Modeling International Trade of Forest Products: Application of PPML to a Gravity Model of Trade

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Abstract

To model international trade of forest products we use a gravity model of trade. In modeling trade, we estimate the impact of importer gross domestic product (GDP), exporter GDP, and distance between trading partners using Poisson pseudo-maximum likelihood (PPML). When estimating the log-linearized gravity model (ordinary least squares [OLS]), two issues arise. First, potential bias associated with truncation of all zero-trade observations due to the nonexistence of the natural log of zero. Second, heteroscedasticity can bias results from the log-linearized gravity model because of the multiplicative error term of the stochastic gravity model. To address these two issues, we propose avoiding the log-linearized gravity model and instead estimate the nonlinear gravity model via PPML. To estimate the model, trade data are compiled from the Food and Agriculture Organization of the United Nations. The observation window is from 1997 to 2014 and covers 13 product categories at a country-pair level. In our estimation, we find systematic differences in estimates from OLS in comparison with estimates from PPML. Using the estimated elasticities, in combination with estimates of future GDP from shared socioeconomic pathways, we project future US exports to the year 2030 for each item category in addition to total exports for Brazilian wood pulp, New Zealand industrial roundwood, and Canadian coniferous sawnwood. Using our approach, we provide a tool for policy makers and industry leaders alike to make informed decisions over prior estimates of forest product trade.

The global forest sector could shift dramatically in the coming years under the influence of new market conditions, regional policies, and environmental change; the cumulative effect of these factors could lead to meaningful impacts on the global trade flow of forest products. For example, the emergence of new multilateral trade deals in some regions and a return to protectionist policies in others could fundamentally shift the import–export balance of forest product flows. Access to the internet and smart phones could decrease demand for traditional pulp and paper products globally, but packaging materials could see a continued demand surge as Amazon and similar service providers continue to grow globally (Latta et al. 2016). Management changes on the resource base could also affect product supply and net trade; for instance, forest conservation efforts and other policies designed to stabilize long-term climate change could significantly alter forest land use and management decisions to increase terrestrial carbon storage (van Vuuren et al. 2017). Finally, recent expansion in international trade of wood pellets and forest biomass resources for energy generation could have important long-term implications for forest resource management and product markets (Galik and Abt 2015, Kim et al. 2018). If the structure of the forest sector undergoes these fundamental changes to accommodate changing market and policy conditions, it is important to assess how long-term forest product markets could be affected by macroeconomic changes.

A necessary first step is to improve our understanding of global forest product trade and sensitivity of regional trade patterns to macroeconomic conditions (e.g., population and gross domestic product [GDP]) and relative transportation costs (e.g., distance between trading partners). With potentially broad application to land management, market

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analysis, and forest bioenergy expansion, econometric analysis of global forest product trade is becoming increasingly important. Recent advances in econometric frameworks for estimating demand elasticities of international trade offer methods for projecting future trends for forest product imports and exports in key forest demand and supply regions globally.

This article builds on the recent literature of the international forest product trade by providing new estimates of trade elasticities from a gravity model estimated via Poisson pseudo-maximum likelihood (PPML) instead of ordinary least squares (OLS) and offering a methodology for projecting future trade flows. The improved econometric estimates of forest product trade can be used to assess the impact of certain policy restrictions (e.g., new or increased import tariffs) on forest product trade flows. Furthermore, such estimates can inform national or global structural economic models of land use systems and markets that are often applied to evaluate the implications of long-term policy efforts (e.g., bioenergy) on forest resource management.

The article closes with a comparison of alternative forest product trade projections using macroeconomic scenarios from the shared socioeconomic pathway (SSP) database to show how assumptions regarding future economic conditions and trade liberalization can influence long-term projections of forest product trade. The SSPs are five narratives that describe future paths along which humanity may travel in the 21st century. These pathways identify key factors that will determine the level of challenges for society to mitigate and adapt to potential climate change. These factors include demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources. The SSPs were designed to serve as a basis for integrated scenarios of emissions and land use, as well as climate impact, adaptation, and vulnerability analysis (O'Neill et al. 2017).

The next section provides a brief literature review of international trade models of the forest products sector and introduces the concept of the gravity model. Then, we discuss our data and econometric estimation procedure, provide results, and discuss implications for a sample of long-term SSP projections.

Literature Review

There is an extensive literature that has evaluated global forest product markets, though many of these studies have relied on structural economic models of the global forestry system or global forest product markets. Examples include partial equilibrium models such as the global timber model (Sohngen et al. 1999, Tian et al. 2016), the global forest products model (Buongiorno et al. 2003, Johnston 2016), the European Forest Institute's global trade model (Kallio et al. 2004)[1] as well as global computable general equilibrium models (Hertel et al. 2009, Suttles et al. 2014), and integrated assessment models (Wise et al. 2009, Eriksson 2015) that include forest product aggregates. Structural models often rely on elasticity assumptions derived from econometric studies to calibrate demand functions (in the case of price endogenous models) or to build exogenous demand projections for different regions and product combinations.

Much of the econometric analysis in the forest products trade literature has focused on trade between a handful of countries, regional trade policies, and analysis of specific products. Perera and Vlosky (2009) analyze the exports of tropical wood products from Sri Lanka. To analyze the imports of wood pulp and recovered paper into China, Tang et al. (2015) implement an augmented gravity model. Wu et al. (2016) perform a comparative study of primary forest product exports in the United States and China. Prestemon (2015) estimates the impact of the Lacey Act Amendment of 2008 on US imports of hardwood lumber and plywood. The common thread that strings these studies together is the narrow scope.

To widen that scope, econometric analysis of the global forest product trade that accounts for trade flows between all documented regional trading partners' perspectives has recently become part of the forest product literature, with emphasis placed on the gravity model for empirical exercises. Borrowing from the physics realm, economists have applied the gravity equation to the context of trade by thinking of each country or region as having gravitational mass, pulling goods and services toward themselves. In this context, gravitational mass can then be thought of as economic mass, measured by a macroeconomic indicator such as GDP. In its most basic form the gravity model of trade states that bilateral trade between two countries is a function of the importing country's GDP, the exporting country's GDP, and the distance between the two countries. However, despite its simplicity and abundant use in empirical work, the gravity model was not originally founded on economic theory. Thus, researchers across the years have made the necessary connections between gravity equations and economic theory.

Before Anderson (1979), gravity models were used in applied contexts with little grounding in economic theory. Using a bottom-up approach, Anderson starts with a Cobb-Douglas national expenditure function. From the expenditure function, a gravity equation is derived, much like those used in the empirical literature. Using more rigorous microeconomic foundations, Bergstrand (1985) derives a gravity equation from a general equilibrium model for international trade. By imposing two assumptions, Bergstrand arrives at a partial equilibrium solution that results in a ''generalized'' gravity equation. The first assumption is a ''small open economy,'' allowing foreign price levels, foreign interest rates, and foreign incomes to be treated as exogenous. The second assumption is that utility and production functions are identical across countries. Applying these two assumptions results in a reduced-form equation, derived from a general equilibrium framework, that can be estimated as a simple linear regression.

In Bergstrand (1989, 1990), the generalized gravity equation is altered to allow for focus on two issues. First, incorporating factor-proportions theory[2] placed emphasis on the factor endowments of each country. Second, using the Heckscher-Ohlin-Samuelson model to explore intraindustry bilateral trade. Although both areas may be considered specific or niche, these latter two extensions of Bergstand's original theoretical contribution show the flexibility of the

[1] A review of partial equilibrium models of the forest sector including regional models can be found in Latta et al. (2013).

[2] Also referred to as the Heckscher-Ohlin-Samuelson model.

gravity model approach in its ability to incorporate other areas of economic theory.

Although certainly not the first application of a gravity model, McCallum (1995) is one of the first to address the issue of trade agreements. Likewise, Rose (2000) includes controls for currency unions to explore the impact of a common currency on trade. The importance of these two papers is not only to showcase the flexibility of the gravity model, but also to attempt to control for a form of heterogeneity that is largely unobserved, trade costs.

Formally exploring the issue of unobserved heterogeneity, such as trade costs, Anderson and van Wincoop (2003) suggest a method that provides consistent estimates and addresses the unobserved heterogeneity issue. In their estimation, the authors use a nonlinear least-squares approach, a novelty in comparison with prior literature. By including country indicator variables, the authors also begin to address the issue of unobserved heterogeneity in terms of trade costs.

Summarizing the stance of the applied literature, Baldwin and Taglioni (2006) outline econometric problems facing gravity models and typical mistakes researchers make as a result. The most important econometric problem the paper points out, aptly dubbed the ''gold medal error,'' is the issue of unobserved trade costs. Outlining both the theoretical source of the bias and evidence in empirical literature, the paper suggests that researchers include nation or country-pair fixed effects (FEs). Including nation or country-pair indicators will control for unobserved characteristics specific to each nation or country pair, partially capturing unobserved trade costs.

The application of the gravity model to the trade of forest products is a relatively new development with respect to the broader trade literature. Zahniser et al. (2002) take a gravity model approach to estimate the impacts of the Central America Free Trade Agreement and the North American Trade Agreement on US agricultural exports.

One of the first papers to apply a gravity model exclusively to the trade of forest products is Akyuz et al. (2010). Using the United Nations Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) trade data, the paper models trade between Turkey and countries within the European Union (EU). The results show a positive relationship between exporter GDP and exports and a similar relationship between importer GDP and exports. Additionally, being a nonmember of the EU is shown to have a negative impact on trade.

Using a different empirical model and data set, Buongiorno (2015) explores the impact of a currency union on the trade of forest products. Diverging from the typical gravity model, the paper presents a differential gravity equation. The first-differenced log-linearized model removes all unobserved time-invariant characteristics and is estimated using OLS and FEs. The results show a positive to neutral impact of the euro on the trade of forest products between eurozone countries.

Applying the first-differenced model once again, Buongiorno (2016) incorporates all international trade of forest products. Using OLS, FE, and random effects estimators, the paper shows a positive impact of both importer and exporter GDP on trade. Additionally, the paper shows no difference in coefficient estimates across the estimators. Using the OLS estimates in concert with International Monetary Fund GDP projections, the growth in exports is projected to the year 2020. Under this framework, the Trans-Pacific Partnership is evaluated on the basis of changes in GDP projections under the trade agreement.

Traditionally, gravity models have been estimated using linear estimators such as OLS. However, because of the multiplicative functional form of the theoretical gravity model, linear estimators can pose a problem (Silva and Tenreyro 2006). Outlining issues associated with log-linearized versions of the gravity model and their subsequent estimation using linear estimators, Silva and Tenreyro (2006) explore the prospects of nonlinear estimators. As such, the paper concludes that the PPML estimator is best suited to applications of gravity models.[3] A similar empirical approach is developed for this article to estimate a gravity model of the forest product trade, building upon the previous empirical approaches of Buongiorno (2015, 2016).

Data and Methods

To estimate a gravity model, three primary data components are required: bilateral trade flows, economic mass (GDP in our analysis), and physical distance. These data must then be modified to account for issues such as imperfect or missing data before inclusion in the empirical model.

Primary data

Each year, the FAO releases annual trade data on forest products. Products are assigned to an item category and aggregated for that year. For each product category, an observation is given an element assignment for production, export (or import) quantities, and values. Depending on the item category and the element assignment, the units are either metric tons, cubic meters, or US dollars. The macroeconomic data used are also collected and compiled by FAOSTAT. Macroeconomic indicators reported include GDP, value added by sector, and gross fixed capital formation. GDP data are available at the country level from 1970 to 2015 and are measured in 2005 US dollars.

Published by the Centre d'Études Prospectives et d'Informations Internationales (CEPII), the GeoDist data set contains a host of time-invariant, country-pair-specific information. The main datum of interest is geographic location. For each country, the coordinates of a major city's geographic center are given. The city used is either the capital city or a different one that is the economic center of the country. These coordinates are used to determine the physical distance between two trading countries. Additionally, other cultural and geopolitical information is available, such as primary language, past colonizer(s), and an indicator for being landlocked. Cultural and geopolitical information is not included in our analysis, though future work could explore these factors in more detail in the context of forest product trade.

Data modifications

To ascertain the final panel used in estimating the gravity model, a few modifications to the data were performed. Given the imperfect measurement of exports, adjustment

[3] In comparison with nonlinear least squares, gamma pseudo-maximum likelihood, and a threshold tobit model proposed by Eaton and Tamura (1994).

observations are often included for a country's observations within any given year. This adjustment enters as a bulk adjustment for all exports from that particular country for that particular year. For the entire panel there are 120,916 adjustment observations. Adjustments to export values[4] range from –\$6,409,535 to \$5,605,691. The larger adjustment observations tend to belong to the larger exporting countries. Adjustments of a few million dollars are small for a country like the United States, which sees exports in the billions of dollars.

In addition to the adjustments, some observations list an unspecified partner country. In total there are 35,639 observations with an unspecified importing country. Of these unspecified observations, export values range from –\$824,574 to \$3,662,085. We exclude the adjustment observations as they are aggregated to the exporter-year level and do not provide enough information to be able to disaggregate the adjustments across each exporter–importer country pair. Excluding the adjustments does not introduce a source of bias but will introduce noise. We expect larger standard errors because of measurement error on the dependent variable.

Observations for the years before 1997 or after 2014 are excluded from the panel. This is due to sporadic and unreliable reporting in the earlier years and incomplete data in the later years. Before implementing the year restrictions there are 2,433,877 observations; 12,271 observations occur before 1997 and 121 observations occur after 2014, resulting in a reduced sample size of 2,429,119 observations.

Adjustment observations and FAO aggregate observations are excluded from the sample, leaving only country-pair imports and exports for each item category in the final sample. Additionally, some country pairs that appear in the FAO trade data set are dropped because of lack of representation in the CEPII data set. The sample size after excluding the adjustment and aggregate observations is 2,040,641 observations.

After implementing the sample restrictions, the resulting data set is an unbalanced panel of country-pair imports and exports for each item category. To balance the panel, we assume that a missing observation is a zero-trade observation. For any country pair that appears in the panel at least once, all nonreporting years receive a zero value for trade. The result is a balanced panel of 5,248,654 observations that includes both import and export values and quantities.

Finally, four merges are performed. Given that each observation represents trade flows in one direction between any two countries, GDP and distance data must be merged onto each observation twice, once for the exporting country and once for the importing country.

Final data

In the final data set, forest products are left in their FAO item categories as reported in the FAOSTAT data set and are not aggregated into broader categories.[5] This finer level of aggregation is a divergence from prior literature on the trade of forest products. Table 1 summarizes the exports of each item category. The largest item category, by share of total US exports, is paper + board, followed by wood pulp and nonconiferous sawnwood. Since most exports fall into one of these three categories, the rest of the paper will exclude the other categories from the discussion.[6]

Empirical model

The key focus of the gravity model is that trade is a function of economic mass and distance. In its simplest form, the gravity model takes on the following form:

$$\mathrm{Trade}_{ijt} = \frac{\mathrm{GDP}_{it}\mathrm{GDP}_{jt}}{\mathrm{Distance}_{ij}}(\mathrm{Costs}_{ijt})\forall i \neq j \tag{1}$$

where

- Trade_{ijt} = trade flows from country i to country j in year t,
- GDP_{it} = nominal GDP for exporting county i in year t,
- GDP_{jt} = nominal GDP for importing country j in year t,
- $\mathrm{Distance}_{ijt}$ = geodesic distance between representative cities of countries i and j, and
- Costs = cost to trade from country i to country j in year t.

The definition of costs in this context extends beyond the transportation costs of the good. Costs encompass any burden or impediment to trade such as protectionist trade policies, tariffs, political instability, cultural differences, and geographic barriers. Some of these impediments are observed, although many are not.

Beginning with the simplified gravity equation, the nonlinear model becomes stochastic with the introduction of an idiosyncratic error term, leading to the following nonlinear stochastic model given in Equation 2:

$$\mathrm{Trade}_{ijt} = \frac{\mathrm{GDP}_{it}\mathrm{GDP}_{jt}}{\mathrm{Distance}_{ij}}\varepsilon_{ijt} \tag{2}$$

where ε_{ijt} represents an idiosyncratic error term specific to trade from country i to country j in time year t. Within the error term are the unobserved trade costs. Without the ability to observe trade costs and include them in the empirical model, estimates will be subject to omitted variables bias. To partially address the issue of unobserved trade costs, two types of FEs are included. First, country FEs, each as an importer and exporter, are included separately but in addition to year effects.

$$\varepsilon_{ijt} = \mu_i + \eta_j + \gamma_t + e_{ijt} \tag{3}$$

Let μ_i be the time-invariant heterogeneity associated with importer i, η_j be the time-invariant heterogeneity associated with exporter j, γ_t be the unobserved heterogeneity associated with time, and e_{ijt} is the remaining unobserved heterogeneity. By including indicators for each importer, exporter, and year, we control for the unobserved heterogeneity associated with μ_i, η_j, and γ_t. Additionally, in the presence of nominal GDP, the time effects (γ_t) encompass

[4] Nominal US dollars.

[5] For greater detail on the inclusion and exclusion of certain goods in the product categories, please refer to the FAO Yearbook on Forest Products.

[6] Results and projections for all other item categories can be found in the Appendix in Tables S1–S4, which are supplemental materials that can be found online when the paper is in print.

Table 1.—Summary of exports by United Nations Food and Agriculture Organization item category.

Item category	Observations	Exports (Millions, 2009 US dollars)) Mean	SD	Zero-trade observations	Maximum
1619: Chips and particles	39,434	1.15	16	29,009	851
1632: Sawnwood (C)[a]	100,770	3.53	80	65,159	11,550
1633: Sawnwood (NC)	139,379	0.94	10	86,319	1,112
1634: Veneer sheets	90,946	0.57	8	56,559	1,726
1640: Plywood	112,768	1.50	19	70,162	1,325
1646: Particleboard	88,869	0.97	27	57,477	4,785
1651: Industrial roundwood WIR (C)	64,152	1.54	25	46,994	1,976
1657: Industrial roundwood WIR (NC) tropical	46,481	0.74	10	36,264	550
1670: Industrial roundwood WIR (NC) other	80,100	0.79	11	56,338	951
1671: Newsprint	73,093	2.13	43	47,969	3,780
1860: Paper + board (ex. newspaper)	183,702	6.61	66	93,054	5,598
1874: Fiberboard	103,612	1.05	8	61,563	430
1875: Wood pulp	62,114	6.83	65	38,655	5,881
1877: Forest products (aggregate)	251,734	12.09	174	124,736	22,529

[a] C = coniferous; NC = nonconiferous; WIR = wood in the rough.

the conversion factors associated with normalizing nominal GDP to a reference year.[7]

The second set of FEs controls for time-varying country effects. Time-varying country effects are controlled by interacting the country indicators with the year indicators. These country–time FEs control for all time-varying characteristics that are unique to each country as an importer and, separately, as an exporter. The time-varying country effects control for additional unobserved trade costs not controlled for in the time-invariant specification, addressing a common criticism of empirical gravity models regarding unobserved trade costs (Baldwin and Taglioni 2006).

Traditionally, empirical gravity models are log-linearized gravity models and estimated via a linear estimator such as OLS. To arrive at the log-linearized gravity model, take the natural logarithm of both sides, as in the following log-log linearized model:

$$\ln(\text{Trade}_{ijt}) = \ln(\text{GDP}_{it}) + \ln(\text{GDP}_{jt}) + \ln(\text{Distance}_{ij}) + \ln(\varepsilon_{ijt}) \quad (4)$$

The log-linearized model of Equation 4, when estimated with a linear estimator such as OLS, is subject to two econometric issues. First, $E(\ln[\varepsilon_{ijt}])E(\ln[y]) \neq \ln(E[y])$ will depend on the variance of ε_{ijt}, as well as other higher moments; thus an issue arises if ε_{ijt} is heteroscedastic. In short, if heteroscedasticity is present, the variance of ε_{ijt} will depend on at least one explanatory variable. Since $E(\ln[\varepsilon_{ijt}])$ depends on the variance of ε_{ijt}, under heteroscedasticity, the OLS exogeneity assumption no longer holds (Silva and Tenreyro 2006). The second issue is that the log-linearized model forces the truncation of zero-trade observations because of the nonexistence of the natural log of zero. The exclusion of zero-trade observations results in a truncated dependent variable, leading to another potential source of bias.

Addressing the two concerns above, one solution is to not linearize the gravity model and estimate the multiplicative form (Equation 2) of the gravity model using a nonlinear estimator. A popular nonlinear approach in the application of gravity models is the PPML estimator. Using PPML provides two distinct advantages over OLS and addresses both econometric concerns. First, heteroscedasticity will not result in biased estimates. Second, zero-trade observations can be included; the PPML estimator remains consistent with and without the inclusion of the zero-trade observations.[8]

As for the trade costs component, there are several approaches for controlling for heterogeneity across trading partners and time, including use of indicator variables for different trading partners and years. We explore three specifications, including year indicators, exporter and importer FEs, and time-varying exporter and importer effects. Ultimately, the specification that is the basis for all projections and results analysis is time-varying exporter and importer FEs. This approach helps account for in-sample changes in macroeconomic conditions or trade policies that may have led to an observed increase or decrease in trade flows that cannot be explained by cost differentials or GDP growth. As discussed in subsequent sections, we use these indicators to develop projections of forest product trade flows between different regions, adopting a projections methodology consistent with Schmalensee (1998).

Results

For each of the FAO item categories, three specifications are estimated in our analysis. The first specification includes only year effects, the second adds importer and exporter FEs, and the third interacts the FEs with the year effects. For all specifications, exports are measured in quantities. Depending on the product category, the units are either metric tons or cubic meters.[9]

[7] There is an extensive discussion of this in Baldwin and Taglioni (2006). In short, using real GDP instead of nominal GDP can introduce bias because of the choice of a single common numeraire when country-pair-specific numeraires are required but unavailable. Using nominal GDP in conjunction with time effects addresses this problem.

[8] The estimator is consistent if zero-trade observations are not assumed to be caused by a separate process from the nonzero observations.

[9] The estimated elasticities are presented in the Appendix in Tables S1–S4, which are supplemental materials that can be found online when the paper is in print.

In Table 2, results from the PPML estimated gravity model for all three specifications are reported. Across paper + board, wood pulp, and nonconiferous sawnwood, importer GDP is estimated to have a larger impact on exports than exporter GDP. For example, focusing on the third specification (country × year indicators), a 1 percent increase in importer GDP results in a 1.022 percent increase in exports of wood pulp, whereas for exporter GDP, a 1 percent increase results in a 0.685 percent increase in exports of wood pulp. Although the difference in coefficient estimates between exporter and importer GDP varies by specification and product category, the estimated impact of exporter GDP is consistently lower than the estimated impact of importer GDP.

Comparing the first specification with the second, inclusion of the country dummies results in lower coefficient estimates for exporter GDP, whereas for importer GDP, inclusion of the country dummies results in higher coefficient estimates for wood pulp and sawnwood but a lower estimate for paper and board. Shifting focus to the time-varying country indicators specification, coefficient estimates are larger in magnitude than the year-effects-only specification. This is due to the bias associated with omitting the time-varying unobservable characteristics when estimating the first specification. Recall that the time-varying country indicators control for trade costs, which vary over time, as well as additional unobserved heterogeneity.

It is important to note that although this article builds on the recent empirical estimates discussed in Buongiorno (2016), it is difficult to directly compare estimated coefficients reported in our study with Buongiorno (2016). In Buongiorno (2016), a first-differenced log-log gravity model is specified. The coefficients of interest provide estimates for the impact of a 1 percent change in the growth rate of exporter and importer GDP on the percent change of the growth rate in exports. Specifying the model in this manner has a limitation, however, as the direction of growth (positive or negative) for future exports is based on the previous year's direction of growth. For example, if exports of wood pulp from the United States to China increased from 2013 to 2014, then projected exports cannot be negative for 2015 and beyond. Thus, even if GDP for both the United States and China are projected to decrease, exports would still be projected to increase but at a slower rate. This is because the coefficients represent changes in growth rates and not changes in growth.

Year effects

Including exporter and importer specific year effects partially controls for unobserved trade costs. However, inclusion of the year effects poses an issue for out-of-sample predictions of exports (i.e., future exports). To include the year effects for future years, we use Equation 5 to model the time trend for each exporter and importer within each item category and use the estimated coefficients from the time-trend models to then predict the effect of future years on exports. Each exporter and importer time trend is modeled as follows:

$$\beta_{t_{(i,j)}} = \gamma_{(i,j)} + \delta_{(i,j)}t + \mu_{t_{(i,j)}} \forall i,j; \text{ where } i \neq j \qquad (5)$$

where $\beta_{t_{(i,j)}}$ is the year effect for a specific exporter or importer in year t from the previously estimated gravity model. The coefficient of interest, $\delta_{(i,j)}$, is the estimated effect of any given year on the year effects for an exporter or importer. After Equation 5 is estimated for each exporter and importer separately, projections of future year effects are made $\left(\widehat{\beta_{t_{(i,j)}}}\right)$ for each exporter and importer. This approach allows us to capture changes in interregional trade policies (e.g., tariffs/quotas) and other factors that may influence the flow of goods and services between two

Table 2.—Results from estimating gravity model with Poisson pseudo-maximum likelihood (PPML).

Variables	PPML exports	PPML exports	PPML exports
1860 Paper + board (ex. newsprint)			
ln(Exporter gross domestic product [GDP])	0.676*** (0.019)[a]	0.172 (0.162)	0.798*** (0.054)
ln(Importer GDP)	0.715*** (0.017)	0.221*** (0.083)	0.846*** (0.043)
ln(Distance)	−1.045*** (0.019)	−1.358*** (0.028)	−1.329*** (0.014)
Constant	2.133*** (0.231)	6.858*** (0.864)	2.899*** (0.409)
Observations	183,702	183,702	178,863
R^2	0.21	0.46	0.80
1875 Wood pulp			
ln(Exporter GDP)	0.515*** (0.015)	0.240*** (0.080)	0.685*** (0.065)
ln(Importer GDP)	0.898*** (0.026)	0.957*** (0.064)	1.022*** (0.099)
ln(Distance)	−0.324*** (0.050)	−1.130*** (0.031)	−1.035*** (0.031)
Constant	−3.864*** (0.294)	−0.144 (0.776)	−0.051 (0.745)
Observations	62,114	62,114	55,455
R^2	0.14	0.86	0.86
1633 Sawnwood (nonconiferous)			
ln(Exporter GDP)	0.307*** (0.017)	−0.111 (0.226)	0.396*** (0.086)
ln(Importer GDP)	0.511*** (0.066)	1.364*** (0.113)	0.767*** (0.053)
ln(Distance)	−0.604*** (0.051)	−1.345*** (0.042)	−1.354*** (0.024)
Constant	1.261*** (0.303)	5.637*** (0.820)	4.748*** (0.706)
Observations	139,433	139,433	133,857
R^2	0.01	0.14	0.91
Indicators	Year	Country and year	Country × year

[a] Standard errors in parentheses: *** = $P < 0.01$, ** = $P < 0.05$, * = $P < 0.1$.

countries directly into our time trend used for developing projections.

For most countries, as we move to 2020 and beyond, the trend in $\widehat{\beta}_{t_{(i,j)}}$ is slight and steady over time in either the positive or negative direction. However, for some countries, the projected trends either rise or fall quickly and continue with no constraint. To temper these runaway trends, we censor the projected time-varying country effects. Thus, for the export projections to follow, the projected year effects are left-censored at the fifth percentile and right-censored at the 95th percentile.

Sensitivity analysis

We conducted a sensitivity analysis for the PPML estimator and excluded the observations assumed to be zero trade.[10] The results of this sensitivity analysis are shown in Table 3. Comparing the results of the no-missing-observations specification (column 2) with the original specification (column 1), there are only slight differences between coefficient estimates. Given that the consistency of the PPML estimator only requires that the conditional mean be correctly specified, adding a large amount of zeroes to the left-hand side does not drastically change coefficient estimates. However, the coefficient estimates for the no-missing observation specification are systematically lower than the original PPML estimates. These systematic differences suggest a source of bias in dropping the zero-trade observations.

Table 3.—Sensitivity of Poisson pseudo-maximum likelihood (PPML) to zero-trade observations.

Variables	PPML exports	PPML exports
1860 Paper + board (ex. newsprint)		
ln(Exporter gross domestic product [GDP])	0.798*** (0.0541)[a]	0.715*** (0.0592)
ln(Importer GDP)	0.846*** (0.0429)	0.784*** (0.0468)
ln(Distance)	−1.329*** (0.0136)	−1.314*** (0.0138)
Constant	2.899*** (0.409)	3.848*** (0.458)
Observations	178,863	91,046
R^2	0.800	0.882
1875 Wood pulp		
ln(Exporter GDP)	0.685*** (0.0650)	0.540*** (0.0148)
ln(Importer GDP)	1.022*** (0.0985)	0.937*** (0.0255)
ln(Distance)	−1.035*** (0.0308)	−0.935*** (0.0500)
Constant	−0.0509 (0.745)	1.018*** (0.294)
Observations	55,455	23,597
R^2	0.863	0.866
1633 Sawnwood (nonconiferous)		
ln(Exporter GDP)	0.396*** (0.0862)	0.294*** (0.0947)
ln(Importer GDP)	0.767*** (0.0532)	0.640*** (0.0587)
ln(Distance)	−1.354*** (0.0240)	−1.253*** (0.0237)
Constant	4.748*** (0.706)	5.726*** (0.770)
Observations	133,857	53,470
R^2	0.912	0.940
Specification	Original	No missing

[a] Standard errors in parentheses: *** = $P < 0.01$, ** = $P < 0.05$, * = $P < 0.1$.

Discussion and Illustrative Application

To estimate how future forest product trade may change over time, using the gravity model estimates, future GDP projections are needed. For this we turn to the SSPs described by O'Neill et al. (2014, 2017). The SSPs offer five narratives that describe future paths along which humanity may travel in the 21st century. These pathways identify key factors that will determine the level of challenges for society to mitigate and adapt to potential environmental, policy, and macroeconomic changes.

The SSPs were designed to serve as a basis for integrated scenarios of emissions and land use, as well as climate impact, adaptation, and vulnerability analysis (O'Neill, 2015). However, SSPs can also be used in the application of market analysis to assess future demand growth for particular market segments under assumed population and income growth measures. This aspect makes the SSPs particularly useful in projecting trade flows under alternative assumed future macroeconomic growth assumptions. Specifically, we use the projections of GDP from 2010 to 2050 reported in O'Neill et al. (2015) to project changes in trade.

The SSPs project alternative futures of income growth and offer policy narratives that are relevant to trade (though we simply adopt the income change assumptions in this analysis for illustrative purposes). Figure 1 displays the global GDP projections for all five SSPs. SSP 5 assumes high levels of growth in international trade, strong globalized markets, and reduced inequality across countries, which results in the highest rate of GDP growth for all SSPs. SSP 1 and SSP 2 follow similar global GDP growth rates. This is due to both scenarios seeing moderate levels of international trade and uneven growth in country-level GDP between low-, medium-, and high-income nations. Even though these two SSPs have similar global GDP estimates, they differ in their assumptions on societies' importance on environmental issues. SSP 1 signals a stark shift in historical trends by moving away from societies that are focused on material-intensive growth, instead valuing the importance of meeting development goals such as reduced inequality (both domestically and abroad), access to clean water and sanitation, increased education levels, and more environ-

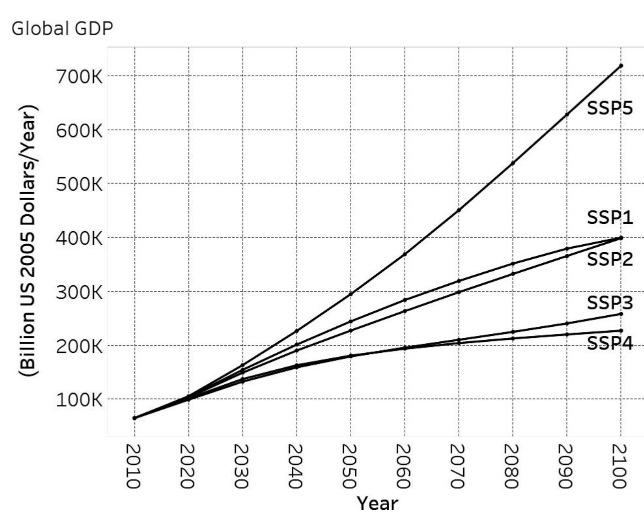

Figure 1.—Global gross domestic product to 2010 by shared socioeconomic pathways.

[10] We assume that any missing trade observation for a country pair is a zero-trade observation.

mentally friendly energy production methods. SSP 2 follows recent historical trends, where developed countries continue to develop at faster rates than developing nations, local environmental issues are given higher priority than global issues, and a ''successful'' nation is one that has high growth in material-intensive consumption.

SSP 3 takes a more nationalistic view of the future. In this scenario nations take a strong view on national security and view the reliance on global partnerships as inhibiting to progress. This leads to an increase in policies that aim to limit trade, as well as valuing energy independence. This limits the ability for many developing and resource-limited countries to grow, forcing global GDP growth to be small. Finally, SSP 4, from a global perspective, sees the lowest growth in GDP in the long term. This scenario assumes that inequality grows within nations. International trade continues to happen at moderate levels; however, globalization is limited to a few ''elite'' nations. Consumption is high in wealthy countries, whereas low consumption and limited mobility are the norm in low-income nations. These five scenarios provide a range of future growth potentials that can be combined with the estimated regression coefficients to predict future trade levels for forest products.

In the following illustrative application, we consider how alternative macroeconomic growth pathways, with differing regional economic growth and energy/environmental policy objectives, might drive global forest product demand and trade flows in the future. The following figures provide an example of how gravity model coefficient estimates can be used to project net exports from a single region under assumed regional macroeconomic growth rates. Projections are calculated using the estimated regression coefficients and income (GDP) growth estimates from the SSPs.

Figures 2, 3, and 4 show historic US export amounts and projected exports of paper and board, wood pulp, and nonconiferous sawnwood, respectively, for each SSP until 2030; Figure 5 shows the percentage of total US exports each country imports using assumptions from SSP 2 (the middle-of-the-road SSP scenario). This range provides a set of possible future export expansion/contraction pathways that can be used to project other forestry-related variables on requisite harvest levels to meet future product demand, and possible changes in market prices and trade flows between particular regions. The main driver of differences in the projections above is GDP, and the same time trend is used for each scenario. This time trend captures changes to taste and preferences, changes in exchange rates or relative prices, changes to trade barriers, or changes to domestic energy policies. It is important to note that future projections do not explicitly capture all of the assumed differences in policies and trade liberalization or contraction assumptions captured by the full SSP narratives. Nonetheless, projections based on changes in country-level macroeconomic growth and a time trend based on country-pair FEs provide a reasonable range of possible future baseline projections for forest product trade flows. Such data can be incorporated into larger sector models or economy-wide models for more comprehensive assessments.

Figure 2 shows the projected US exports of paper and board products excluding newsprint. In the short term, exports are expected to fall, consistent with expectations that digitalization will continue to reduce the demand for printed material. Near the end of the projection period exports begin to level off, driven by higher levels of GDP. There are multiple factors at play regarding the demand for paper and board; paper products can be seen as an inferior good, now being replaced by digitalized media (Latta et al. 2016). However, at the same time, demand for cardboard and shipping materials are increasing because of the rise of online shopping retailers such as Amazon.

In the short term, US wood pulp exports are projected to increase slightly initially, but then fall over time. By the end of the projection period exports are declining in all scenarios except SSP 5, which has the highest global GDP projections, as shown in Figure 3. Wood pulp is an intermediate good used in applications such as paper, cardboard, and tissue

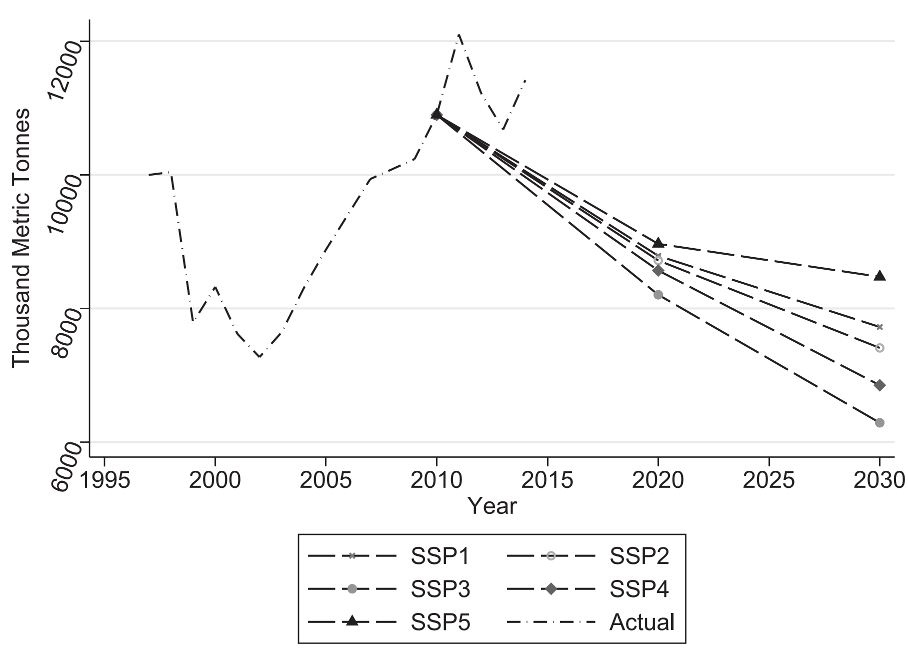

Figure 2.—Projected US exports of paper + board.

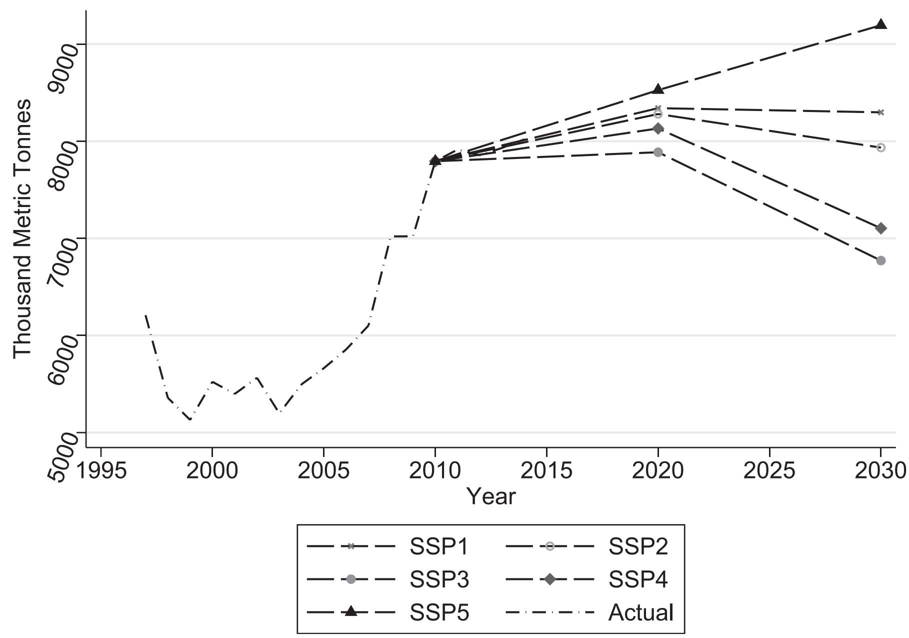

Figure 3.—Projected US exports of wood pulp.

paper. Although the estimated elasticities for importer and exporter GDP are positive, the effects of the time trend for US exports of wood pulp are large and negative. This negative pull on exports outweighs the positive push that increased importer and exporter GDP has on trade, so over time the expected demand for US wood pulp declines in our projections.

Although the projections for nonconiferous sawnwood do not capture the shock that was seen in 2012 in which exports increased dramatically relative to previous years, our projections show a steady increase in exports beginning in 2020. In the past, sawnwood has been used as a proxy for home starts, which are highly correlated with GDP, so as GDP increases, the demand for home starts, and thus sawnwood, should increase. The reason that our results don't show larger increases in sawnwood exports is due to the time trend pulling exports down. This is likely driven by other nations increasing sawnwood production or use of substitute nonwood building material to meet growth in domestic demand. For all SSPs GDP is growing at a rate high enough to offset the downward-pulling time trend.

In aggregate, projected US exports of these key forest product groups will increase over time. Although wood pulp exports are projected to decline in the future, total exports of wood pulp still falls within 2000 to 2010 levels. These US-centric results suggest that continued intensive and exten-

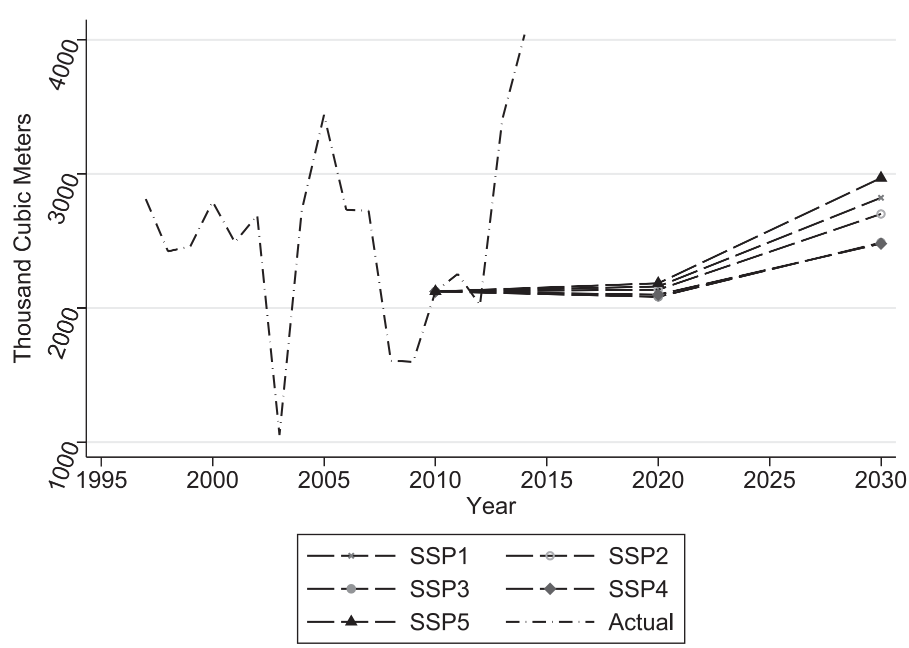

Figure 4.—Projected US exports of nonconiferous sawnwood.

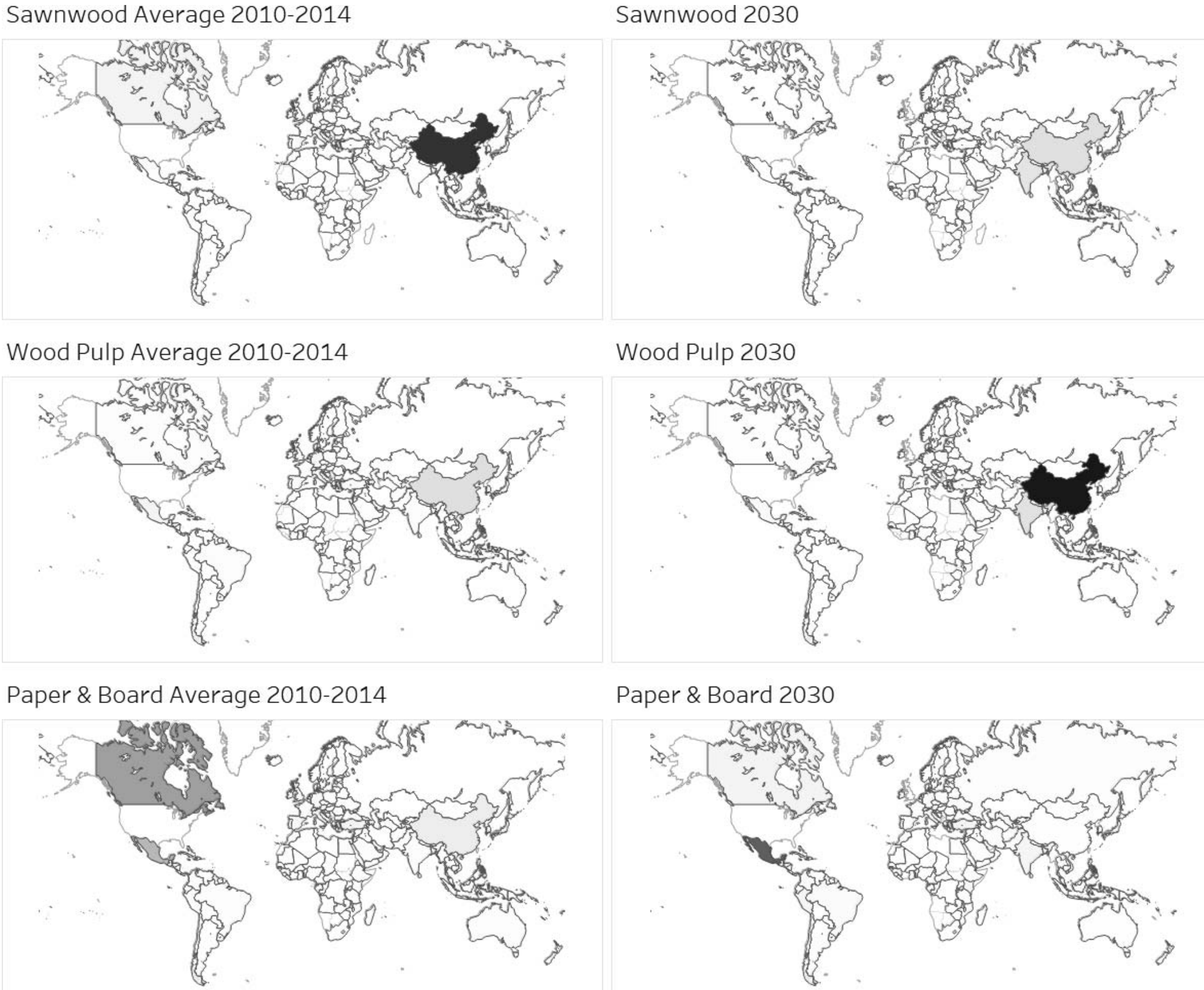

Figure 5.—Maps of projected exports from the United States by product category (shared socioeconomic pathway 2).

sive margin investments in the US forest resource base may be necessary to meet future export demands.

Projected trade between countries

In addition to total US exports, we project individual bilateral trade amounts between the United States and its top 10 trading partners. Table 4 compares the average exports from 2010 through 2014 with the projected exports in 2030 for the top 10 importing countries from the United States. As expected, China is the largest importer for nonconiferous sawnwood and wood pulp, whereas Canada is the largest importer of paper and board.

Sawnwood imports from the United States are projected to grow for China and India, whereas imports decline for Canada and Germany. This provides further insight into the trends of domestically supplied sawnwood. Our projections show that developing countries will continue to meet domestic demand for sawnwood through imports, whereas developed countries are able to limit or slow growth in imports from the United States.

Paper and board imports show a decline for most countries; however, as seen with the other selected product categories, India has a large increase in US imports. This increase is driven by large anticipated GDP growth in India. Brazil also exhibits an increase in imported paper and board, but to a smaller extent, which is also driven by continued development and GDP growth. Brazilian import growth does not increase as rapidly, however, since the country is a substantial supply source of forest products, so it is able to increase consumption while limiting import growth as incomes rise. Whereas the other countries in Table 4 are also expected to see increased income over time, these respective GDPs are not expected to grow rapidly enough to compensate for the individual trading-pair time trend present in our results. Thus, even though these countries are gaining buying power, the taste and preferences and other country-specific factors that are captured in the time trend result in declining demand for US imports of paper and board. This result could be caused by either a shift toward using more digital media, or from an increase in an importer country's ability to domestically supply paper and board products.

Finally, wood pulp also sees large increases in US imports by China and Brazil, whereas the other top trading

Table 4.—Projected US exports to top 10 importing countries.

Country	Sawnwood (NC)[a]		Paper + board		Wood pulp	
	Average US exports 2010–2014 (MMT)	Projected US exports 2030 (MMT)	Average US exports 2010–2014 (MMT)	Projected US exports 2030 (MMT)	Average US exports 2010–2014 (MMT)	Projected US exports 2030 (MMT)
China	1,545,400	3,932,134	910,400	67,016	2,277,200	4,618,606
Canada	295,200	35,396	2,162,600	521,923	181,200	39,743
Germany	53,200	34,336	339,800	213,183	581,000	107,572
South Africa	23,400	29,782	37,769	—	39,461	12,341
Malaysia	19,200	14,854	59,600	18,151	80,111	20,957
Indonesia	17,675	16,693	52,051	51,020	184,800	109,958
South Korea	12,715	3,171	183,079	18,613	277,600	97,303
Chile	1,211	3,668	192,823	80,307	26,963	367
Brazil	701	874	129,517	209,437	253,200	10,952
India	1,712	3,240,348	133,292	422,551	166,400	996,790

[a] NC = nonconiferous; MMT = mean metric tons.

countries are lessening both their total exports and the percentage of US wood pulp exports. The expansion of trade with China and India is not large enough to compensate for the decline in other countries and thus we see an overall decline in US exports of wood pulp by 2030.

This econometric framework can also be applied to evaluate non-US-centric trade projections. To highlight this option, we have also developed estimated export projections for three important regional forest product supply sources, including Brazilian softwood, New Zealand coniferous sawnwood, and Canadian coniferous sawnwood. Figures 6, 7, and 8 show total projected exports for each of these country and export product combinations; Figure 9 shows the percent share of total imports that other countries hold for each specific product and country-of-origin category.

Figure 6 shows a large increase in Brazilian exports of wood pulp between 2010 and 2020, which follows historical trends. This is followed by a slowdown in expansion between 2020 and 2030. Figure 7 shows relatively flat to slightly declining export demand for New Zealand coniferous sawnwood, though projected values remain within the observed range seen from 2005 to 2015. Figure 8 similarly shows projected changes in Canadian sawnwood exports. Here, the strong declining time trend reduces projected Canadian exports for the first several years of the projections horizon, but a relatively strong elasticity of GDP flips the sign and results in increased demand projections. By 2030, Canadian sawnwood exports lie within the range observed from 2000 to 2008, when exports fell dramatically from a peak in 2000. The range in projected exports is relatively wide across SSPs for Canadian sawnwood given the strong influence of regional GDP growth on these projections. Figure 9 shows how these exports are moving away from the United States and the EU, and shifting to being imported primarily by China, and to a lesser extent, India. New Zealand softwood exports are initially evenly spread across the United States, Australia, and China. However, by 2020 the majority of exports are going to China.

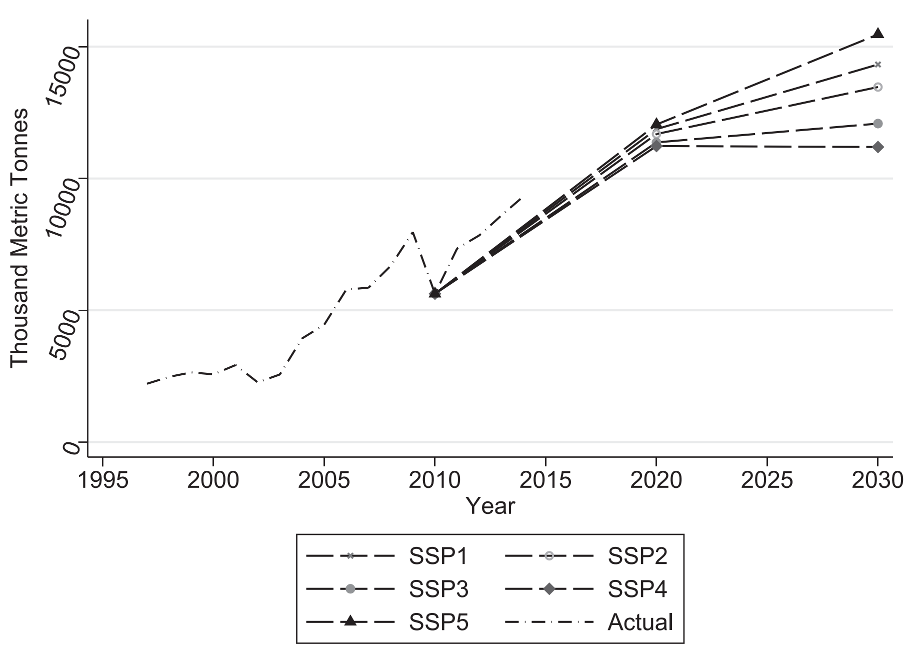

Figure 6.—Projected exports of wood pulp from Brazil.

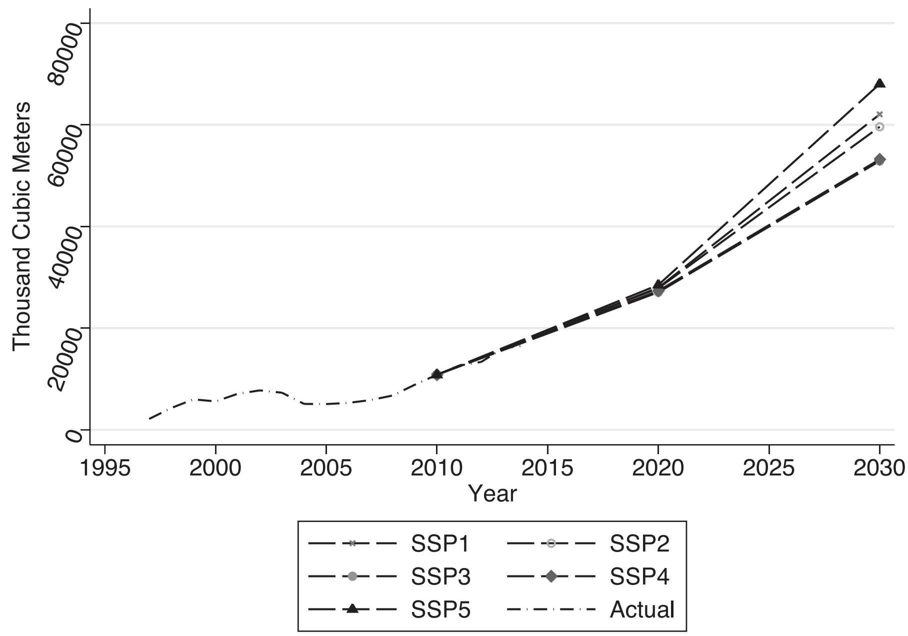

Figure 7.—Projected exports of coniferous sawnwood from New Zealand.

The examples above demonstrate how the gravity model specification developed for this article can be used to project regional trade-flow shifts under assumptions of heterogeneous regional GDP growth as affected by broader macroeconomic and policy conditions. The illustrative application can be thought of as a bounding exercise for export projections across different SSP scenarios as we are not assuming any changes in policy conditions consistent with the SSP story lines on trade and cooperation. However, by holding other policy and geopolitical factors constant, we can isolate projected theoretical bounds on trade shifts given regional income changes.

Furthermore, other trade-related policy issues (e.g., tariffs or quotas established between trade partners) can be addressed through simple applications of the gravity framework. For instance, tariffs can be represented by adjusting the relative distance metric (as a proxy for trade costs) commensurate with the tariff level. Although not as ideal as simulations conducted via structural market modeling, such applications can reveal quick insight into potential implications of trade policy changes.

The SSP scenarios provide a simple illustration of how an isolated market (trading partner and forest product category) could potentially change under the influence of alternative regional income growth scenarios. Such projections can

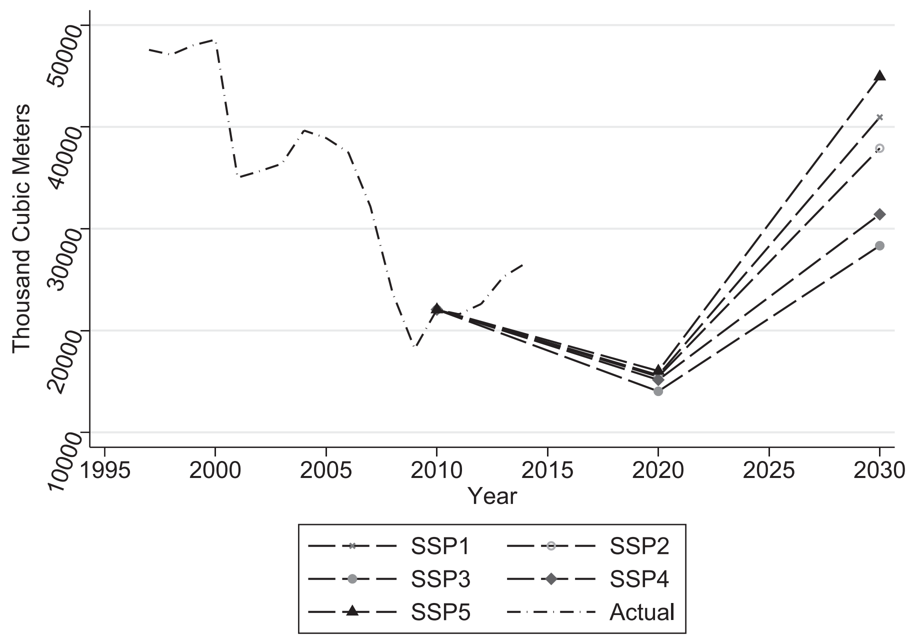

Figure 8.—Projected exports of coniferous sawnwood from Canada.

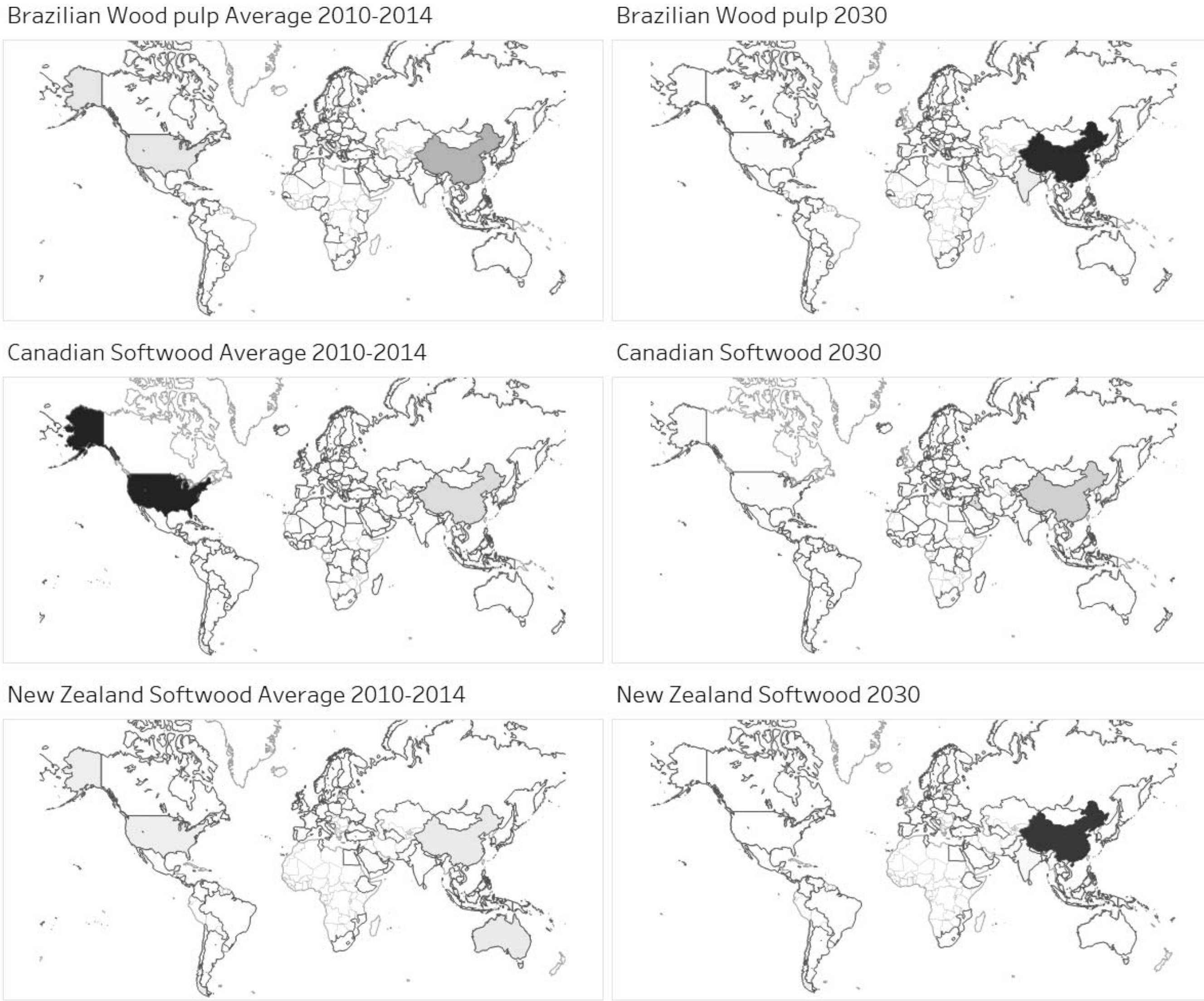

Figure 9.—Maps of projected wood pulp exports from Brazil and coniferous sawnwood from New Zealand and Canada.

offer insight to the forestry or integrated assessment modeling community, providing theoretical upper lower bounds on export changes given relative macroeconomic growth level and assumptions of regional cooperation or trade liberalization.

Conclusions

Developing robust projections of future forest product trade flows is becoming increasingly important to improve analysis of forest product supply and demand under alternative macroeconomic, policy, and environmental futures. In this manuscript we develop a gravity model of trade with near-comprehensive coverage of global forest product trade. Although prior literature on the trade of forest products has focused on linear applications of the gravity model, few published studies have addressed the econometric issues surrounding the log-linearized gravity model (Das et al. 2018). In this analysis, we apply a PPML approach and argue that this is a more appropriate estimator for an empirical gravity model.

Additionally, using the PPML estimates, we have shown ranges of projected trade patterns for select forest products, combining a trend of estimated country and time-varying FEs with expected country-level macroeconomic growth rates from the SSP database. There is need for more robust product- and region-specific projections of trade flows to inform both structural modeling efforts in the land-use sectors and rapid assessment of emerging trade policy issues. Results from our analysis have broad applicability to assess the potential changes in trade flows resulting from changes in macroeconomic conditions, or protectionist policies that directly or indirectly increase the barriers (cost) of forest product trade between different countries. Econometric equations can be used to parameterize exogenous import/export demand schedules for larger sector models representing country-specific or global forestry and other land-use systems for baseline establishment and improved policy analysis.

Illustrative projections show significant expansion of forest product demand in the developing world, especially China and India. As these countries continue to develop, their demand for products such as sawnwood and wood pulp will also continue to increase. To meet this increased demand, countries will be required to expand imports. This increased demand has the potential to influence the expansion of forestry across the world. By using updated trade estimates based on improved empirical approaches, analysis of potential policies related to forestry, tariffs, and trade agreements can be more robust.

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