



Gravity model of timber trade from Latin America

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ABSTRACT

This study investigates the determinants of timber trade from 21 Latin American countries to global markets over the period 1996–2023 using a gravity model framework. We focus in particular on roundwood, that is the dominant primary forest product in international trade, and we address the high prevalence of zero trade flows by estimating a Negative Binomial hurdle gravity model in a Bayesian setting, with posterior inference obtained via the Integrated Nested Laplace Approximation. Our study contributes to the literature by proposing a novel statistical methodology for gravity models and by providing insights into Latin America's bidirectional timber trade. The results show that importer countries' economic size significantly increases both the probability and the volume of roundwood trade, while exporter-side production capacity and forest endowments are key drivers of export intensity. Managed forestry plays an important role: a higher share of planted forests is positively associated with export volumes, suggesting scope for trade expansion without increasing pressure on natural forests. Climate-related natural disasters in importing countries increase the probability of trade, indicating growing demand for timber following extreme events. Institutional quality consistently enhances trade on both the extensive and intensive margins, while currency appreciation in exporter countries reduces competitiveness and trade flows. Finally, participation in selected trade agreements, particularly APEC, ITTA, and MERCOSUR, positively affects trade outcomes. These findings highlight the importance of sustainable forest management, institutional quality, macroeconomic stability, and context-specific trade agreements in strengthening Latin America's position in global timber markets, while mitigating deforestation risks and increasing resilience to climate-related shocks.

1. Introduction

Global deforestation has led to the loss of approximately 178 million hectares of forests since 1990 (FAO, 2025a). South America has been the region which experienced in the past decades the highest level of forest loss, with a peak of 5,2 million of ha per year during the first decade of the new century, then shrunk down to 2,6 million of ha per year during the period 2010–2020.

Starting from the 1960s, the globalization of forest product markets has intensified forest loss by increasing trade at all levels of the supply chain Perez-Garcia and Robbins (2014). The timber industry is an important part of the global wood market, currently valued at US\$ 751.77 million, and is expected to grow to US\$ 785.77 million in 2029 at a compound annual growth rate of 0.74% (Intelligence, 2024). Nonetheless, this market suffers from the pervasive presence of illegal timber trade, responsible for nearly half of the global timber market (Lawson and MacFaul, 2010; Tacconi et al., 2019; Bösch, 2021) and representing between 10% and 15% of the total value of global forest product trade (Curtis et al., 2018).

Timber trade has been widely explored in the forestry economics literature (Barbier et al., 1994; Trømborg et al., 2000; Peck, 2001), often through the use of gravity models. These models typically consider factors such as gross domestic product (GDP) and distance between trading partners to explain trade flows (Tinbergen, 1962; De Benedictis and Taglioni, 2011). Recent studies have expanded on traditional gravity approaches, including additional variables like production, consumption, and policy factors to better explain forest products trade (Morland et al., 2020; Lamica and Parajuli, 2022). Researchers have employed various estimation techniques, including ordinary least squares, fixed and random-effects or Poisson pseudo-maximum likelihood, in order to address challenges such as zero-trade observations and heteroscedasticity (Buongiorno, 2016; Larson et al., 2018; Apeti and N'doua, 2023; Khanal et al., 2024). These models have been applied to diverse forest products, from roundwood to paper, and have been used to forecast trade flows and analyze policy impacts.

The purpose of the present study is the adoption of a gravity model for modeling timber trade flows originating in Latin America countries

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with destination the whole world in the time span 1996–2023. We consider in particular trade of roundwood, which represents the major timber production and export at a worldwide level.

Notice that in 2020 Latin America accounted only for 3.6% of worldwide industrial roundwood export, followed by Africa (2.3%) and Asia (2%), and only for 12.8% of industrial roundwood production, after North America, Europe, and Asia (FAO, 2025b). Despite this relative role in terms of trade and production, understanding the determinants of timber trade flows from Latin America is crucial due to the presence in the region of high valuable wood and to the fact that its forests are currently facing three major challenges (Gan et al., 2016; Blackman, 2020): (i) deforestation and degradation, with an annual loss of about 3 million hectares over the past five years (FAO, 2025a): in particular, commodity-driven factors account for 56% of forest loss, followed by shifting agriculture (31%), forestry activities (13%), wildfires (1%), and urbanization (<1%) (Curtis et al., 2018); (ii) the consequent reduction of CO₂ storage, hindering climate change mitigation and exacerbating desertification and temperature volatility (Cusack et al., 2016; Scheffers et al., 2016); (iii) limited sustainable forest management due to weak incentives, illegal logging, and competition from Asian markets like China and Vietnam (Sohngen, 2020). Interestingly, all these challenges are in some way related to timber trade, and may apply also to other regions in the same climatic zone, hence the relevance of our case study. Furthermore, Latin America is severely affected by anthropogenic climate change, which leads to drought and massive forest fires like those occurred in 2024 (GFW, 2025; GWIS, 2025). For this reason, in our analysis we have deliberately investigated also the role of environmental shocks on timber trade.

In particular, in recognizing that trade data typically include a large number of zeros (81% in our case study), and that even approaches such as Poisson pseudo-maximum likelihood (PPML), that estimate gravity models in their multiplicative form via generalized linear models, can often explain only part of these zeros (Burger et al., 2009; Conigliani, 2024), we adopt a Negative Binomial hurdle gravity model (Mullahy, 1986). In doing so, we implicitly treat our target variable (*i.e.*, the amount of traded roundwood in cubic meters) as a count. Recall that hurdle regression models are two-component mixture models of a distribution that generates non-zero values (usually a truncated-at-zero count distribution) and a point mass at zero. Moreover, we consider a Bayesian approach, and for approximating the resultant posterior distribution we apply the Integrated Nested Laplace Approximation, that can deal with complex models and provides accurate results in short computing time (Rue et al., 2009).

Our work fits within the literature aimed at identifying the determinants of international timber trade with three major innovations: (i) the focus of bidirectional trade in Latin America, generally less explored within this topic compared to Africa or Asian countries; (ii) the use of an innovative statistical approach to estimate the gravity model of trade; (iii) the use of institutional and climate-related variables to identify additional drivers of timber trade.

The rest of the paper is organized as follows. We first present an overview of the literature that uses gravity models for modeling international timber trade in Section 2. Then we introduce the hurdle gravity Negative Binomial model in Section 3 and illustrate the dataset in the following Section 4. The results of the analysis are discussed in Section 5, while a methodological discussion is proposed in Section 6. Finally, Section 7 concludes with some final remarks, policy implications and suggestions for future research.

2. Literature review

The use of gravity models for modeling trade flows grounded in the work of Tinbergen (1962). In its simpler form, a gravity equation assumes that trade between countries is directly proportional to the product of their economic sizes, represented by their gross domestic products (GDP), and inversely proportional to their distance. Therefore,

larger economies are more prone to engage larger trade volumes: countries with high GDP should have low relative prices so to sell all their production (*i.e.*, market clearing condition).

The literature significantly evolved since then, in particular in the direction of identifying reasonable theoretical economic foundations for the gravity equation (Leamer and Levinsohn, 1995; Deardorff, 1998). The first attempts in this sense are represented by Linnemann (1966), that used a Walrasian general equilibrium approach, and Anderson (1979), under the assumptions of product differentiation by place of origin and constant elasticity of substitution expenditures. A lot of research has been done since then in this direction. Anderson and Van Wincoop (2003), for instance, extended the work of Anderson (1979) and emphasized the importance of the general equilibrium effects of trade costs. To this day, gravity models have been successfully applied in international trade and many other fields for modeling data that provide quantitative information about relationships among units, such as portfolio capital flows (Okawa and Van Wincoop, 2012), foreign direct investment (Jörn and Farid, 2010) or migration flows (Karemera et al., 2000; Anderson, 2011; Conigliani, 2024).

Purpose of this section is to present a brief review of the main literature on gravity models for timber trade, both within specific countries and at an international level.

The work of Vu et al. (2020), for instance, examines Vietnam's wood product trade from 2001 to 2016, identifying GDP, trade openness, population, and forest resource endowments as key determinants. Their findings underscore the role of Vietnam's logging restrictions and trade agreements, showing that participation in the WTO (World Trade Organization) and APEC (Asia-Pacific Economic Cooperation) had little effect on timber trade, whereas free trade agreements and common borders significantly boosted exports. Similarly, Lamica and Parajuli (2022) focus on the U.S. South, where intraregional trade of softwood sawlogs and pulpwood is crucial for local supply chains. Their study highlights the importance of economic (and classic) factors such as federal states' GDP, timber production, and transportation costs in determining trade patterns.

The impact of economic factors on timber trade is further examined by Nasrullah et al. (2020), who estimate a gravity model for China's forest products trade over the period 2001–2018. Specifically, their work focuses on five major forest product groups and the results stress that GDP and forest area positively influence trade, while distance remains a key deterrent. Additionally, trade disruptions such as countervailing duties and global economic crises have significantly affected China's timber trade. The study also emphasizes the effect of being a member of organizations such as APEC and OECD (Organization for Economic Co-operation and Development) on trade volumes.

Similarly, Buongiorno (2016) applies the gravity model to forecast trade in three key forest product categories: raw wood, pulp, and paper products. His model, applied at global level for the period 2005–2014, shows that trade elasticities vary by product type, with raw wood exports being highly sensitive to importer GDP, whereas pulp and paper trade being linked more to both exporter and importer economic conditions. Additionally, the study explores the potential impact of trade agreements such as the Trans-Pacific Partnership (TPP), forecasting significant growth in Vietnam's timber exports. Buongiorno (2015) employed a similar gravity approach to show how the introduction of the euro has boosted the trade of wood and derivatives in Europe.

The limitations of log-linearized gravity models estimated using OLS has been highlighted for instance in Larson et al. (2018), that advocate the use of Poisson pseudo-maximum likelihood (PPML) for obtaining more reliable trade elasticity estimates. Their analysis was conducted over the time span 1997–2014 for 13 product categories. Morland et al. (2020) further extended this approach by applying a structural gravity approach to forest product trade. Their results point out that traditional models tend to overestimate the impact of income on trade flows and that different wood products respond differently to economic factors. Notably, processed wood products (*e.g.*, furniture, paper) are more

influenced by economic conditions than raw materials like roundwood. The study underscores the importance of sector-specific trade analysis to improve the accuracy of policy recommendations.

Because regulatory measures aimed at curbing illegal logging have become a significant factor in shaping global timber trade, they have been investigated also within trade gravity models. For example, [Khanal et al. \(2024\)](#) investigate the effects of the Forest Law Enforcement, Governance, and Trade Voluntary Partnership Agreement (FLEGT VPA) and the Lacey Act Amendment (LAA) on wood exports from Cameroon, Ghana, and the Republic of Congo. The authors apply a PPML estimation and their results indicate that FLEGT VPA generally reduces exports, particularly of industrial roundwood and sawnwood, except in specific cases like the Republic of Congo. Meanwhile, the LAA shows mixed effects, restricting some exports while boosting others, such as Cameroon’s sawnwood.

Again relying on PPML, [Apeti and N’doua \(2023\)](#) analyze the impact of timber trade regulations in the United States, the European Union, Australia, and South Korea between 1995 and 2019. These regulations are found to effectively reduce illegal timber trade but also to impose substantial compliance costs on exporters, reshaping trade flows and market structures. Additional insights into China’s timber trade are provided by [Zhang and Yanshu \(2009\)](#), which implements different models, including PPML. Despite the role played by GDP, distance, exchange rate, and APEC membership, also forest resource endowments of China’s trade partners shows a positive effect on wood imports and a negative one on exports. Also logging restrictions started in 1998 have a positive effects on imports. Focusing again on the Chinese case, [Guan and Gong \(2015\)](#) find that international regulations aimed at curbing illegal logging — they considered seven different government regulations — affect negatively roundwood trade and positively that of furniture and wood-based panels. On the other hand, bilateral agreements affect negatively all the forest products considered in the study. Finally, [Das et al. \(2018\)](#) examine the Indian case — the world’s second-largest importer of wood products — also using a PPML framework. The authors analyze seven different forest products separately, showing that regulatory quality is positively correlated with certain products, such as wood pulp, paper, and paperboard. The pulp and paper industry is further investigated by [Hujala et al. \(2013\)](#) using an augmented gravity model, although without relying on PPML estimation.

Notice that the majority of gravity models of timber trade in the literature focus on the role of specific trade agreements or trade bans by evaluating their impact on bilateral trade flows. However, several contributions also account for other factors that may significantly influence trade outcomes. For instance, [Apeti and N’doua \(2023\)](#) include proxies for countries’ institutional quality — such as control of corruption, rule of law, and regulatory quality — and report mixed effects on timber trade. The same authors also incorporate climate-related predictors, and in particular measures of countries’ resilience to climate change, finding a positive association with timber product exports. Similarly, [Lamica and Parajuli \(2022\)](#) include climate-related covariates such as precipitation levels, showing statistically significant effects that vary across different forest products. These two groups of variables — institutional quality and climate-related factors — are therefore of particular relevance when analyzing cross-country timber trade from Latin America, and this motivates their inclusion in our empirical analysis.

3. The negative binomial hurdle gravity model

As pointed out in the Section 1, we suggest modeling timber trade flows with a Negative Binomial hurdle gravity model ([Mullahy, 1986](#)). Letting y_{ijt} be the export of roundwood from exporter country i to importer country j in year t (in m^3 , approximated to the nearest integer), the general structure of the hurdle gravity model is given by:

$$p(y_{ijt} | \mu_{ijt}, \theta, p_{ijt}) = \begin{cases} 1 - p_{ijt} & y_{ijt} = 0 \\ p_{ijt} \frac{f_{NB}(y_{ijt} | \mu_{ijt}, \theta)}{1 - f_{NB}(0 | \mu_{ijt}, \theta)} & y_{ijt} > 0 \end{cases}$$

where $f_{NB}(\cdot)$ is the probability mass function of a Negative Binomial random variable, p_{ijt} represents the probability of trade, μ_{ijt} is the mean parameter of the Negative Binomial distribution, and θ is the corresponding size (dispersion) parameter.

Notice that in hurdle regression models, covariates can be associated with both the probability of occurrence and the mean function of the count model. Using standard link functions, the two linear predictors of the hurdle model can then be written as:

$$\begin{aligned} \text{logit}(p_{ijt}) &= \alpha_p + \beta_p^T x_{it} + \gamma_p^T x_{jt} + \delta_p^T x_{ijt} + a_{it} + b_{jt} + c_{ij} \\ \log(\mu_{ijt}) &= \alpha_\mu + \beta_\mu^T x_{it} + \gamma_\mu^T x_{jt} + \delta_\mu^T x_{ijt} + a_{it} + b_{jt} + c_{ij} \end{aligned} \tag{1}$$

where the vectors x_{it} , x_{jt} , and x_{ijt} include predictors specific to the exporter i , to the importer j and to the ordered pair (i, j) respectively, the subscripts p and μ on the intercepts α and on the regression coefficients β , γ and δ indicate if they pertain to the equations modeling the probability of trade or the mean trade flow, and a_{it} , b_{jt} , and c_{ij} capture exporter-year, importer-year, exporter-importer specific effects respectively ([Baltagi et al., 2015](#)) affecting both the probability of trade and trade volume.

Note that the effects a_{it} , b_{jt} , and c_{ij} can either be treated as random or as fixed. In the literature on trade the use of fixed effects (FEs) is extremely common ([Head and Mayer, 2014](#); [Baltagi et al., 2015](#)), especially when the item of primary interest is bilateral accessibility (defined for instance in terms of regional trade agreements). Here, on the contrary, given the interest in assessing the significance of individual drivers of timber trade flows (that would be wiped out by FEs), and in order to limit the parameter dimensionality (with two linear predictors the number of FEs would double), we focus on random effects. Notice that this choice is particularly natural in a Bayesian setting. More specifically, we assume that a_{it} , b_{jt} , and c_{ij} are independent and identically distributed Gaussian random effects with precision hyperparameters τ_a , τ_b , and τ_c respectively.

3.1. Prior specifications and resultant posterior distribution

The hurdle regression model (Eq. (1)) needs to be completed with appropriate prior distributions for all the unknown quantities. Here in most cases we rely on weak prior distributions, so that the posterior inference is mostly determined by the data.

More specifically, for the three precision hyperparameters τ_a , τ_b , and τ_c of the random effects a_{it} , b_{jt} , and c_{ij} , we assume a penalized complexity prior with parameters $u = 0.1$ and $\alpha = 0.01$ ([Simpson et al., 2017a](#)), that penalizes the complexity of the model with respect to the base model with no random effects. Similarly, for the size parameter of the truncated Negative Binomial we assume a penalized complexity prior with parameter $\lambda = 7$ ([Simpson et al., 2017b,a](#)), that penalizes the complexity of the model with respect to the base Poisson model.

Moving now to the different regression parameters in Eq. (1), in the present work we follow the approach of [Gelman et al. \(2008\)](#) and [Conigliani \(2024\)](#), and we include just enough prior knowledge to regularize the extreme inferences that can be obtained in generalized linear models with totally non-informative priors. More specifically, *a priori* we assume that actual effects of the predictors in both regression equations of the hurdle model tend to fall within a limited range.¹ Note that under this framework the intercept represents the average

¹ This requires first centering binary predictors, rescaling numeric predictors, and log-transforming those with very skewed distributions and a large amount of relative variation. For the predictors that enter the model linearly we then introduce independent zero-mean Gaussian prior distributions with scale equal to 2.5 (that corresponds to a prior scale equal to 2.5 divided by twice the standard deviation of the corresponding predictor in the unscaled model) ([Gelman et al., 2008](#)). For the log-transformed predictors we introduce independent zero-mean Gaussian prior distribution with scale equal to 2.5 divided by twice the standard deviation of the log-transformed predictor ([Conigliani, 2024](#)).

predicted outcome with all covariates at their mean value, while the regression parameters can be interpreted in terms of changes from the low to the high end of the corresponding predictors for those that enter the model linearly, and as elasticities (*i.e.*, as relative changes in the odds for trade or in the mean trade flow per relative change in the predictor) for those that are log-transformed (Gelman et al., 2008; Conigliani, 2024).

Under the Bayesian paradigm the posterior distribution is proportional to the likelihood function times the prior distribution. Assuming the Negative Binomial hurdle gravity model, and following the prior specifications above, the resultant posterior distribution does not have closed form, and in the present work is approximated through the Integrated Nested Laplace Approximation (INLA) (Rue and Held, 2005; Rue et al., 2009; Martins et al., 2013; Gómez-Rubio, 2020; Van Niekerk et al., 2021, 2023). The INLA framework was designed to deal with the class of latent Gaussian Markov random field models, that is a subclass of Bayesian structured additive regression models that includes the majority of the (time series, spline, and spatial) models used in practice. The INLA approach exploits the assumptions of the model to produce a numerical approximation to the marginal posteriors for each unknown quantity of interest based on the Laplace approximation method (Tierney and Kadane, 1986). It can be implemented in R with the INLA package (Martino and Rue, 2008, 2010).

4. The dataset

The analysis relies on a database which comprises 21 countries from South and Central America as exporter countries and 115 trader countries (including the aforementioned Latin American countries) from 1996 to 2023.² Note that the forest surface of our exporter countries accounts for 90.4% of the total forest area of Latin America, while the average forest cover of all countries included in the analysis represents 99.7% of the global forest area in the considered time span (FAO, 2025b).

Notice that from our analysis we excluded small countries (*i.e.*, those with a land surface area below 1 million ha) because they play a relatively limited role in international trade, and several of them are fiscal havens, whose inclusion could have significantly affected our results. For similar reasons, following Cropper and Griffiths (1994), we excluded countries that on average over the period considered, had less than 1 million ha of total forest area according to the Forest Resources Assessment (FRA) classification of FAO (2025a). A few additional countries were excluded due to data limitations; one example is represented by South Sudan and Timor-Leste, that gained independence during the time span of our analysis and officially reconstructed data for previous years are not available.

4.1. Target variable and covariate selection

The response variable of our model is the export of roundwood forest products from exporter country i to importer country j in year t (trade_{ijt}). We focus exclusively on roundwood because it represents the main primary forest product produced and traded at the global level (FAO, 2025b). Notice that, following Khanal et al. (2024), we measure exports in physical quantities (m^3) rather than in monetary values. This choice is motivated by our interest in a primary forest product such as roundwood, which is directly linked — particularly in quantity rather than value terms — to land-cover changes resulting from tree harvesting in natural, regenerated, or planted forests for market sale. Trade data has been retrieved from the BACI database (Gaulier and Zignago, 2010; CEPII, 2025a), while the selection of forest products was made following FAO's guidelines.³

The main predictors included in both equations of the hurdle model consist of forest-related variables retrieved from FAO (2025b). In particular, for both importer and exporter countries, we included the amount (m^3) of total roundwood production (prod_rwood_{ijt}). In fact, it is common for gravity models of trade to involve the internal production of traded products; see for instance, in the context of timber trade, Lamica and Parajuli (2022) and Zhang and Yanshu (2009), that use timber production as a proxy for forest resource endowments. Then, again for both importer and exporter countries, we included the total amount of forest area (forest_area_{ijt}) retrieved from the latest FRA (FAO, 2025a,b). This variable is typically included in gravity models of timber trade to account for supply and demand conditions in exporter and importer countries (Polyakov and Teeter, 2007); see for instance (Hujala et al., 2013), Das et al. (2018), and Apeti and N'doua (2023). Finally, for both importer and exporter countries, we included the share of planted forest over total forest area ($\text{plant_forest_share}_{ijt}$), that has not received much attention in the literature on timber trade, although large values of it should push toward greater exports of forest products. Even this variable has been retrieved from FRA (FAO, 2025a,b).

The remaining predictors include a number of variables that have been employed in the literature for modeling timber trade (Hujala et al., 2013; Das et al., 2018; Nasrullah et al., 2020). In particular, for both the exporter and the importer countries from the World Development Indicators (WDI) of the World Bank (WB, 2025) we obtained the total GDP in constant 2015 US\$ (gdp_{ijt})⁴ and the total population (population_{ijt}). Moving to the dyadic predictors, from WDI we obtained the official exchange rate ($\text{exchange_rate}_{ijt}$), expressed in trade partner country's currency per exporter's currency unit,⁵ while from the gravity database developed by the Centre d'Etudes Prospectives et d'Informations Internationales (CEPII, 2025b) we obtained a number of time-constant predictors related to the exporter-importer pair; these include the distance between the capital cities ($\text{dist_capitals}_{ij}$) and three dummies indicating whether the two countries share a common official language ($\text{common_language}_{ij}$), have had a colonial link ($\text{colonial_link}_{ij}$), and are contiguous (contiguous_{ij}).

Furthermore, following Nasrullah et al. (2020), we have built four time-varying dummy variables to account for the simultaneous participation of the exporter and importer countries into the following major international trade agreements: the international tropical timber agreement (ITTA_{ijt}), entered into force on December 2011 (ITTO, 2024; IUCN et al., 2024), the Southern Common Market (MERCOSUR_{ijt}), the Asia-Pacific Economic Cooperation (APEC_{ijt}), and the Organization for Economic Co-operation and Development (OECD_{ijt}).

The role played by institutional quality in halting deforestation and illegal logging is largely explored in the literature (Culas, 2007; Bösch, 2021; Moreira-Dantas and Söder, 2022). However only few studies directly account for them in their gravity models of trade; the majority of the analyses focus on the effects of country-specific

³ Specifically, we considered all Harmonized System (HS) codes corresponding to the roundwood category, as defined in the Definitions and Standards of Forestry Production and Trade provided by FAO (2025b). These codes were converted into the Central Product Classification (CPC) system in order to ensure consistency with the nomenclature adopted by the BACI database. The selected codes are as follows: 440110, 440310, 440320, 440331, 440332, 440333, 440334, 440335, 440391, 440392, 440399, 440610, 440690, 440710, 440721, 440722, 440723, 440791, 440792, and 440799.

⁴ We have imputed some missing observations on GDP using data from the Statistics Division of the United Nations (UN, 2025) and the Penn World Table (PWT) (Feenstra et al., 2015), retrieved from the Groningen Growth and Development Centre (GGDC, 2025).

⁵ We have imputed some missing observations on the exchange rate using data from the PWT (GGDC, 2025).

² The full list of countries is provided in Table A.1 in the Appendix.

bans. One exception is represented by [Apeti and N'doua \(2023\)](#), following which we retrieved three specific institutional quality indicators, namely the control of corruption ($\text{control_corruption}_{it/jt}$), the regulatory quality ($\text{regulatory_quality}_{it/jt}$), and the rule of law ($\text{rule_law}_{it/jt}$). Notice that in order to avoid collinearity issues, we applied principal component analysis (PCA) to the three institutional indicators separately for exporter countries and importer countries, and we retained the first component of the two analyses ($\text{pc_institutional_quality}_{it/jt}$), that turned out to be direct indicators of institutional quality,⁶ and resume 83% and 95% of the total variability, respectively.

One aspect that has not received much attention in the literature is the effective impact of climate change on timber trade; exceptions are represented for instance by [Apeti and N'doua \(2023\)](#), that consider the vulnerability and readiness indices of climate change developed by [of Notre Dame \(2024\)](#), and [Lamica and Parajuli \(2022\)](#), which consider the amount of precipitations. Notice that changes in environmental conditions are diverse, ranging from long-terms variations, that can be expected to have an effect on timber production, to short-term extreme events, that may be regarded as additional shocks affecting trade. Given our focus on Latin America, that as mentioned in the Section 1 is severely affected by anthropogenic climate change, we find it crucial to take into account also this aspect, and in particular we concentrate on the effect of climate-related natural disasters. More specifically, we focus on the disasters which may have a negative impact on forest areas (namely extreme temperatures, droughts, floodings, storms, and wildfires), and for both the exporter and the importer countries as additional predictors we consider the number of natural disasters that occurred yearly in each country ($\text{num_disasters}_{it/jt}$) as well as the total number of individuals affected by the disaster ($\text{pop_disasters}_{it/jt}$). The former represents a measure of hazard risk or extensive margin, while the latter is a measure of the intensity of exposure. The data are sourced from the International Disaster Database (IDD) developed by [CREED \(2025\)](#).

The complete list of variables included in our analysis, along with some descriptive statistics, is presented in [Tables A.2, A.3, and A.4](#) in the [Appendix](#).

5. Discussion of results

The results of our analysis are summarized in [Figs. 1 and 2](#), that show the posterior means and the corresponding 95% posterior credible intervals (PCIs) for the parameters of the regression equations for modeling the probability of timber trade p_{ijt} and the mean timber trade flow μ_{ijt} . In particular, [Fig. 1](#) concerns the predictors related solely to exporter countries and to importer countries, while [Fig. 2](#) refers to the predictors related to the exporter-importer pair. The corresponding actual figures can be found in [Table A.5](#) in the [Appendix](#).

As expected from the literature which investigates timber trade through gravity models, the economic size of importer countries, here represented by their GDP, has a positive effect both on the probability of timber trade from Latin America and on the magnitude of the flow ([Huang et al., 2019](#)). In particular, a 1% increase in the importer's GDP leads to a 1.68% increase in the odds for roundwood trade and to a 0.56% increase in its imported amount. The GDP of the exporter countries, on the other hand, shows a negative effect on the probability of trade flows, albeit with lower magnitudes. This might uncover some kind of absorption effect: larger economies in Latin America consume a significant portion of their own production domestically and therefore have lower level of exports.

⁶ For both exporter countries and importer countries the first principal component is positively correlated with the three institutional indicators, with correlation coefficients equal to 0.89 and 0.97 respectively for the control of corruption, to 0.88 and 0.96 respectively for the regulatory quality, to 0.97 and 0.99 respectively for the rule of law.

Moving to predictors related to forestry and land use, for total forest area we find a positive effect on the exporter side and a negative effect (at least on the odds for trade) on the importer side. In particular, a 1% increase in forest surface of exporter countries leads to a 0.72% increase in odds for trade as well as to a 1% increase in export quantities. Conversely, a 1% increase in forest area of importer countries leads to a 0.28% decrease in the odds for trade. These results are expected and in line with the findings of [Apeti and N'doua \(2023\)](#).

Looking now at the role of the amount of roundwood produced at the national level, the Negative Binomial hurdle model finds a positive effect for both exporter and importer countries. For exporter countries this is expected, reflecting the fact that higher domestic production allows exporting countries to supply more products to foreign markets; in particular, a 1% increase in national roundwood production leads to a comparable increase in the odds of trading and to a 0.63% increase in export volumes. On the importer side, on the other hand, a negative sign might have been expected. However, our result might reflect the fact that domestic demand of importer countries may not be fully met by increasing domestic production alone and therefore still requires reliance on imports, as shown by [Lamica and Parajuli \(2022\)](#). It is also important to note that several major importers of Latin American roundwood, such as China, India, and the United States, are characterized also by large and growing domestic timber production.

Another interesting result concerns the share of planted forest in exporter countries, which has a positive effect on export volumes from Latin American countries: a 1% increase in the share of planted forest leads to a 0.69% increase in the amount of roundwood exported from the region. This is an important result, as larger areas of planted forest can be managed specifically for production and directed toward export markets without the need to expand deforestation of natural forests, thereby also helping to curb illegal logging activities.

Proceeding now to the role of climate change, another important point that arises from our analysis concerns the effect on timber trade of climate-related extreme events ([Easterling et al., 2000](#); [Rahmstorf and Coumou, 2011](#); [Stott, 2016](#)), in particular on the importer side. In fact, controlling for all other predictors (including roundwood production), our results show that the probability of timber trade increases with the frequency of natural disasters in importer countries: a 1% increase in the number of climate-related natural disasters leads to a 0.28% increase in the odds for trade. Notice that these results might be explained by the additional primary forest products needed for restoring damages from natural hazards or by timber load losses due to the disasters, and are in line with those obtained through the vulnerability index in [Apeti and N'doua \(2023\)](#), who found a positive effect on the importer side and a negative effect on the exporter side. Also [Gan et al. \(2016\)](#) stressed the reduction in tropical timber use due to environmental concerns.

Looking now at the predictor that proxies institutional quality, that captures several relevant dimensions (including control of corruption, law enforcement, property rights, and judicial effectiveness), for both importer and exporter countries we consistently observe a positive effect, both on the probability of trade and on trade magnitude. This result is in line with the literature, which typically identifies institutional quality as a trade-enhancing factor for both importing and exporting countries ([Álvarez et al., 2018](#)). For exporting countries, higher-quality institutions may incentivize local investment and productive activities in the timber sector by reducing uncertainty, strengthening contract enforcement, and improving access to formal markets. For example, stronger property rights may raise the opportunity cost of using forest-managed land for agricultural or other extractive activities, thereby encouraging roundwood production and, consequently, trade ([Hyde, 2012](#)). For importing countries, by contrast, better institutional quality may translate into more stringent domestic regulations and tighter controls on illegal timber activities, inducing substitution between locally produced and foreign timber products.

Regarding the role of the exchange rate, notice that a devaluation of the exporter's national currency is expected to make its products more

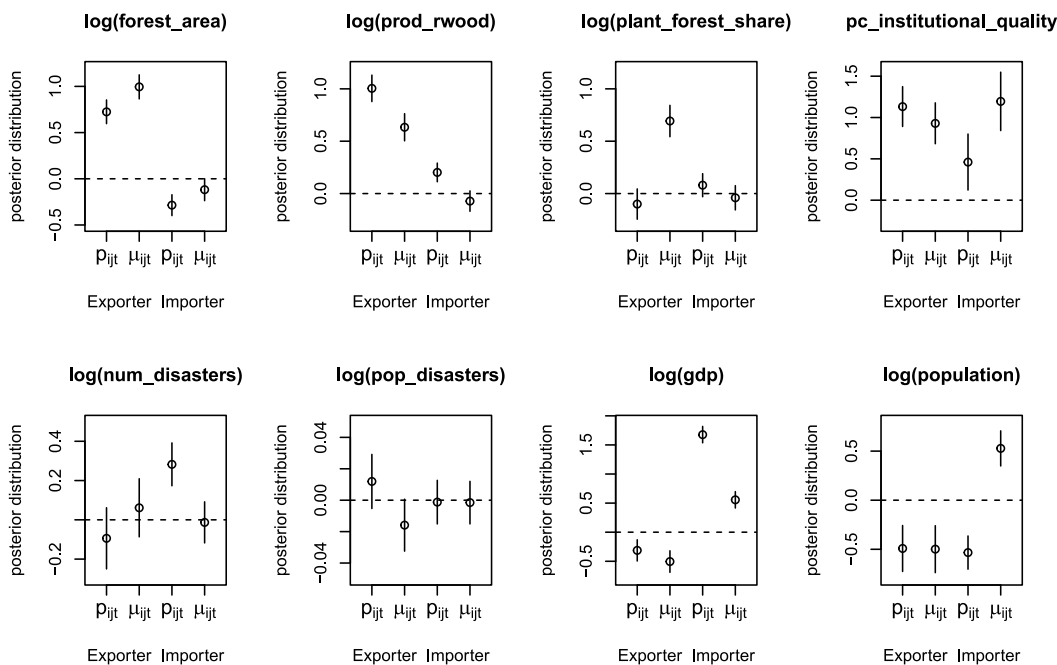


Fig. 1. Modeling the probability p_{ijt} of trade and the corresponding mean trade flow μ_{ijt} : posterior means (open circles) and 95% PCI (vertical lines) for predictors related to the exporter and to the importer countries.

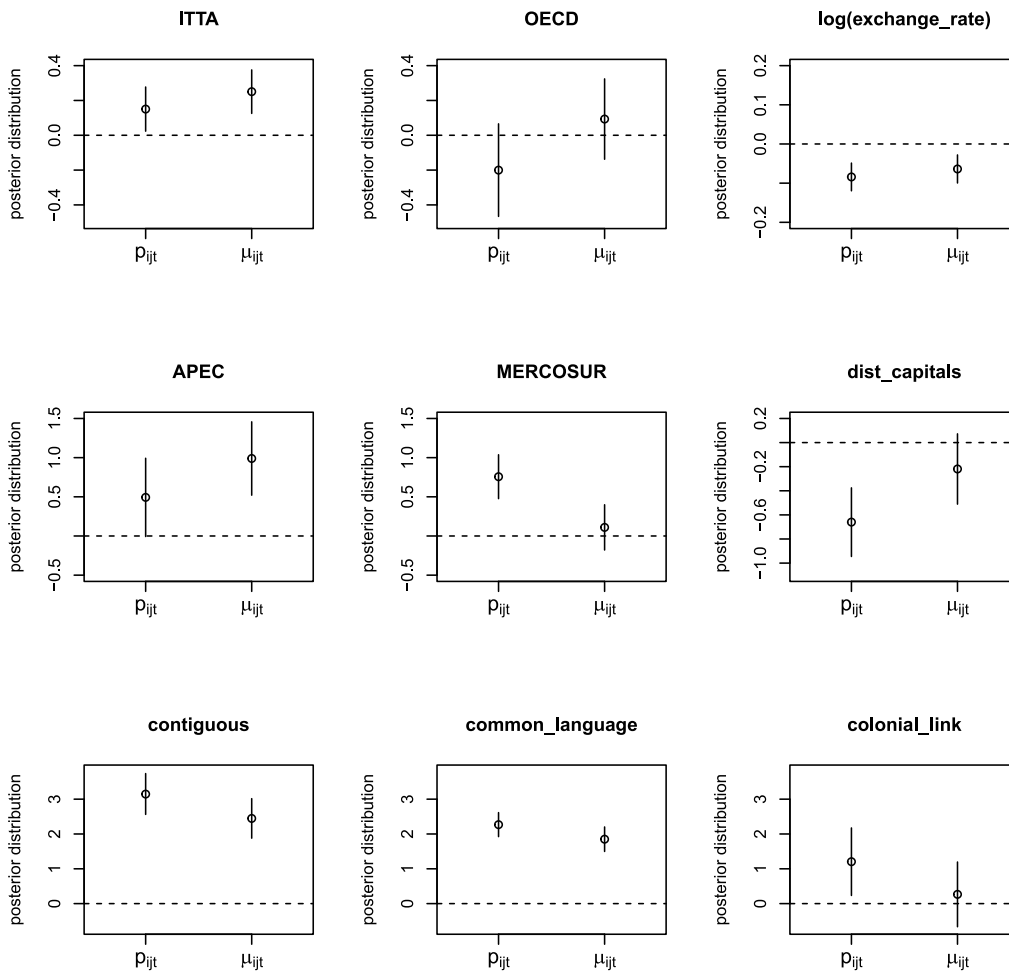


Fig. 2. Modeling the probability p_{ijt} of trade and the corresponding mean trade flow μ_{ijt} : posterior means (open circles) and 95% PCI (vertical lines) for predictors related to the exporter-importer pair.

competitive in foreign markets, thereby increasing exports. Nonetheless, its role in bilateral timber trade is not unequivocally established in the literature and appears to vary across countries and products. Khanal et al. (2024), for instance, focus on selected African countries and show that currency depreciation enhances international competitiveness, leading to higher trade volumes by making exports cheaper. Similarly, Apeti and N'doua (2023) find a positive effect of the exchange rate, whereas Abrams et al. (1980) do not detect a significant relationship. Moreover, Zhang and Yanshu (2009) and Nasrullah et al. (2020) report mixed results for China, depending on the specific forest product considered. It should also be noted that, in the Latin American context, several countries (such as Argentina and Venezuela) have experienced extremely high inflation and exchange rate volatility, which may have influenced the impact of exchange rates on timber exports (Hyde and Olmos, 2024). In our case, an increase in the exchange rate corresponds to an appreciation of the exporter's currency and is therefore expected to reduce exports. This expectation is confirmed by the model results: a 1% increase in the exchange rate leads to a 0.08% reduction in the odds for trade and a 0.06% decrease in trade volumes.

The estimated coefficients for the remaining dyadic predictors, reported in Fig. 2, are largely consistent with the gravity-model literature on timber trade. Controlling for other factors, distance exerts a negative effect on the probability of trade, whereas contiguity between exporter and importer countries increases both the probability and the magnitude of timber trade. Similarly, sharing a common language positively affects both the probability and the volume of trade, resulting in larger trade flows among Hispanic South and Central American countries. Sharing a colonial link also has a positive effect, but only on the odds for trade. Comparable results emerge for participation in trade agreements. Joint membership in MERCOSUR, in particular, shows a positive impact and represents the agreement with the largest effect on the probability of trade among those considered. Joint ITTA membership, on the other hand, has a positive effect on both the odds for trade and trade volumes, while joint APEC membership — which includes Chile, Mexico, and Peru among Latin American countries — has a positive effect solely on trade volumes. Only OECD membership does not appear to significantly affect timber trade. It is worth noting that these findings on trade regulations are not fully aligned with the existing literature. In fact, while Nasrullah et al. (2020) also find a positive effect of APEC membership and no effect of OECD membership, Apeti and N'doua (2023) and Khanal et al. (2024) conclude that ITTA membership tends to hinder trade. However, as discussed in Section 2, the effects of timber trade regulations depend crucially on the region under analysis and on the specific products traded. To the best of our knowledge, no previous studies have focused specifically on roundwood trade flows from Latin America.

Finally notice that, through the inclusion of random effects a_{it} , b_{jt} , c_{ij} , the Negative Binomial hurdle model also accounts for exporter-year, importer-year, and exporter-importer characteristics that are not explicitly included in it as predictors. Valuable insights can then be gained by examining the posterior summaries of these random effects.

In particular, Fig. 3 shows the posterior means of exporter-year a_{it} and importer-year b_{jt} random effects for roundwood flows originating from Latin America countries. Although these means fluctuate around zero, their trends reveal interesting patterns not captured by the predictors of the Negative Binomial hurdle model. The first panel, for instance, shows the posterior means of a_{it} for specific exporter countries such as Brazil (BRA) and Chile (CHL), that are the main timber producers within this region, as well as for Bolivia (BOL) and Ecuador (ECU), whose current constitutions (since 2009 and 2008, respectively) are based on the ancestral concept of *sumak kawsay*⁷ or

⁷ Meaning 'good life' in the Kichwa language, is a fundamental Indigenous principle that envisions a way of living that is community-centered, ecologically balanced, and culturally mindful. Rooted in the cosmivision of Andes' indigenous communities, it emphasizes harmonious coexistence with nature as the foundation for collective well-being.

buena vivir, that seeks to create an harmonious relationship between humans and the environment. Notice that the trend for Chile does not show great deviations from zero, implying that most of the variation in the response is accounted for by the predictors included in the model; the posterior mean of a_{it} for Ecuador, on the other hand, is positive over the whole period. In the case of Brazil, the plot shows a sharp decrease between 2005 and 2010, which corresponds to the first Lula's presidency, characterized by a strong reduction in deforestation rates within the Amazon region. Regarding Bolivia, it is interesting to notice the positive peak right before the implementation of their new constitution, that might reflect the fact (not accounted for by the predictors included in the model) that the country experienced extra amount of roundwood exports in the year preceding that event (Cappelli et al., 2022).

Similar comments can be made from the second panel of Fig. 3, that shows the posterior means of b_{jt} for specific importer countries such as Italy (ITA), India (IND), the United States of America (USA), and China (CHN), that is the largest importer and consumer of timber in the world and that has been implementing a strict ban policy on natural timber logging in recent years. More specifically, while the results for Italy and USA do not show any particular pattern over time, for the other two countries there is an upward trend, especially from 2008. In fact, after controlling for forest cover, roundwood production, GDP, and all the other predictors, the posterior means of b_{jt} for China and India reveal that there are specific forces in these countries that have led to an increasing demand of timber from external markets and from Latin America in particular (Zhang et al., 2023). Regarding China, in particular, from the end of the 1990s the government has adopted strict policies (such as the Natural Forest Protection Program) to halt deforestation, followed in 2017 by a complete prohibition of the commercial cutting of natural forests, resulting in a significant increase of imported timber (Zhang and Chen, 2021). India, on the other hand, is characterized by a low internal timber production which leads to a high dependence on imports from foreign countries, including Latin American ones (Norman and Canby, 2020). Within these context it is important to recall the risk of deforestation displacement arising from the shifting of timber production abroad when responding to domestic environmental objectives, and these trends of the REs may conceal this effect (Meyfroidt et al., 2010).

Likewise, additional insights about the exporter-importer pair characteristics (besides conventional factors such as distance, sharing an official language, or having had a colonial relationship) can be captured by the posterior distribution of the c_{ij} random effects. In particular, Figs. 4 and 5 show the posterior means of the exporter-importer random effects for trade flows among Latin American countries and for trade flows between Latin America and a group of European and other major economies, respectively. In both figures, dark-colored squares identify exporter-importer pairs whose time-constant characteristics boost (red) or deflate (blue) timber trade between them, while soft-colored squares represent country-pairs whose trade is explained by the predictors of the model.

Fig. 4, in particular, shows that the dyadic predictors included in the model are adequate for capturing timber trade patterns among Latin American countries, as most of the posterior means of the c_{ij} random effects are close to zero. Exceptions are represented by routes from Venezuela (VEN) to Chile (CHL), from Honduras (HND) to the Dominican Republic (DOM) and to Guyana (GUY), and from the Dominican Republic (DOM) to Guyana (GUY), along which higher-than-expected flows have been observed, and by the route from Guatemala (GTM) to Cuba (CUB), that on the contrary recorded lower levels of trade. Interestingly, the majority of these results might be explained by specific agreements that have been reducing trade barriers. The Chile–Venezuela Economic Complementation Agreement (ACE 23), for instance, signed in 1993 with the aim of liberalizing trade between the two countries, may justify the positive posterior mean of c_{ij} for

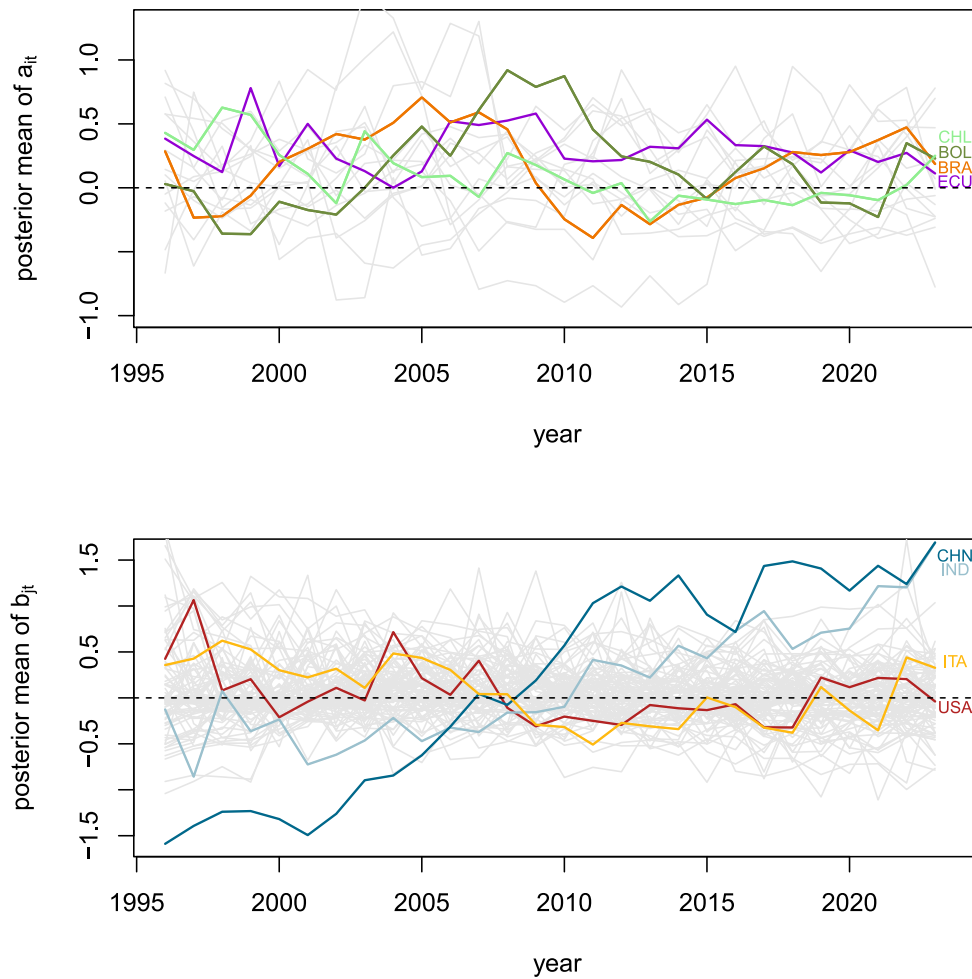


Fig. 3. Posterior mean of exporter-year a_{it} and importer-year b_{jt} random effects (selected countries in colors).

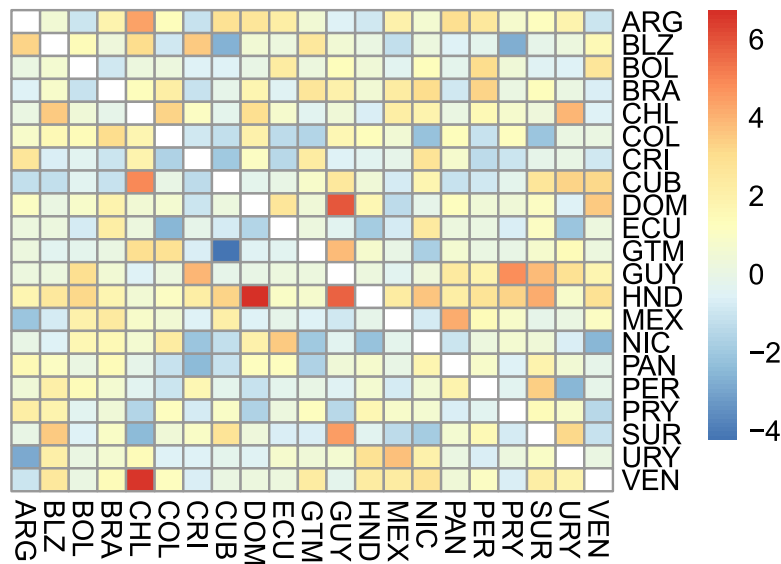


Fig. 4. Posterior mean of origin-destination random effects c_{ij} for timber trade flows among Latin American countries (exporter countries on y axis).

the Chile–Venezuela country-pair. Similarly, the Dominican Republic–Central America Free Trade Agreement (DR-CAFTA), that includes

Honduras and the Dominican Republic, and the Caribbean Community (CARICOM), a regional intergovernmental organization that includes

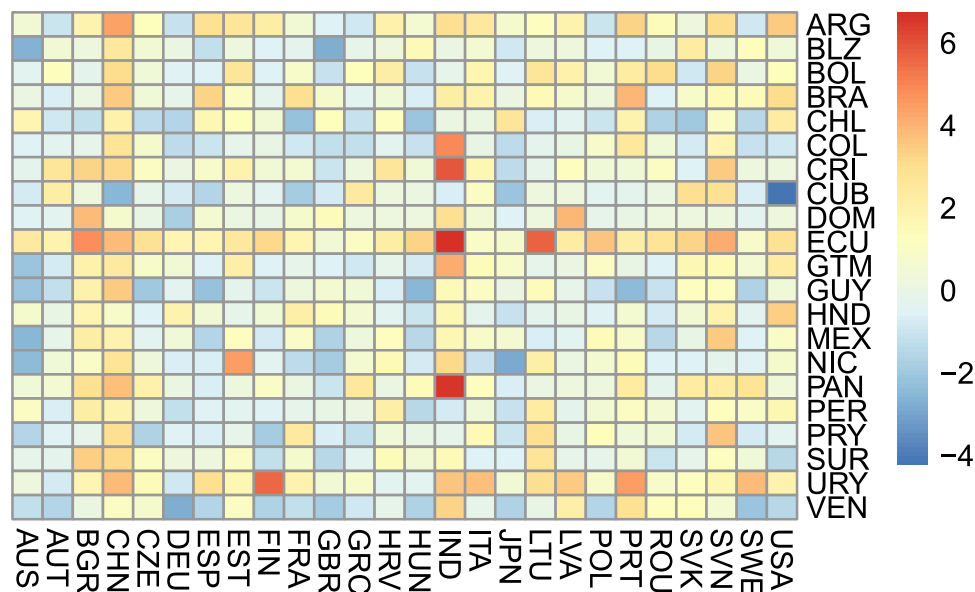


Fig. 5. Posterior mean of origin–destination random effects c_{ij} for timber trade flows from South and Central America countries (y axis) to selected countries (x axis).

the Dominican Republic and Guyana, might be responsible for the positive posterior means of the corresponding exporter–importer random effects. Instead, the result for the Guatemala–Cuba country-pair may be justified by the fact that the Guatemala’s economy is oriented primarily toward the United States and to markets that, unlike Cuba, have greater payment capacity and financial stability.

Similarly, Fig. 5 highlights country-pairs whose characteristics enhance or reduce timber trade between Latin America and major importing partners. We observe in particular that India (IND) stands out as the importer country associated with the largest number of high posterior means of c_{ij} across several Latin American trading partners. This result might be explained by the fact that this rapidly growing economy is characterized by strong domestic demand, which increasingly relies on imports from foreign suppliers, including Latin American countries, particularly for teak wood. Note that this dependence has further intensified following the log export bans introduced by Myanmar in 2014, as this country has historically been a key trading partner in this sector (Norman and Canby, 2020). For China (CHN), by contrast, the posterior means of the c_{ij} random effects are never particularly large. This suggests that the model effectively captures China’s timber imports from Latin America without the need for large country-pair-specific adjustments. It is also noteworthy that Cuba (CUB) and the United States (USA) display a strong negative deviation, indicating that actual timber trade has been lower than might have been expected given the characteristics of the two countries. This result, however, is clearly driven by the long-standing embargo against Cuba, which continues to severely limit actual trade flows.

Finally, as a robustness check, we replicated our analysis using an alternative source of forest cover data. The FRA database, in fact, while offering several advantages (which lie in its institutional relevance and the standardized guidelines that each country is required to follow), presents also some limitations, as it is updated every five years and it relies on interpolated values (Grainger, 2008). For this reason, we repeated the analysis using satellite-based data, which are now widely used in the literature and allow access to multiple alternative sources. More specifically, we used land cover (LC) satellite data provided by the Climate Change Initiative (CCI) of the European Space Agency (ESA)—hereafter referred to as CCI-LC—constructed by aggregating tree-covered and mangrove areas. In fact, they represent a suitable compromise between detailed resolution (300 m) and longitudinal span (1992–2022) compared to other similar sources which lack the

Table A.1
Exporter and importer countries.

Exporter countries (n = 21)	
Argentina, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, Guatemala, Guyana, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru, Suriname, Uruguay, Venezuela.	
Importer countries (n = 115)	
Afghanistan, Algeria, Angola, Argentina, Australia, Austria, Azerbaijan, Bangladesh, Belarus, Belize, Benin, Bolivia, Bosnia and Herzegovina, Brazil, Bulgaria, Burkina Faso, Cambodia, Cameroon, Canada, Central African Republic, Chad, Chile, China, Colombia, Congo, Rep., Costa Rica, Cote d’Ivoire, Croatia, Cuba, Czech Republic, Congo, Dem. Rep., Dominican Republic, Ecuador, Equatorial Guinea, Eritrea, Estonia, Ethiopia, Finland, France, Gabon, Georgia, Germany, Ghana, Greece, Guatemala, Guinea, Guinea-Bissau, Guyana, Honduras, Hungary, India, Indonesia, Iran, Islamic Rep., Italy, Japan, Kazakhstan, Kenya, Kyrgyzstan, Lao PDR, Latvia, Liberia, Lithuania, Madagascar, Malawi, Malaysia, Mali, Mexico, Mongolia, Morocco, Mozambique, Myanmar, Nepal, New Zealand, Nicaragua, Niger, Nigeria, Norway, Pakistan, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Poland, Portugal, Korea, Rep., Romania, Russian Federation, Saudi Arabia, Senegal, Sierra Leone, Slovak Republic, Slovenia, Somalia, South Africa, Spain, Sri Lanka, Suriname, Sweden, Switzerland, Thailand, Togo, Turkey, Turkmenistan, Uganda, Ukraine, United Kingdom, Tanzania, United States, Uruguay, Uzbekistan, Venezuela, Vietnam, Zambia, Zimbabwe.	

former (Liu et al., 2020) or the latter (Hansen et al., 2013). Data has been retrieved from FAOSTAT (FAO, 2025b). Results are reported in Table A.6 in the Appendix and are largely in line with those of our baseline model, confirming previous results.

6. Discussion of methods

The statistical approach that we are proposing for estimating the gravity model of timber trade presents two new features with respect to the existing literature. The first one concerns the choice of the hurdle model to analyze trade data in order to deal with zero trade flows. The second one has to do with the introduction of country-specific random effects (rather than FEs) to avoid omitted variable bias. It is important to point out that because we are unsure of the process generating our timber trade data, comparing the behavior of different methods and models (that almost inevitably would lead to different results) in our opinion would not contribute much to the discussion. Comparative analyses in this sense are much more effective using simulated datasets,

Table A.2
Main statistics - variables related to the exporter-importer pairs (1996–2023).

Variable	Description	Statistic	Value
trade _{ijt}	Export of roundwood (m ³)	total	157,911,493
		% zeros	81%
		mean annual route value (non-trivial flows)	12,227
		standard deviation (non-trivial flows)	66,300
		min annual route value (non-trivial flows)	1
		max annual route value (non-trivial flows)	2,070,431
exchange_rate _{ijt}	Exchange rate (LCU per US\$, period average)	mean value	11,929
		standard deviation	1,876,651
		min	0
		max	427,768,997
dist_capitals _{ij}	Air distance from capitals (km)	mean value	9905
		standard deviation	4,353
		min	215
		max	19,812
ITTA _{ijt}	Countries members of ITTA	% zeros	74%
		% zeros (non-trivial flows)	58%
APEC _{ijt}	Countries members of APEC	% zeros	98%
		% zeros (non-trivial flows)	94%
OECD _{ijt}	Countries members of OECD	% zeros	98%
		% zeros (non-trivial flows)	95%
MERCOSUR _{ijt}	Countries members of MERCOSUR	% zeros	97%
		% zeros (non-trivial flows)	92%
contiguous _{ij}	Countries with contiguous borders	% zeros	97%
		% zeros (non-trivial flows)	90%
common_language _{ij}	Countries with common language	% zeros	83%
		% zeros (non-trivial flows)	71%
colonial_link _{ij}	Countries with a (former) colonial link	% zeros	99%
		% zeros (non-trivial flows)	96%

Notes: APEC stands for Asia-Pacific Economic Cooperation; OECD stands for Organization for Economic Co-operation and Development; ITTA stands for International Tropical Timber Agreement; MERCOSUR stands for Southern Common Market.

and have been done (at least in a cross-sectional setting) (Santos Silva and Tenreyro, 2006; Santos Silva and Tenreyro, 2011; Head and Mayer, 2014; Martin and Pham, 2020). Rather, we find it important to fully motivate our choices and methods, which is what this section is devoted to.

Bilateral trade data sets often contain many zeros, resulting from both sample selection and missing data (Martin, 2020), with shares around 50% for total trade and larger shares for trade of specific goods. Up to the early 2000s, gravity equations were typically estimated in logarithms, excluding the zero observations, despite the evidence that such sample truncation results in bias. The scenario then changed significantly with the publication of a very influential paper by Santos Silva and Tenreyro (2006), that highlighted the potential for bias from the combination of heteroscedasticity and nonlinearity in gravity equations; since then the PPML estimator has become extremely popular for the analysis of trade data. Many authors have argued that PPML also eliminates the bias associated with zero trade flows (Yotov et al., 2016). Indeed, because of its multiplicative form, the Poisson specification provides a natural way to deal with zero-valued trade flows. However the experiments presented in Santos Silva and Tenreyro (2006) included no zeros. In a later paper, Santos Silva and Tenreyro (2011) presented a simulation experiment for which PPML was unbiased even with a large number of zeros; nonetheless, as noted by Head and Mayer (2014) and Martin and Pham (2020), these zeros were not economically determined, as it is usually the case with trade. As a result, the behavior of the PPML estimator (in particular in terms of its bias) in the presence of a large number of zero trade flows is still an open problem (Martin, 2020). In this sense it is interesting to look at Burger et al. (2009), who advocate a zero-inflated Poisson estimator (Lambert, 1992) as a potential way to retain the perceived advantages of the Poisson estimator while allowing for substantial

numbers of zeros. Recall that zero-inflated trade models assume that the profitability of trade (which reflects the trade potential) and the volume of trade are stemming from two different processes. Simulation studies for comparing zero-inflated trade models and PPML in the presence of different degrees of heteroskedasticity can be found for instance in Martin and Pham (2020).

Our model is clearly related to that of Burger et al. (2009). The main difference is that their zero-inflated model considers two different kinds of zero-valued trade flows: countries that will never trade (for instance because of trade embargoes) and countries that are not trading but potentially could trade. A hurdle model, on the other hand, only distinguishes whether or not trade between countries occurs and, given that two countries are trading, how large a volume of trade takes place. For this reason, hurdle models are computationally more tractable than their zero-inflated counterparts, and especially in a panel setting like ours, tractability is indeed an issue (Cameron and Trivedi, 2013).

The early 2000s represented a milestone for gravity models of trade also from another point of view: with the works of Eaton and Kortum (2002) and Anderson and Van Wincoop (2003), the perception that gravity equations lacked micro-foundations was finally dismissed. And it soon became clear that importer and exporter FEs could be used to capture the multilateral resistance terms (affecting the prices of import-competing goods in importing countries, as well as export opportunities in exporting countries) that emerged in different theoretical models, thus allowing to overcome the omitted variable bias affecting the traditional specification of gravity models (Head and Mayer, 2014). For panels of trade flows, however, that structurally require exporter-importer specific effects, the importer and exporter FEs should be time-varying (Baltagi et al., 2003, 2015), and the estimation might run into computational feasibility issues due to the very large number of resulting dummies to be estimated. Several suggestions can be found in

Table A.3
Main statistics - variables related to exporter countries (1996–2023).

Variable	Description	Statistic	Value
forest_area _{it}	Total forest area (FRA, he)	mean annual country value	47,824,611
		standard deviation	111,032,000
		min annual country value	1,153,550
		max annual country value	583,809,526
forest_area [†] _{it}	Total forest area (CCI-LC, he)	mean annual country value	45,343,982
		standard deviation	92,252,413
		min annual country value	1,743,830
		max annual country value	459,283,800
prod_rwood _{it}	Roundwood production (m ³)	mean annual country value	21,962,489
		standard deviation	53,195,390
		min annual country value	140,491
		max annual country value	316,046,000
plant_forest_share _{it}	Share of planted forest (FRA, %)	mean annual country value	4.90
		standard deviation	11.21
		min annual country value	0.00
		max annual country value	57.12
num_disasters _{it}	No. of climate-related natural disasters	mean annual country value	2.01
		standard deviation	2.04
		min annual country value	0.00
		max annual country value	16.00
pop_disasters _{it}	No. of individuals affected by climate-related natural disasters	mean annual country value	324,809
		standard deviation	1,470,705
		min annual country value	0.00
		max annual country value	27,618,152
gdp _{it}	Total Gross Domestic Product (constant 2015 US\$)	mean annual country value	2.0e+11
		standard deviation	3.9e+11
		min annual country value	1.0e+09
		max annual country value	2.0e+12
control_corruption _{it}	Control of corruption (GWI)	mean annual country value	-0.31
		standard deviation	0.68
		min annual country value	-1.69
		max annual country value	1.61
regulatory_quality _{it}	Regulatory quality (GWI)	mean annual country value	-0.19
		standard deviation	0.69
		min annual country value	-2.39
		max annual country value	1.54
rule_law _{it}	Rule of law (GWI)	mean annual country value	-0.45
		standard deviation	0.64
		min annual country value	-2.33
		max annual country value	1.35
population _{it}	Total population	mean annual country value	26,479,657
		standard deviation	44,364,520
		min annual country value	210,310
		max annual country value	211,140,729

Notes: † 1996–2022.

the literature to overcome this problem, including approaches based on trade ratios or on double-demeaning the gravity data-set (see [Head and Mayer \(2014\)](#) and the references therein). Our proposal is to replace the exporter-year, importer-year, exporter-importer specific FEs with corresponding random effects. This choice is particularly natural in a Bayesian setting, but has two main advantages even in a frequentist one: (i) it significantly limits the parameter dimensionality, and (ii) it allows assessing the significance of individual drivers of trade, that would be wiped out by FEs. Notice that, at least for exporter-importer specific effects, the use of random effects rather than FEs (depending on the interests of the analysis, the country sample, the data properties, the theoretical model) has been considered for instance in [Egger and Pfaffermayr \(2003\)](#).

7. Conclusions

This study investigates the determinants of roundwood trade flows from 21 Latin American countries using a Negative Binomial hurdle gravity model estimated in a Bayesian setting through the Integrated Nested Laplace Approximation. To the best of our knowledge, this is the first study to examine timber trade specifically for Latin America

and the first to apply this modeling approach within the literature on gravity models of timber trade.

Notice that the applicability of the Negative Binomial hurdle gravity model is clearly not restricted to modeling roundwood trade. We investigated this type of primary forest product because it represents the major timber production and export at a worldwide level. Nonetheless, some Latin America countries are major exporter of other forest products such as pulp and paper. This leaves room for future research. Moreover, the gravity model approach implemented here could be employed to model not only other forest products but also, for example, agricultural goods that have a significant impact on deforestation (e.g., livestock and soil in the Brazilian Amazon) or that are vulnerable to climate change (e.g., cocoa and coffee, whose prices have risen sharply since 2023). Notably, the model is well-suited for handling both zero-inflated and zero-deflated data.

The findings of the present work highlight the significant role of economic, geographic, environmental, and institutional factors in shaping roundwood trade dynamics. Moreover, they suggest several relevant policy implications for sustainable forest management and timber trade regulation in Latin American countries seeking to strengthen their position in the global timber trade, particularly with respect to primary products such as roundwood.

Table A.4
Main statistics - variables related to importer countries (1996–2023).

Variable	Description	Statistic	Value
forest_area _{jt}	Total forest area (FRA, he)	mean annual country value	35,582,347
		standard deviation	101,142,700
		min annual country value	970,228
		max annual country value	830,950,838
forest_area [†] _{jt}	Total forest area (CCI-LC, he)	mean annual country value	36,626,209
		standard deviation	109,710,404
		min annual country value	66,730
		max annual country value	959,388,300
prod_rwood _{jt}	Roundwood production (m ³)	mean annual country value	30,831,153
		standard deviation	66,860,670
		min annual country value	0.00
		max annual country value	469,750,000
plant_forest_share _{jt}	Share of planted forest (FRA, %)	mean annual country value	12.80
		standard deviation	19.97
		min annual country value	0.00
		max annual country value	94.78
num_disasters _{jt}	No. of climate-related natural disasters	mean annual country value	2.28
		standard deviation	3.73
		min annual country value	0.00
		max annual country value	43.00
pop_disasters _{jt}	No. of individuals affected by climate-related natural disasters	mean annual country value	1,603,083
		standard deviation	14,129,520
		min annual country value	0.00
		max annual country value	346,548,559
gdp _{jt}	Total Gross Domestic Product (constant 2015 US\$)	mean annual country value	5.3e+11
		standard deviation	1.9e+12
		min annual country value	5.2e+08
		max annual country value	2.2e+13
control_corruption _{jt}	Control of corruption (GWI)	mean annual country value	-0.22
		standard deviation	0.98
		min annual country value	-1.85
		max annual country value	2.45
regulatory_quality _{jt}	Regulatory quality (GWI)	mean annual country value	-0.14
		standard deviation	0.99
		min annual country value	-2.55
		max annual country value	2.08
rule_law _{jt}	Rule of law (GWI)	mean annual country value	-0.23
		standard deviation	1.00
		min annual country value	-2.59
		max annual country value	2.12
population _{jt}	Total population	mean annual country value	5.7e+07
		standard deviation	1.7e+08
		min annual country value	2.1e+05
		max annual country value	1.4e+09

Notes: † 1996–2022.

First, the positive association between the share of planted forests and export volumes highlights the potential role of sustainable forest management policies in promoting trade without exacerbating deforestation pressures on natural forests. Policies encouraging the expansion and efficient management of planted forests may therefore support export growth while contributing to forest conservation and the reduction of illegal logging.

Another key implication concerns the relationship between timber trade and climate change. Our results indicate that climate-related natural disasters, whose frequency and intensity are increasing globally, are associated with higher import demand in affected countries. This underscores the importance of climate adaptation and disaster resilience policies in forestry sectors, both to mitigate supply disruptions and to respond to shifting demand patterns in international markets.

Exchange rates also continue to play an important role in shaping international timber trade. Despite the high macroeconomic instability experienced by some South American countries in recent decades, currency devaluation remains a factor that enhances export competitiveness, including in the timber sector. This suggests that macroeconomic conditions and trade performance remain closely intertwined.

On the institutional side, we find that higher institutional quality is positively associated with trade for both exporter and importer countries. This implies that improvements in governance — such as strengthening the rule of law, enhancing regulatory quality, and reducing corruption — can facilitate timber trade while promoting more transparent and formal market structures. In exporting countries, stronger institutions may support sustainable production and reduce illegal logging, whereas in importing countries they may increase demand for legally sourced timber, potentially reshaping trade patterns through substitution effects.

Finally, membership in specific trade agreements, such as APEC, ITTA, and MERCOSUR, appears to increase the probability and/or volume of timber trade. This finding highlights the importance of context-sensitive and product-specific international cooperation. Trade agreements that not only facilitate market access but also promote sustainable forestry practices and environmental standards can play a crucial role in aligning trade objectives with forest conservation goals. Ensuring such alignment is essential if timber trade is to contribute simultaneously to economic development and ecological preservation in Latin America and beyond.

Table A.5
Posterior summaries - with forest cover data retrieved from FRA (1996–2023).

Component	Bernoulli			Count		
	mean	0.025	0.975	mean	0.025	0.975
Intercept	-4.35409	-4.58268	-4.15600	2.20395	2.05394	2.35345
log(forest_area) _{it}	0.72444	0.59672	0.85316	0.99479	0.86488	1.12512
log(forest_area) _{jt}	-0.28551	-0.39865	-0.17255	-0.11810*	-0.23693	0.00068
log(prod_rwood) _{it}	1.00456	0.87852	1.13129	0.63298	0.50348	0.76266
log(prod_rwood) _{jt}	0.20190	0.11257	0.29126	-0.07205*	-0.16967	0.02561
log(plant_forest_share [†]) _{it}	-0.10029*	-0.24508	0.04428	0.69291	0.54282	0.84249
log(plant_forest_share [†]) _{jt}	0.07983*	-0.03041	0.18997	-0.04026*	-0.15633	0.07547
log(num_disasters [†]) _{it}	-0.09426*	-0.25012	0.06163	0.06121*	-0.08664	0.20923
log(num_disasters [†]) _{jt}	0.28244	0.17337	0.39183	-0.01315*	-0.11765	0.09165
log(pop_disasters [†]) _{it}	0.01194*	-0.00530	0.02916	-0.01588*	-0.03245	0.00066
log(pop_disasters [†]) _{jt}	-0.00123*	-0.01511	0.01265	-0.00152*	-0.01510	0.01201
log(gdp) _{it}	-0.31273	-0.49525	-0.13002	-0.50484	-0.69005	-0.31944
log(gdp) _{jt}	1.67640	1.53603	1.81839	0.55638	0.41536	0.69764
log(population) _{it}	-0.49162	-0.72604	-0.25773	-0.49871	-0.73800	-0.25974
log(population) _{jt}	-0.53346	-0.70269	-0.36438	0.52762	0.34878	0.70627
pc_institutional_quality _{it}	1.13160	0.89132	1.37355	0.92895	0.68281	1.17712
pc_institutional_quality _{jt}	0.46055	0.12240	0.80000	1.19465	0.84210	1.54822
ITTA _{ijt}	0.15035	0.02347	0.27729	0.25049	0.12552	0.37547
APEC _{ijt}	0.49270*	-0.00678	0.99213	0.98936	0.52049	1.45746
OECD _{ijt}	-0.20022*	-0.46618	0.06573	0.09311*	-0.13768	0.32403
MERCOSUR _{ijt}	0.75665	0.47653	1.03699	0.10945*	-0.17931	0.39850
log(exchange_rate [†]) _{ijt}	-0.08417	-0.11957	-0.04878	-0.06381	-0.09965	-0.02794
dist_capitals _{ij}	-0.65994	-0.94508	-0.37564	-0.21907*	-0.51093	0.07255
contiguous _{ij}	3.14550	2.56220	3.73538	2.44652	1.87951	3.01502
common_language _{ij}	2.26786	1.92409	2.61401	1.84994	1.49800	2.20200
colonial_link _{ij}	1.20399	0.23429	2.17369	0.26549*	-0.66452	1.19499
Hyperparameters	mean		0.025			0.975
Size for NB observations	0.628		0.609			0.648
Precision for a _{it}	4.558		3.841			5.437
Precision for b _{jt}	2.760		2.447			3.094
Precision for c _{ij}	0.250		0.228			0.275

Notes:

- † logarithmic transformation applied to the variable value +1;
- * not statistically significant as the corresponding posterior credible interval includes zero.

Table A.6
Posterior summaries - with forest cover data retrieved from CCI-LC (1996–2022).

Component	Bernoulli			Count		
	mean	0.025	0.975	mean	0.025	0.975
Intercept	-4.37750	-4.61932	-4.17285	2.19784	2.04618	2.34902
log(forest_area) _{it}	0.77796	0.63065	0.92643	1.01831	0.86840	1.16865
log(forest_area) _{jt}	-0.21972	-0.32500	-0.11452	-0.14998	-0.26063	-0.03933
log(prod_rwood) _{it}	1.03055	0.90116	1.16059	0.65043	0.51777	0.78314
log(prod_rwood) _{jt}	0.21674	0.11946	0.31404	-0.02603*	-0.13237	0.08034
log(plant_forest_share [†]) _{it}	-0.12926*	-0.27852	0.01971	0.62660	0.47150	0.78107
log(plant_forest_share [†]) _{jt}	0.13079	0.02431	0.23718	-0.06878*	-0.18071	0.04275
log(num_disasters [†]) _{it}	-0.09211*	-0.25551	0.07126	0.01830*	-0.13717	0.17392
log(num_disasters [†]) _{jt}	0.29457	0.18247	0.40704	0.01429*	-0.09307	0.12199
log(pop_disasters [†]) _{it}	0.01038*	-0.00751	0.02826	-0.01134*	-0.02857	0.00586
log(pop_disasters [†]) _{jt}	0.00058*	-0.01373	0.01489	-0.00449*	-0.01863	0.00954
log(gdp) _{it}	-0.19226	-0.38323	-0.00093	-0.36302	-0.55748	-0.16831
log(gdp) _{jt}	1.64692	1.50554	1.79016	0.53455	0.39259	0.67674
log(population) _{it}	-0.65082	-0.89854	-0.40378	-0.64618	-0.89935	-0.39330
log(population) _{jt}	-0.55823	-0.73103	-0.38555	0.52844	0.34585	0.71084
pc_institutional_quality _{it}	1.09095	0.84313	1.34057	0.90230	0.64806	1.15881
pc_institutional_quality _{jt}	0.46023	0.11121	0.81070	1.25114	0.88837	1.61497
ITTA _{ijt}	0.14867	0.01917	0.27824	0.22711	0.09988	0.35434
APEC _{ijt}	0.44230*	-0.05982	0.94444	0.93321	0.46309	1.40252
OECD _{ijt}	-0.38256	-0.66541	-0.09974	0.09411*	-0.15105	0.33948
MERCOSUR _{ijt}	0.71323	0.42973	0.99693	0.18516*	-0.10564	0.47627
log(exchange_rate [†]) _{ijt}	-0.08926	-0.12544	-0.05311	-0.06672	-0.10337	-0.03002
dist_capitals _{ij}	-0.66805	-0.95631	-0.38071	-0.24017*	-0.53499	0.05444
contiguous _{ij}	3.16968	2.58300	3.76387	2.45278	1.88434	3.02274
common_language _{ij}	2.34453	1.99858	2.69293	1.83792	1.48340	2.19232
colonial_link _{ij}	1.19758	0.22129	2.17407	0.24465*	-0.68961	1.17852

(continued on next page)

Table A.6 (continued).

Hyperparameters	mean	0.025	0.975
Size for NB observations	0.634	0.614	0.654
Precision for a_{it}	4.331	3.636	5.189
Precision for b_{jt}	2.704	2.403	3.048
Precision for c_{ij}	0.249	0.226	0.273

Notes:

† logarithmic transformation applied to the variable value +1;

* not statistically significant as the corresponding posterior credible interval includes zero.

CRedit authorship contribution statement

Nicola Caravaggio: Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Formal analysis, Data curation, Conceptualization. **Caterina Conigliani:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Formal analysis, Conceptualization.

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Declaration of competing interest

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

Appendix A

See Tables A.1–A.6.

Data availability

Data and code for the reproducibility of this work have been uploaded as Supplementary Material and can be found [online](#). Furthermore, they have also been shared on [GitHub](#). Note that the analysis was carried out using version 25.06.13 of INLA.

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