supply is affected by landowner interest in nontimber goods and services (e.g., recreation, wildlife, and environmental protection; Favada et al. 2009), forest ownership (Newman and Wear 1993), market mechanisms (e.g., price uncertainty; Newman and Wear 1993), and government policies (e.g., the tenure reform of forestland in China; Zhang and Buongiorno 2012, Young et al. 2015). Timber price as a market indicator is also considered to have an important role in determining timber supply (Kuuluvainen et al. 1996, Kuuluvainen and Tahvonen 1999, Prestemon and Wear 2000, Bolkesj and Baardsen 2002, Bolkesj and Solberg 2003). For example, many studies conducted in various parts of North America and Europe revealed that timber supply is positively related to price (Binkley 1981, Kuuluvainen and Tahvonen 1999, Bolkesj and Baardsen 2002). However, investigators such as Cubbage (1986), Skog and Haynes (1987), and Prestemon and Wear (2000) concluded that timber supply is fairly unresponsive to price. Therefore, considerable variation exists in the literature as to whether and to what extent timber supply responds to market price. In other words, the studies have mixed conclusions regarding the price elasticity of supply (PELS), which is a measure of relative responsiveness of timber supply to market price. Thus, what contributes to the variation in PELS of timber supply is an interesting research question.

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Human dimension studies of nonindustrial private forest (NIPF) landowners' behavior have demonstrated significant effects of owner characteristics such as age, education, and income, as well as management objectives on the volume of timber supply or intention to supply timber (e.g., Kuuluvainen et al. 1996, Favada et al. 2009, Kittredge and Thompson 2016). Forest ownership objectives are also considered to have a substantial effect on timber supply (Kuuluvainen et al. 1996, Favada et al. 2009, Kittredge and Thompson 2016). Moreover, several other variables characterizing forest (e.g., standing stock) or landowner-specific circumstances (e.g., interest rate option) are considered to affect timber supply. Forest standing stock has been found to have a positive effect on timber supply (Brännlund et al. 1985, Kuuluvainen et al. 1996, Toppinen and Kuuluvainen 1997, Bolkesj et al. 2010). However, a lack of landowner-specific data often limits researchers' ability to evaluate the effects of personal (e.g., demographics) and financial (e.g., interest rate) variables on timber supply. Arguably, if panel data were to be used, the effects of forest owner–specific variables (say interest rate she or he faces in a particular decision time) may be implicitly taken into account by the estimated individual (fixed or random) effects (e.g., Bolkesj and Solberg 2003, Sun et al. 2015), but conducting this type of study requires data from the same landowners at multiple time periods.

Other studies attempted to identity the determinants of timber supply by modeling it as a function of a range of factors. Prestemon and Wear (1999) used aggregate supply models to analyze the aggregate effects of price changes on timber supply in North Carolina. Toppinen and Kuuluvainen (1997) conducted a similar study on sawlog and pulpwood markets in Finland. In addition, Bolkesj et al. (2010) summarized the earlier timber supply studies and classified them with micro- and macro-level analyses according to the data types used. Several studies (Binkley 1981, Dennis 1989, Hyberg and Holthausen 1989, Carién 1990, Kuuluvainen and Salo 1991) focused on NIPF owners using cross-section or time-series data, whereas others utilized data over a larger region or country using panel data (e.g., Bolkesj et al. 2010, Solberg 2011). In general, although these studies suggest that different factors influence the volume of timber supply to varying extents, not all factors are as clear as ''market price'' to provide any signal to potential suppliers and buyers in the market. Considering that econometric studies have shown mixed results in terms of whether, and to what extent, market price affects timber supply, it is important to explore the role of various possible factors that contribute to observed variation in PELS.

The PELS as reported in studies is typically computed as the percent change in timber volume supplied in response to a percent change in price (Lowenstein 1954). This unitless measure explains the magnitude of impact of price on supply, and is therefore comparable across multiple studies. Among the studies that found a significant effect of price on timber supply, some report that supply is inelastic, whereas others report that it is highly elastic. For example, Toppinen and Kuuluvainen (1997) reported 2.18 as the PELS of pulpwood in Finland, whereas Solberg (2011) calculated a PELS of 0.01 for pulpwood in France. Likewise, Prestemon and Wear (1999) indicated that the PELS of sawlogs in the United States was 4.57, whereas Nilsson (2002) estimated that for sawlogs in Sweden, it was as low as 0.08. Consequently, the large variability in reported PELS estimates motivated this study to explore the determinants of this variation.

It is important for market participants and policy makers to recognize the primary factors that affect PELS to better understand and predict future timber markets. It is difficult to refine timber supply models and accurately forecast future market conditions without understanding the exact sources of variation in the PELS of timber supply. To fill this knowledge gap, we conducted a meta-analysis of studies involving PELS of timber supply to investigate whether, and to what extent, various factors (price, market circumstances, statistical modeling, etc.) contribute to observed variation in PELS. Meta-analyses and systematic reviews were used to synthesize evidence from several studies for a given question or objective, taking into account variation in replication and precision among studies to arrive at a global weighted average (Borenstein et al. 2009). This tool analysis allows us to examine mean consistency in PELS across the literature, and consequently test which factors influence the magnitude of the variation. Specific objectives of the study were (1) to quantify how much PELS varies among studies, and (2) to characterize how specific explanatory variables affect PELS: forest products, geographic regions, econometric model form, ownership characteristics (owner of supplier, nonforest income, age), data type, price observations frequency, interest rate, standing stock, price deflation, and time period.

Materials and Methods

Data collection

Studies appropriate for meta-analysis (to be discussed in detail later) were identified by using the ISI Web of Science (Thomson Reuters Corp., Toronto, Canada) search tool on 11 electronic databases for both refereed and nonrefereed articles including theses and dissertations. On August 24, 2015, we conducted a search of these databases with the search terms timber market and price* elasticity of supply. A total of 76 unique articles were extracted from 3 databases: 49 from Web of Science Core Collection, 26 from CABI, and 1 from BIOSIS Citation Index. Through examining the 76 eligible articles, 55 were excluded because they did not meet our criteria: PELS was not reported (18), standard error was not provided and it was not calculable from data provided (19), and full articles could not be located (18). The Google Scholar search tool was also used to search using these search terms, which provided about 34,800 results. The first 20 pages were examined, which resulted in 4 additional journal articles for the analysis. A total of 25 articles met the criteria, from which 51 studies were extracted, spanning 35 years (1980 to 2015).

Price elasticity and standard error were collected from each study. The majority of the studies included in our data set violated the assumption of study independence described by Mengersen et al. (2013). In other words, studies from the same article may not be completely independent; their effect size values may be more related to one another than to study effect sizes reported in other articles (Mengersen et al. 2013). It is common to treat multiple studies reported in a single article as if they were independent. Meta-analysis acknowledges the likely nonindependence among multiple studies, but it is typical practice to proceed this way because excluding data reduces statistical power (e.g., Veresoglou et al. 2012, Slattery et al. 2013, Omondi et al. 2016, Zuber and

Villamil 2016). As in the Lehmann and Rillig (2015) work, studies were not combined in instances in which they differed in categories assigned to moderator effects, to maintain the ability to conduct moderator analysis. Therefore, following Lehmann and Rillig (2015), we addressed the nonindependence for articles presenting multiple PELS means (often termed subgroups, observations, trials, or studies in the meta-analysis literature) by combining subgroups to a single effect size value using a random-effects meta-analytical approach. Subgroups were not combined where they differed in factors assigned to moderator effects and hence needed to remain independent to maximize moderator analysis. For example, subgroups were not combined when they addressed different forest product types or econometric models. Following this process, we extracted a total of 339 PELS observations from the above-mentioned 51 studies from 25 different articles.

Effect size and moderator variables

PELS was the single-group effect size[1] evaluated across studies in the meta-analysis. PELS, a measure of the sensitivity of timber supply to price, was computed as:

$$\mathrm{PELS} = \frac{\%\ \text{change in quantity supplied}}{\%\ \text{change in price}} \tag{1}$$

Generally, PELS can be classified into three categories: elastic (PELS $>$ 1), unit elastic (PELS $=$ 1), and inelastic (PELS $<$ 1; Lowenstein 1954). In addition to price elasticity and standard error, we recorded information for 12 moderator variables for each study (Table 1) that are believed to affect the PELS.

Forest products.—The PELS could differ among different types of forest products because of different harvesting requirements and market situations for respective products (Toppinen and Kuuluvainen 1997). Three primary timber products—pulpwood, sawlogs, and roundwood—were included in the analysis (as classified in the articles reporting their data). It should be noted that we included only the primary timber products for analysis and excluded the secondary products (e.g., plywood, sawn wood), which are different market goods.

Region.—The response of supply to price could also depend on the geographic scope and nature of the regional timber market (Bolkesj et al. 2010). A unit change in timber price in the US market may not necessarily have the same impact on timber supply in the Malaysian market. Therefore, geographic region was used as another moderator with three categories: North America, Europe, and Asia. We believe that these three geographic regions represent a broader market of timber on a global scale.

Econometric model form.—Econometric models (especially the functional form) used in modeling the relationship between timber supply and the contributing factors could have an impact on the PELS estimate (Bolkesj and Solberg 2003). Three categories of econometric model specifications were evaluated: linear, log-linear, and log-log. These three model forms were classified depending on whether one or both the volume of timber and price were transformed with logarithm form.

Data type.—Timber supply studies have mainly utilized data from one or more places or suppliers at various points in time (Bolkesj et al. 2010). The kind of econometric model researchers can use partly depends on whether data are available from multiple markets (or submarkets) and time periods. By summarizing the corresponding empirical timber supply articles, three categories of data type including cross-section, time series, and panel data were obtained. Compared with cross-section and time-series data, panel data (i.e., combination of cross-section and time series) may yield more reasonable and stable PELS estimates because they cover multiple markets and time periods.

Price observations frequency.—In addition to the data type, it is reasonable to expect that the number of price data points observed (for a given market) for the estimation of PELS may have some effect on PELS estimates. Studies that use more price observation points may offer a more rigorous analysis and therefore likely yield more unbiased and precise estimation of PELS than other studies with fewer price observations. Unfortunately, not all articles we reviewed mentioned the price observation frequency, which is different from the sample size. However, we took a proxy approach in creating a categorical moderator that controls for differences in studies with various price observation frequencies. The basic assumption in using this proxy is that studies utilizing more frequent data observations (i.e., monthly) are likely to have more price data points than those using less frequent data observation (i.e., annual). Therefore, we included the price observations frequency moderator in meta-analysis with three levels: monthly, quarterly, and annually.

Ownership, owner age, nonforest income.—Numerous studies, especially those focusing on the NIPF owners, have demonstrated that various characteristics of ownership (e.g., owner's objective and motivation, nonforest income, age, and education) are related to timber supply (Kuuluvainen et al. 1996, Pattanayak et al. 2002, Beach et al. 2005, Favada et al. 2009). Thus, three moderators associated with ownership characteristics were examined: ownership type, owner age, and nonforest income. Ownership type included four categories: NIPF, industry, government, and aggregate (i.e., more than one ownership type involved). Studies classified in the aggregate category combined those that did not report specific forest ownership and instead analyzed timber supply at the market level. Owner age and nonforest income were treated as two-level categorical variables (yes/no): whether or not they were included in econometric models of timber supply studies.

Standing stock.—Standing stock is believed to affect timber supply significantly (Kuuluvainen et al. 1996, Pattanayak et al. 2002, Beach et al. 2005). Theoretically, standing stock positively affects harvesting, which implies that the higher the level of standing stock, the higher the harvest and supply. To examine whether and how the standing stock of timber influences PELS, we included it in meta-analysis as a two-level variable (yes/no): whether or not it was included in models that estimated the PELS.

[1] Although the effect size for most meta-analyses defines the relationship between two groups, commonly mean difference or ratio of means, some meta-analyses are focused on means of a single group or population. This is the case for PELS; it is a single-group effect size or simply single-group summary (because effect implies a relationship). Whether the index is a two-group effect size or single-group summary has no bearing on the meta-analysis computations (Borenstein et al. 2009).

Table 1.—Description of moderators used to characterize heterogeneity in price elasticity of supply.

Moderators	Description
Forest product	Materials derived from forests for direct consumption or commercial use
Region	Areas that have generally similar timber markets (classified as Asia, Europe, and North America)
Econometric model form	Function form used to build the relationship between timber supply and associated factors including: linear, log-linear, and log-log
Data type	Types of data include: 1. Cross-section: data from units observed at the same time or in the same time period 2. Time series: data from a unit (or a group of units) observed in several successive periods 3. Panel data: multidimensional data involving observations of multiple units over multiple time periods
Price observations frequency	Types of data sample: 1. Monthly data: data used in the studies were observed monthly 2. Quarterly data: data used in the studies were observed quarterly 3. Annual data: data used in the studies were observed annually
Ownership	Owners of the forestlands, which mainly include industrial, government, nonindustrial private forest, and aggregate
Owner's age	Dummy variable, 1 if included in the econometric model, 0 otherwise
Nonforest income	Dummy variable, 1 if included in the econometric model, 0 otherwise
Standing stock	Dummy variable, 1 if included in the econometric model, 0 otherwise
Interest rate	Dummy variable, 1 if included in the econometric model, 0 otherwise
Price deflation	Dummy variable, 1 if price is deflated using consumer index, 0 otherwise
Time	Categorical variable, 1 if the article was published between 1980 and 1990, 2 if between 1991 and 2000, 3 if between 2001 and 2010, and 4 if after 2011

Interest rate, *price deflation*.—Interest rate and price deflation based on inclusion in econometric models were also considered as two-level moderators in meta-analysis. PELS estimation may vary among studies depending upon whether the model accounts for interest rate in the market. This is because with higher interest rates, the cost of holding standing stock increases for those forest landowners who act in perfect capital market and do not place a lot of value on nontimber amenities (e.g., Amacher et al. 2009, Bolkesj et al. 2010). Several previous studies (Duerr 1960, Binkley 1987, Amacher et al. 2009, Bolkesj et al. 2010) found a positive effect of interest rate on timber supply, whereas a study in China by Zhang and Buongiorno (2012) reported that interest rate had no effect on timber supply. Hence, it is necessary to consider the interest rate variable in meta-analysis to test the sensitivity of PELS estimates with respect to interest rate. In addition, some articles (Brännlund et al. 1985, Bolkesj and Baardsen 2002, Polyakov et al. 2005, Favada et al. 2009, Bolkesj et al. 2010, Solberg 2011, Zhang and Buongiorno 2012) deflated price data using consumer price index, whereas other articles did not (Raj 1985, Newman and Wear 1993, Prestemon and Wear 1999, Nilsson 2002). Thus, the price deflation moderator was included as a two-level variable to test if studies that took inflation into account showed different estimates of the PELS than others.

Time.—Change in market circumstances over time can affect price responsiveness of timber supply. The PELS has been found to vary over time (Dennis 1989, 1990). To quantify how time period has been related to PELS variation, we classified articles into four categories as 10-year intervals by year of publication (1980 to 1990, 1991 to 2000, 2001 to 2010, and 2011 to 2015) and included them in the meta-analysis.

Meta-analysis

Meta-analysis is a method of systematically reviewing and analyzing results from numerous studies to develop a new single conclusion. Following Beach et al. (2005), we began the analysis with a simple method of vote counting to explore the commonality among studies in terms of independent variables considered. This method summarized the percentage of each independent variable used in these studies. We estimated the summary size (weighted average effect size across studies) with comprehensive meta-analysis (CMA) software (version 3, 2014; Biostat, Englewood, New Jersey). We used a random-effects model, considering that true effects probably varied across studies (rather than a fixed model, which assumes the same value or true effect for all studies). Individual studies within the meta-analysis were weighted by the reciprocal of variance, computed from standard errors obtained directly from each study. Heterogeneity was assessed with the Q statistic, a measure of weighted squared deviations. Total variation (Q_t) is composed of expected or within-study variation (Q_w) and excess or between-study variation (heterogeneity; Q_b). Heterogeneity was quantified using I^2, a descriptive index that estimates the ratio of true variation (heterogeneity) to total variation across studies:

$$I^2 = (Q_t - df)/Q_t \times 100 \tag{2}$$

where df denotes the expected variation Q_w and $Q_t - df$ represents the excess variation (Q_b). I^2 is set to 0 when df exceeds Q_t. A value of 0 percent indicates no heterogeneity, and positive values indicate presence of heterogeneity in the data set, with larger values reflecting a larger proportion of the observed variation because of true variation among studies. Assumptions of homogeneity were considered invalid when P values for the Q test (P_{hetero}) for heterogeneity were less than 0.1 (e.g., Bristow et al. 2013, Iacovelli et al. 2014). For each moderator, we assumed a common among-study variance.

Meta-regression analysis was conducted using CMA (restricted maximum likelihood, Knapp-Hartung model; Inthout et al. 2014) to quantify the correlations between PELS change and the 12 moderators. Categorical moderators are described by discrete categories or levels. Meta-regression produces both intercept and slope estimates, where the intercept is the summary effect size when the moderator is zero, and the slope is the change in effect size in the corresponding level of moderator compared with the reference category or level. The meta-regression P value tests if this slope is equal to zero compared with the reference level.

Sensitivity analysis was performed for the overall summary effect by removing one study and rerunning the meta-analysis for every study remaining in the analysis. The one-study-removed process was repeated for each of the 51 studies. Change in summary effect in response to removing a study shows the contribution of that particular study. The analysis characterizes summary effect consistency and tests for extreme values.

In meta-analysis of effect sizes, where the summaries of interest involve comparison of two groups (often treatment and control) via a mean response ratio or mean difference, it is important to test for publication bias. The idea regards the possibility that nonsignificant treatment effects may be less likely to be published than significant ones (Rothstein et al. 2005). If this were true, studies based on smaller sample size would tend to have larger effect sizes—statistical power declines as sample size declines—raising a concern about missing data from smaller, unpublished studies. The issue of treatment significance is absent from single-group meta-analyses, and the conventional tests related to publication bias (Borenstein et al. 2009) do not apply. Still, it is important to test for the possibility of missing data in meta-analyses of single-group means (such as PELS). There is no reason to suspect that papers reporting proportionately larger or smaller mean PELS would be more or less likely to be rejected for publication. We did examine the funnel plot, to note if there was any tendency for smaller, less precise studies (those with larger standard errors) to vary more than larger studies from the overall summary value. In particular, we noted whether smaller studies whose mean PELS was close to zero were conspicuously absent. Visually, the funnel plot for PELS showed no pattern that would reflect bias toward not reporting small absolute values or negative values. Studies based on large and small sample sizes across the range of standard errors had the expected variability around the common effect size. Applying the Begg and Mazumdar (1994) rank correlation test across all study means in our analysis resulted in an absolute Kendall tau value below 0.07, indicating no tendency for PELS values to either increase or decrease as study size decreased.

Results

Overall summary effects

On the basis of 25 articles summarized (see Appendix Table 1), we found that with regard to data type, 16 studies used time-series data, 6 used cross-section data, and the remaining 8 used panel data. In additon, two studies (Bolkesj et al. 2010 and Sun et al. 2015) included all three data types. For econometric models, 13 studies used linear models to estimate PELS, 8 used log-linear models, 8 applied log-log models, and 2 used all three models to estimate PELS. In reference to the ownership-type moderator, 9 studies focused on NIPF, and 3 on industry and NIPF ownership. In addtion, 10 articles analyzed the total timber supply without considering specific ownership. Among these studies, 76 percent incorporated the standing stock variable in econometric models to examine its relationship with timber supply. By contrast, approximately 48 percent included the interest rate in timber supply modeling. As for studies focusing on NIPF owner characteristics, 33 percent incoporated the owner's age into econometric models, whereas 67 percent had nonforesty income.

The stability of the overall summary size and relative contribution of individual studies was assessed with sensitivity analysis. There were no extreme studies; each one-study-removed summary size in the series from low to high values differed from its neighboring value by no more than 0.002. The most that the overall summary size was changed by the removal of one study was 0.025; with the removal of PELS of 1.242 reported in Kuuluvainen et al. (2014), the overall summary size was reduced from 0.291 to 0.267. Removal of the study by Bolkesj et al. (2010) that reported a low PELS of –0.185 caused a shift of 0.014 in the summary size. The summary PELS was stable and, because of the clear heterogeneity in the data set, resolved to values between –0.02 (highly inelastic) and 1.24 (elastic) across moderators and their respective levels.

Moderator variable analysis

In interpreting the summary PELS, we followed Cooper (2009), who stressed that the size of the summary values and their likely scientific significance is of greater importance than their statistical significance. Similarly, Borenstein et al. (2009) pointed out that although a significant heterogeneity P value provides evidence that subgroups differ among trials (true effects vary), the converse does not hold. A P value above 0.05 does not provide evidence that subgroups are consistent among trials; lack of significance may be due to low statistical power. Even substantial dispersion of true effects might yield $P > 0.05$ with a small number of studies or large within-study variance. Several of the moderator subgroups for which the analyses found no evidence of statistical difference may in reality differ, but insufficient research (low number of studies) precludes ability to resolve the difference. Summary effect precision is denoted by confidence intervals (CIs), which can be used to assess distinctness of moderator levels and degree to which summary effects overlap zero. However, many meta-analysts still use statistical significance to guide their interpretations of results. Hence, we have attempted to note both scientific significance (magnitude of PELS differences) and statistical significance ($P < 0.10$) in summarizing our findings.

There was substantial heterogeneity in the summary size of PELS across studies. Eight of the 12 moderators explained heterogeneity of PELS to a statistically significant level on the basis of the overall P value (<0.10; Figs. 1 and 2). Moreover, the I^2 ($\approx 60\%$) of these various moderators also indicated that the heterogeneity was high.

Forest products.—Across studies, a significant variation of PELS within the forest products moderator was observed ($P_{\text{hetero}} < 0.10$, $I^2 = 63\%$). PELS of roundwood (CI = 0.31, 0.80) and pulpwood (CI = 0.04, 0.22) subcategories appear different, as CIs do not overlap. The summary size of PELS for pulpwood was 0.13, whereas it was 0.56 for roundwood, suggesting that roundwood was slightly more sensitive to price than pulpwood. Likewise, a true variation in PELS between pulpwood (0.13) and sawlogs (0.39) was also found and sawlog supply was more elastic to price. On the contrary, no significant difference was seen on the basis of the overlapped CIs and summary size of PELS between sawlogs and roundwood (Fig. 1).

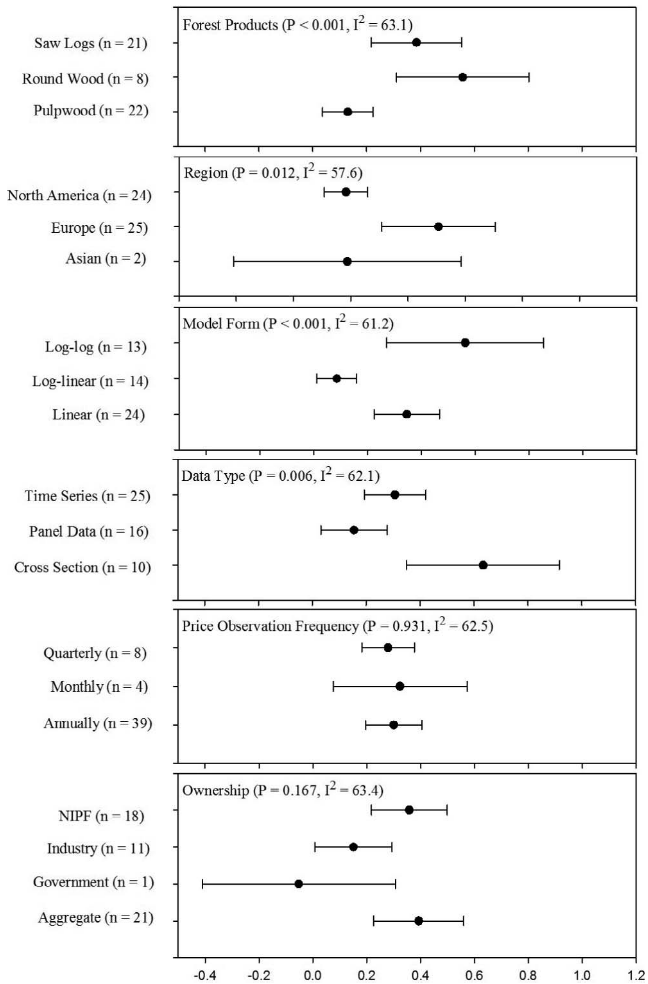

Figure 1.—Weighted summary sizes for multilevel moderators explaining the variance of price elasticity of supply (PELS). n = *number of studies; heterogeneity* P *denotes the probability that all studies share a common PELS;* I^2 *denotes the proportion of observed variance that reflects real differences in PELS among moderator levels.*

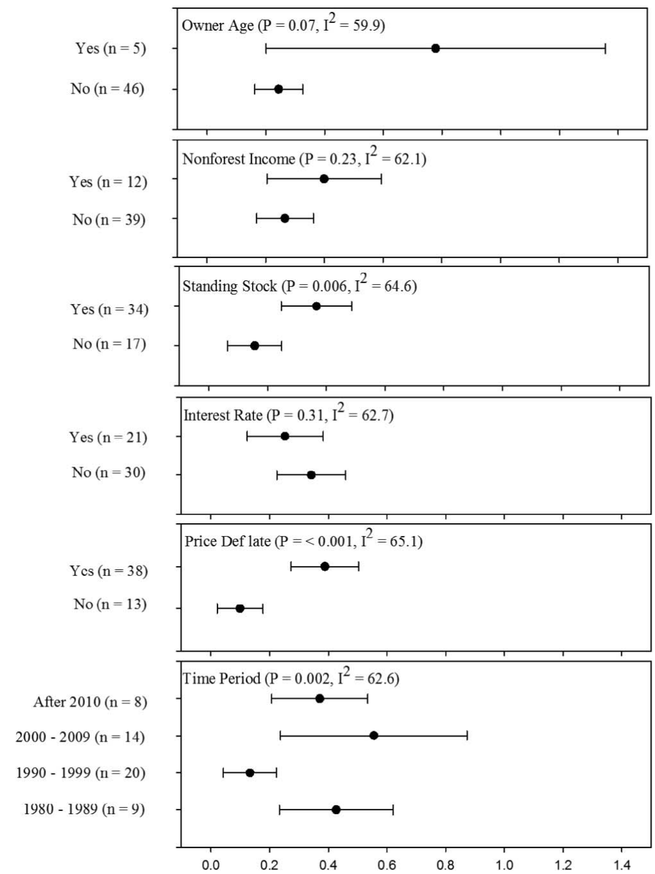

Figure 2.—Forest plots for two-level (Yes/No) moderators and time period variable for explaining variance of price of elasticity of supply.

Region.—Regarding the geographic region moderator, a large heterogeneity of PELS was found ($P_{\text{hetero}} < 0.10$, $I^2 = 58\%$). PELS was estimated to be between 0.31 and 0.71 in Europe, but the same was 0.11 to 0.26 in North America, yielding a statistically significant difference. By contrast, we found that neither the North American region (0.18) nor the European region (0.51) PELS significantly differed compared with studies from Asia (0.19) based on the overlapped CIs of PELS (Fig. 1).

Econometric model form.—Analysis of the PELS variation with respect to the econometric model form moderator showed that the PELS varied greatly among the studies that used different model forms ($P_{\text{hetero}} < 0.10$, $I^2 = 61\%$). A statistically significant difference in PELS was found between a log-log model (0.56, CI = 0.27, 0.86) and a log-linear model (0.09, CI = 0.01, 0.16). Likewise, a noteworthy difference was found between a log-linear model (0.09, CI = 0.01, 0.16) and a linear model (0.35, CI = 0.23, 0.47). By contrast, no difference was found between the log-log and linear models according to the overlapped CIs.

Data type, price observations frequency.—The results of the meta-analysis showed that great heterogeneity of PELS within the data type moderator was found ($P_{\text{hetero}} < 0.10$, $I^2 = 62\%$). However, the estimated summary size of PELS for time-series data (0.31, CI = 0.19, 0.42) and cross-section data (0.63, CI = 0.35, 0.92) did not show heterogeneity based on the overlapped CIs. Similarly, regarding the studies using panel data, the PELS was estimated to be 0.15 and the CI was between 0.03 and 0.28, which overlapped the CIs of studies using time-series data type; thus, no true variation in PELS was found between them. On the contrary, distinct variation of summary size of PELS was observed between the studies using cross-section data type (0.63) and those using panel data (0.15). No significant variation of the PELS was found among the levels of the price observations frequency moderator ($P_{\text{hetero}} > 0.10$, $I^2 = 63\%$). Also, the overlap of the CIs among monthly (0.07, 0.57), quarterly (0.18, 0.38), and annual (0.19, 0.41) data indicated that no great heterogeneity of PELS was seen among them.

Ownership, owner age, nonforest income.—Results indicated that heterogeneity of PELS was not statistically significant in the ownership moderator ($P_{\text{hetero}} > 0.10$, $I^2 = 63\%$). Specifically, no significant PELS difference was seen between NIPF (0.36) and aggregate (0.39) ownership. A similar result in PELS was found between government (–0.05) and industry (0.15) ownership. Likewise, no PELS difference between NIPF and industry, and between NIPF and government ownership was found on the basis of the summary size of PELS. Those results were also indicated by the overlapped CIs in the forest plot (Fig. 1). The PELS estimated from supply models with and without taking owner age into account were 0.78 (CI = 0.20, 0.36) and 0.24 (CI = 0.16, 0.33), respectively, a statistically significant ($P_{\text{hetero}} < 0.10$, $I^2 = 60\%$) difference. However, the overlapped CIs suggested that no significant heterogeneity of PELS estimation was found between studies that did and did not control for the owner's age in timber supply modeling. No true variation in PELS was found between studies with and without nonforest income in the timber supply models ($P_{\text{hetero}} > 0.10$, $I^2 = 62\%$). The summary size of PELS was 0.40 (CI = 0.20, 0.59) and 0.27 (CI = 0.17, 0.36), respectively, with and without taking the nonforest income into account in timber supply modeling.

Standing stock.—Forest characteristics represented by standing stock showed that variation in PELS estimates was found while considering it in timber supply models ($P_{\text{hetero}} < 0.10$, $I^2 = 65\%$); the summary size of PELS was 0.37 (CI = 0.25, 0.49) and 0.16 (CI = 0.06, 0.25), respectively, with and without taking standing stock into account in timber supply modeling. In other words, the heterogeneity of PELS could be explained by whether researchers accounted for the size of standing stock in the models estimating PELS.

Interest rate, price deflation: In addition, meta-analysis results of the two-level categorical moderator of interest rate showed no significant heterogeneity of PELS between the studies with and without it in timber supply modeling ($P_{\text{hetero}} > 0.10$, $I^2 = 63\%$). Specifically, summary size of PELS was estimated to be 0.25 (CI = 0.12, 0.38) and 0.34 (CI = 0.23, 0.46), respectively, for supply models with and without considering interest rate. Regarding the price deflation moderator, the estimation of PELS varied greatly between the two categories ($P_{\text{hetero}} < 0.10$, $I^2 = 65\%$). The summary size of PELS was estimated to be 0.39 (CI = 0.27, 0.50) for studies that did deflate price and 0.10 (CI = 0.02, 0.18) for the studies that did not.

Time.—The results showed that the variance of PELS varied significantly in the time period moderator ($P_{\text{hetero}} < 0.10$, $I^2 = 63\%$). No significant PELS difference was seen among 1980 to 1990, 2001 to 2010, and 2011 to 2015, but a slight difference was found in the time period 1991 to 2000. Specifically, the PELS was between 0.21 and 0.87 in periods 1980 to 1990, 2001 to 2010, and 2011 to 2015. By contrast, the estimated PELS was between 0.04 and 0.22 in the period 1991 to 2000.

Meta-regression

Meta-regression results (Table 2) indicated that PELS changed significantly within the subgroups of the moderators including forest products, region, econometric model form, and data type. We used roundwood as the reference category for forest products and the results suggested that compared with roundwood, the variation in PELS was significantly lower in the case of pulpwood. This result indicated that the estimated PELS of pulpwood was 0.48 times lower than that of roundwood, which was consistent with the summary effect of meta-analysis. Moreover, results from meta-regression for forest products suggested that a significant difference of PELS was found between pulpwood and roundwood, but no big difference of PELS between roundwood and sawlogs. Using Asia as a reference category, the dummy variable to capture the study involving the timber market in Europe was positively related to the change of PELS and the coefficient 0.39 indicated that PELS reported in European studies was 0.39 times greater than those reported in the Asian studies. By contrast, a similar dummy variable to capture studies involving the timber market in North America showed an insignificant effect on the variation in PELS, suggesting that the PELS in North American markets were not significantly different from that in the Asian markets.

Table 2.—Significant moderators of meta-regression to explain the variation of price elasticity of supply.[a]

Moderator	Subcategories within moderator	Coefficient	SE
Forest product	Roundwood	—	—
	Pulpwood	−0.48	0.09**[b]
	Sawlogs	−0.08	0.11
Region	Asia	—	—
	Europe	0.39	0.23*
	North America	−0.07	0.23
Econometric model form	Linear	—	—
	Log-linear	−0.23	0.11
	Log-log	0.41	0.11**
Data type	Panel data		
	Cross-section	0.77	0.11**
	Time series	0.10	0.11
Price observations Ffrequency	Annually	—	—
	Monthly	−0.05	0.13
	Quarterly	−0.09	0.18
Ownership	Aggregate	—	—
	Government	−0.36	0.30
	NIPF	0.14	0.11
	Industry	−0.27	0.12
Owner age	Yes	0.83	0.11
Nonforest income	Yes	0.38	0.09
Standing stock	Yes	0.42	0.08**
Interest rate	Yes	−0.10	0.09
Price deflation	Yes	0.49	0.10**
Time	Period 1	—	—
	Period 2	−0.48	0.17**
	Period 3	0.29	0.18
	Period 4	−0.05	0.18

[a] $R^2 = 0.33$, $Q_{\text{explain}} = 42.5$ percent, $n = 339$. The first category within each group was the reference category in meta-regression model. NIPF = nonindustrial private forest.

[b] ** = $P = 0.05$; * = $P = 0.10$.

For econometric model form, we used the linear model as the reference level and the result indicated that the PELS estimated from the log-log model had a significantly positive effect on the change of PELS compared with the linear model. The coefficient 0.41 represents that the estimated PELS using the log-log model was 0.41 times greater than that of the linear model. This result was in line with the meta-analysis, which also suggested that there was a great heterogeneity of PELS between the linear and log-log models. Regarding the data type, a positive relationship between cross-section data type and variation in PELS was found. Specifically, the PELS estimated with cross-section data was 0.77 times greater than that estimated with panel data. It was consistent with the meta-analysis result in which a big difference of PELS was found between studies using cross-section data and panel data. No significant effect of price observation frequency was found on the variation in PELS. Similarly, no significant association was found between the ownerships and the variation in PELS. Inclusion of owners' age and nonforest income in the model also were not significantly associated with the variation in PELS.

In addition, a significant variation of PELS was seen in the two-level category moderators including standing stock and price deflation, suggesting that variation in estimated PELS was significantly influenced by the inclusion or exclusion of these factors in the supply model. Standing stock was also found to have significant and positive effects on the variation in PELS. Specifically, PELS was 0.42 times greater in studies that included standing stock in the supply model than those not including this variable. On the other hand, the interest rate variable was statistically insignificant, suggesting that the variation in PELS was not significantly different between studies that incorporated interest rate in supply models and studies that did not. However, PELS in studies that deflated price to the consumer price index were found to be 0.49 times larger than those that did not account for inflation. Last, study time period had a significant influence on the estimation of PELS indicated by the meta-regression results using 1980 to 1990 as the reference level. The negative coefficients suggested that the studies conducted in more recent years were more likely to find significantly higher variation in PELS than their older counterparts.

Discussion

Meta-analysis results demonstrated that PELS varied with different forest products, which is consistent with Dennis (1990), who also found that price elasticity varies substantially between different forest products. Summarized mean PELS was significantly larger in roundwood and sawlogs compared with pulpwood. Relatively less sensitivity of pulpwood supply with respect to price may be attributable to the fact that it is often considered an outcome of ''joint production'' with roundwood. Therefore, when the roundwood price increases in the market, it will raise the probability of both final harvests and thinning, which both produce pulpwood, but not roundwood. Pulpwood supply being less sensitive to price (compared with sawlogs) may be explained by the fact that pulpwood markets are often less competitive than sawlog markets because of their low value and residual nature of the product and the fact that there are fewer buyers. Moreover, pulpwood is supplied to paper mills and oriented strand board mills that are larger corporations with more contractual relationships developed with suppliers.

Variation in PELS was found among different geographic regions. The difference in PELS between North America and Europe is particularly interesting and is partly attributable to differences in forest harvest–related policies, ownership structure, and market demand (Sohngen et al. 1999, Sohngen and Sedjo 2000). However, no distinct variation of PELS in North America or Europe from Asia is probably because of the relatively small sample size of studies from Asia. This does not suggest that there is no PELS difference between Asia and the other two regions, but instead warrants more research to statistically test this potential difference.

Econometric model form also explained PELS variation among different studies. Consistent with the results reported by Bolkesj and Solberg (2003), econometric theories and statistical methods used in timber supply analysis had a marked effect on the PELS. Likewise, Prestemon and Wear (2000) described that the variance of econometric models (e.g., linear and logit) applied in the previous studies indicate different sensitivities of timber supply to market price.

Furthermore, although no evidence of statistical difference in PELS was found among the price observation frequency in meta-analysis, it does not necessarily mean that in reality there is no difference among them. This could be due to the insufficient statistical power to resolve the difference (e.g., only four studies for monthly data). For the three data types, variation of PELS existed between cross-section and panel data on the basis of their summary estimation of PELS, which was consistent with the previous studies. Kuuluvainen et al. (2014) reported that the PELS was around 2.5 by using cross-section data, which was not in line with the results reported by Bolkesj et al. (2010) using panel data. Moreover, Bolkesj et al. (2010) analyzed the PELS of sawlogs and pulpwood by using all three different data types and concluded that the PELS varied among them. The explanation for the variation of PELS among different data types is that regional timber prices are highly correlated with omitted region-specific variables. Nonetheless, it is infeasible to consider the price dynamics with so few observations over time.

Meta-analysis results indicated that no true variation of PELS was found between NIPF and aggregate ownership, which is possibly because NIPFs dominated the number of owners in aggregate studies. Moreover, no heterogeneity of PELS was found by meta-analysis and meta-regression in this study among ownerships of NIPF, industry, and government—suggesting that further research is needed for all these ownerships to statistically test their potential differences. An intuitive explanation is that different ownerships have different forest management objectives and they might react in a different way to change in market price. For example, timber production is the main purpose of industry-owned forests; by contrast, management objectives of NIPF owners ranging from amenity to timber to heritage are affected by various nonmarket factors (Salmon et al. 2006, Kittredge and Thompson 2016). Moreover, Cubbage (1986) argued that NIPF owners' relative lack of knowledge about timber price partly contributes to their unresponsiveness to timber price, resulting in a less than socially desirable quantity of timber supply. Many studies (Robinson 1974, Kuuluvainen et al. 1996, Karppinen 2000, Pattanayak et al. 2002, Wiersum et al. 2005, Ní Dhubháin et al. 2007, Favada et al. 2009, Kittredge and Thompson 2016) also suggested that NIPF-owned forests had great heterogeneity of PELS owing to multiple management objectives, which are influenced by various nonprice factors. On the contrary, industry ownership is profit oriented and may respond quickly to supply (or lack thereof) of more timber when price increases (or decreases). Regarding government ownership, lack of heterogeneity in PELS may relate to the fact that government-owned production forests are primarily used to supply timber to meet a wide range of societal needs rather than profit maximization, even during the periods of high prices.

Referring to the ownership characteristics, no heterogeneity of PELS was found for owner age, which could be due to the insufficient statistical power. However, the findings of Favada et al. (2009), Kuuluvainen et al. (1996), and Kuuluvainen and Tahvonen (1999) reported that PELS variation was correlated with the owner age. The possible reason for this heterogeneity of PELS is that the owners' preference possibly varies with age. For instance, older forest owners might be less willing to harvest timber, but instead more interested in nontimber benefits such as ecosystem services (e.g., Mackerron et al. 2009, Knoot et al. 2015, Tian et al. 2015) than younger ones and thus, supply less timber to the market. The nonforest income variable was found to have no impact on PELS in our analysis. This contradicts the conclusion of Hyberg and Holthausen (1989) that reported that income negatively relates to timber supply, an observation consistent with Uusivuori and Kuuluvainen (2005).

With regard to the two-level moderators in meta-analysis, inclusion of standing stock and price deflation in the supply models was significantly related to variation in PELS estimates. For standing stock, Favada et al. (2009) and Bolkesj and Solberg (2003) found that this variable positively affected timber supply, which is consistent with the meta-analysis results in our study. No previous study considered the variable of price deflation with consumer price index in timber supply modeling research. Meta-analysis and regression results demonstrated that the price deflation moderator was considerably correlated with PELS heterogeneity. However, meta-analysis and meta-regression results both indicated that interest rate variable in econometric models was not significantly related to the change of PELS. Although the interest rate can affect the opportunity cost of delaying forest harvest, it is unclear how it affects timber supply if the net savings is less than or equal to zero. On the contrary, it has a positive effect if the net savings is greater than zero (Bolkesj and Solberg 2003).

In line with Dennis (1990), time period had a marked effect on PELS variation and the four levels of time periods influenced PELS differently. The reason is probably due to the difference in technological advancement and market situation.

Conclusions

This study identified factors that affect the heterogeneity of PELS. These findings may provide a theoretical as well as empirical basis to assist practitioners and policy makers to develop a deeper understanding of market dynamics. Policy makers are concerned with the responsiveness of producers in supplying timber as price changes. Our meta-analysis results suggest that PELS variation depends on forest products and geographic regions. Specifically, a large difference in PELS was found between sawlogs and pulpwood, indicating that the responsiveness of timber suppliers to price change differs with different categories of forest products. Moreover, pulpwood is less elastic to price than sawlogs, suggesting that pulpwood supply would not change as much as sawlog supply with price change. Regarding the geographic regions, a large heterogeneity of PELS was found within North America and Europe, implying that dividing a large geographic region into more homogeneous subregions may be beneficial in understanding the market dynamics of timber supply. The other important implications from our findings are that future efforts to forecast timber supply should pay attention to the fact that PELS varies by product type, geographic region, and other factors identified in this study. Hence, econometric models should take those differences into account for accurate forecasting. Additionally, forest market planners and policy makers interested in regulating the timber market through price-related instruments (e.g., price subsidy, tariffs) may also benefit from our findings in understanding the relative efficacy of such tools in influencing market supply.

A few limitations of this study should be noted. First, the meta-analysis of PELS in this study does not consider the interaction effect of multiple moderators to explore the combined or conditional effect on the PELS. Therefore, evaluating the interaction effects of price and other variables on heterogeneity of PELS may be an interesting area of future research on this topic. The second limitation is that our study did not consider the PELS variation estimated from a mixed data set. In other words, there might be a varying number of observations for different variables within studies using cross-sectional time-series data. For instance, forest owner income and age vary over each cross section but not over time, so using regional price observations might result in fewer cross-section observations on prices than cross-section observations on the quantities traded. This could arguably influence the heterogeneity of PELS but it was not included in meta-analysis. Third, although the number of actual price observations might have a potential effect on the variation of PELS, it could not be included in the analysis, as many of the reviewed studies did not provide this information.

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Appendix Table 1.—Studies included in meta-analysis.[a]

Study	Variables									
	Wood product	Regions	Econometric model	Data type	Price observations frequency	Ownership	Standing stock	Interest rate	Age	Income
Brännlund et al. (1985)	Pulpwood, sawlogs	Sweden	Linear	Time series	Annual	Aggregate	No	No	No	No
Kumar (1985), Raj (1985)	Sawlogs	Malaysia	Log-linear	Time series	Annual	Government	No	No	No	No
Daniels and Hyde (1986)	Sawlogs, pulpwood	United States	Log-linear	Time series	Annual	Aggregate	Yes	No	No	No
Newman (1987)	Pulpwood, sawlogs	United States	Linear	Time series	Annual	Aggregate	Yes	Yes	No	No
Kuuluvainen et al. (1988)	Sawlogs, pulpwood	Finland	Linear	Time series	Quarterly	NIPF[b]	Yes	No	No	No
Hultkrantz and Aronsson (1989)	Roundwood	Sweden	Linear	Time series	Annual	NIPF	Yes	Yes	No	No
Newman (1990)	Pulpwood, sawlogs	United States	Linear	Time series	Annual	Aggregate	Yes	No	No	No
Carter (1992)	Sawlogs, pulpwood	United States	Linear	Time series	Annual	Industry	Yes	Yes	No	No
Hetemäki and Kuuluvainen (1992)	Pulpwood	Finland	Linear	Time series	Quarterly	NIPF	Yes	Yes	No	Yes
Newman and Wear (1993)	Sawlogs, pulpwood	United States	Linear	Cross-section	Quarterly	Industry, NIPF	No	No	No	No
Toppinen and Kuuluvainen (1997)	Pulpwood, sawlogs	Finland	Linear	Time series	Annual	NIPF	Yes	Yes	No	Yes
Prestemon and Wear (1999)	Pulpwood, sawlogs	United States	Log-linear	Panel data	Annual	Industry, NIPF	No	No	No	No
Prestemon and Wear (2000)	Pulpwood, sawlogs	United States	Log-linear	Panel data	Annual	Industry, NIPF	No	No	No	No
Bolkesj and Baardsen (2002)	Roundwood	Norway	Linear	Panel data	Annual	NIPF	Yes	Yes	Yes	Yes
Nilsson (2002)	Pulpwood	Sweden	Log-log	Time series	Annual	Aggregate	Yes	No	No	No
Polyakov et al. (2005)	Pulpwood	United States	Linear	Time series	Annual	Aggregate	No	No	No	No
Mutanen and Toppinen (2005)	Sawlogs	Finland	Log-linear	Time series	Quarterly	NIPF	Yes	Yes	No	No
Favada et al. (2007)	Sawlogs	Finland	Log-log	Cross section	Annual	NIPF	Yes	Yes	Yes	Yes
Favada et al. (2009)	Sawlogs	Finland	Log-log	Cross-section	Annual	NIPF	Yes	No	Yes	Yes
Bolkesj et al. (2010)	Sawlogs, pulpwood	Eastern Norway	Log-log	Cross-section, time series, panel data	Annual	Aggregate	Yes	Yes	No	No
Solberg (2011)	Roundwood	Europe (different countries)	All three models	Panel data	Annual	Aggregate	Yes	Yes	No	No
Zhang and Buongiorno (2012)	Roundwood	China	Log-log	Panel data	Annual	Aggregate	Yes	Yes	No	Yes
Fooks et al. (2013)	Roundwood	United Kingdom	Log-linear	Time series	Monthly	Aggregate	Yes	No	No	No
Kuuluvainen et al. (2014)	Roundwood	Finland	Log-log	Cross-section	Annual	NIPF	Yes	No	Yes	Yes
Sun et al. (2015)	Sawlogs, pulpwood	United States	All three models	Cross-section, time series, panel data	Monthly	Industry	Yes	Yes	No	Yes

[a] If the variable was considered in the study, we denote Yes; otherwise No.
[b] NIPF = nonindustrial private forest.