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The impact of trade measures to address illegal wood trafficking on the global forest products market

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ABSTRACT

Illegal wood trafficking has been a global issue because of its detrimental environmental, economic, and social impacts. Several countries have attempted to take proactive trade measures to address the problem and prevent illegally traded timber from coming to their markets. Policy measures in key consuming jurisdictions-—Australia, the European Union, Japan, and the US-—have affected trade patterns of imported wood products. To understand current policy structures and to shed light on future policy tools, we explore the impacts of existing trade measures taken by global forest products consumers (Australia, the EU, Japan, and the US) to ban illegal timber trade and point out differences in trade measures taken by those consumers. Using a gravity model, we find that these measures taken by countries to combat illegal wood trafficking have, in all jurisdictions and for most products examined, decreased import values and resulted in trade pattern shifts.

1. Introduction

The exploitation of forest resources through illegal wood trafficking has been a growing concern and a significant global challenge to effectively resolve. In recent years, illegal wood trafficking has gained considerable attention because activities associated with illegal wood trafficking are symptoms of environmental abuses that have considerable implications at a global level (United Nations Office on Drugs and Crime, nd).

The entry of illegal wood products into both global and domestic forest product supply chains puts pressure on wood prices and market shares, threatening future sustainability of the forest industry and distorting wood markets. Illegal wood trafficking has economically impactful effects (Li et al., 2008; Gutierrez-Velez and MacDicken, 2008).

While assessing many of the economic losses generated by illicit production and trade is challenging, several studies have sought to tally them. As Gutierrez-Velez and MacDicken (2008) indicate, impacts are multidimensional and operate at different scales, including the loss of royalties, reduced timber production efficiency, and higher unemployment. Interpol (2019) estimates that $15–150 billion flows into illegal activity channels in the forest sector, generating economic losses in the legal forest sector. The environmental and ecological ramifications of illegal wood trafficking are similarly vast, including loss of biodiversity and thus degradation of ecosystem functions, higher greenhouse gas emissions, loss of forest cover, and deterioration of water quality (Moiseyev et al., 2010).

Concerns about illegal wood trafficking have prompted private and public decision makers to deploy an array of both broad-based and targeted policy instruments. Over the past two decades, a range of voluntary and regulatory instruments has emerged to promote sustainable timber management and curb illegal logging and trade. These include national and bilateral legal frameworks such as the EU's Forest Law Enforcement, Governance and Trade (FLEGT) initiative and its associated Voluntary Partnership Agreements (VPAs), mandatory due diligence regulations such as the EU Deforestation Regulation (EUDR), the US Lacey Act, satellite-based forest monitoring systems (e.g. Global Forest Watch), corporate zero-deforestation commitments, and finance-based mechanisms such as REDD+. Within this broader landscape, voluntary certification schemes—including those implemented by the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC)—play a distinct role by operating at the level of individual forest management units and supply chains.

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Rather than regulating trade or national policy, they provide a market-based mechanism for tracing timber from forest to final product, enabling consumers, businesses, and regulators to verify legal and responsible sourcing at the product level, complementing rather than substituting for broader governance and regulatory efforts. Certification was conceived as a way to bolster timber legality in the international trade of forest products (Brack, 2013), to advance sustainable forest management (Rametsteiner and Simula, 2003), protect and enhance forest biodiversity (Johansson and Lidestav, 2011; Gullison, 2003), and improve air quality (Miteva et al., 2015). However, in the absence of uniform forest certification standards followed by all certifying authorities and the inconsistency in their application as policy instruments, their effectiveness is hampered (Konstantinavičienė et al., 2026). Certification is also less likely to be effective in countries where forest governance is weak and lacking in legal and financial incentives.

Multiple countries have enacted both supply- and demand-side regulatory measures designed to shrink markets for illegal wood. Supply-side actions focus on enhancing legality and building institutions in countries known to have a history of illicit timber production and weak law enforcement capacity. As a centerpiece of its strategy, the European Union (EU) created the EU Forest Law Enforcement Governance and Trade (FLEGT) Action Plan (European Commission, 2003). Under the FLEGT, the European Commission is authorized to negotiate bilateral agreements that ensure that only legally produced timber products enter the EU market from the signatory country (Brusselaers and Buysse, 2021). VPAs include provisions requiring the exporting country to implement a Timber Legality Assurance system, thereby advancing new processes and the accountability and transparency of institutions. The US and Australia have taken similar approaches and work closely with other governments to strengthen their efforts to promote forest governance and combat illegal logging. For example, the US-Peru Free Trade Agreement (PFTA) includes an environmental chapter that is designed to address illegal logging, forest conservation, and the protection of biodiversity (Office of the United States Trade Representative, 2026).

Furthermore, individual countries have passed laws and created programs, independently of explicit external pressure, that allocate greater resources toward enforcement of land use laws, forests conservation, better regulated logging, and more effectively extract royalty payments from forest concessionaires. Notable tropical wood exporters include Brazil with its Forest Code (Law No. 12651) (Climate Change Laws of the World, 2012), Indonesia with its Timber Legality Assurance System and Law No.18/2013 on the prevention and eradication of forest destruction, was developed and formalized through Indonesia's 2013 Voluntary Partnership Agreement (VPA) with the EU under the FLEGT framework (Council of the European Union, 2013). Malaysia with its Timber Tagging System focuses on the better track wood movement (Wells et al., 2008).

Addressing illegal wood trafficking has prompted independent but convergent regulatory action among major importing countries, including the United States, the European Union, Australia, Japan, and the Republic of Korea (Melissa Blue Sky, 2026). Although the exact specifications of such trade regulations differ across these jurisdictions, they share the same goal: to reduce illegal wood trafficking and, therein, complement supply-focused actions in timber-exporting countries. Key measures have included the Australian Illegal Wood Trafficking Prohibition Act (ILPA), the European Union Timber Regulation (EUTR) within the framework of the EU FLEGT Action Plan, the Japanese Clean Wood Act (JCAW), and the U.S. Lacey Act, as amended in 2008 (hereafter, “LAA”). Although the JCAW focuses primarily on a registry of firms who agree to only trade in legal wood, the ILPA and the EUTR impose stringent requirements to prohibit trade of illegal wood products and require companies importing wood products to have in place due diligence processes to manage and mitigate risks. The LAA, instead, asks companies to show due care in assuring legality of traded wood and requires importers to file form PPQ 505, the Lacey Act Declaration form, describing species and point of origin of the imported products, which serves as a legal affirmation of legality.

Recent new legislation seeks to strengthen due diligence processes and tackle forest loss and degradation.The European Union's 2023 Regulation on deforestation-free products (EUDR; Regulation (EU) 2023/1115) exemplifies this shift, extending due diligence obligations beyond timber to a range of forest-risk agricultural commodities, including cattle, cocoa, coffee, palm oil, rubber, and soy (Forest Governance and Policy, 2026). The United Kingdom has introduced the UK Environment Act in 2021 to restrict commodities causing illegal logging from its supply chain (Environmental Audit Committee, 2024). In 2023, the bipartisan US Forest Act was introduced, which would apply only to products linked to illegal deforestation (United States Congress, 2023). Several countries have paired up to form bilateral trade agreements in support of efforts to create legal assurance systems and advance forest governance (United Nations Office on Drugs and Crime, 2026).

Multiple studies have examined individual demand-side and supply-side actions to address illegal wood fiber sourcing, but few have examined them jointly. For example, although the effects of both VPAs and the EUTR have been studied in the previous literature, there is only a handful of research studies that examine the implications of both components in combination. In a simulation study, Moiseyev et al. (2010) found that the implementation of VPAs would lead to reductions in wood harvest and production and price increases in industrial roundwood produced by countries targeted for VPAs. The combination of the EUTR and FLEGT licensing under the VPAs was predicted to cause a moderate decline in illegal wood trafficking (Bosello et al., 2013). The joint implementation of both the LAA and the VPAs were predicted to generate more substantial reductions in illegal logging than either the LAA or VPA's alone (Gan et al., 2013). Brusselaers and Buysse (2021) further concluded that the FLEGT overall would not expand the global market share of one measure of increased legality, certified wood products, and indeed leads to a contraction overall in the size of the global wood products sector.

Trade measures, targeted at reducing illegal wood imports, naturally would be expected to alter international trade patterns and offer an inducement by some exporters to divert their products toward less regulated destinations (Lawson and MacFaul, 2010). For example, Masiero et al. (2015) provided evidence on trade diversion, indicating that imports of tropical wood diminished in the US, the EU, and Australia while they increased in emerging economies such as China, India, and Vietnam.

Kim et al. (2023) found that the introduction of the timber legality requirement under the EUTR and the LAA led to a decrease in lumber imports in the US and EU. Their findings also showed that timber exports declined in countries that signed a Voluntary Partnership Agreement (VPA) with the EU, suggesting that VPAs support legal timber trade. Khanal et al. (2024) found that VPAs had a negative and significant impact on industrial roundwood export quantities from Cameroon, Ghana and the Republic of Congo, while the LAA had mixed effects. Apeti and N'Doua (2023) found that the trade measures of the United States, Australia, South Korea, and the EU led to smaller import quantities following implementation, particularly for roundwood, pulp, and wood furniture.

Although various trade measures have been addressed in the previous literature with special emphasis on either single trade measures and/or countries, no empirical study, to our knowledge, has assembled observational data to assess the empirical evidence of the effects of multiple trade measures on a common set of specific product groups for each importing country. Hence, it is important to compare dissimilarity among these policies because changes in trade flows for specific product groups could be attributed to implementation differences in legislation in importing countries and how the various policies are directed differently on either the demand for or the supply of illegal wood. The contribution of this study is to quantify the effects of illegal wood trafficking trade measures on the global forest market by identifying key

differences in trade measures taken by countries to prevent illegal wood trafficking. Using a gravity model, we separately examine the impacts of trade measures on import values in each product group by focusing on four country groups: Australia, the EU, Japan, and the US.

The remainder of the paper proceeds as follows. Section 2 outlines the empirical strategy and describes the data sources used in this study. Section 3 discusses estimation results. Section 4 presents policy discussions. Finally, section 5 offers concluding remarks.

2. Estimation strategy and data

2.1. Empirical approach

To quantify the impacts of trade measures regarding illegal wood trafficking in the global forest market, we employ the gravity model pioneered by Tinbergen (1962) which explains the size of bilateral trade between two countries. It is based on the economic size of two countries and the geographic separation (distance) between two countries. According to the gravity model, the size of bilateral trade is positively associated with economic size (respective national incomes such as GDPs) while it depends inversely on the distance between two countries i and j. A simple form of Tinbergen's gravity equation can be shown as

$$M_{ij} = A\frac{Y_i Y_j}{D_{ij}} \tag{1}$$

where M_{ij} is the traded physical quantity of the commodity between country i and country j, Y_i and Y_j are the respective economic sizes of countries (i and j), D_{ij} is a measure of the distance between country i and j, and A is a constant of proportionality.

Although the earlier specification of the traditional gravity model introduced by Tinbergen (1962) has been a robust estimation approach to explain the patterns of international trade, it lacked theoretical foundations. Subsequent studies demonstrated model improvements on the theoretical front. Seminal work by Anderson (1979) was the first to offer a theoretical foundation of the gravity model, using Cobb-Douglas expenditure and constant-elasticity of substitution (CES) preferences, which illustrated imperfect product substitution.

Anderson and van Wincoop (2003), following and proposing an augmented version of Anderson (1979), argue that the gravity model should control for the multilateral resistance (or fixed effects) in order to avoid misspecification of the model. The augmented gravity equation is

$$X_{ij} = \frac{y_i y_j}{y_w}\left(\frac{t_{ij}}{P_i P_j}\right)^{1-\sigma} \tag{2}$$

where X_{ij} denotes the trade flow between country i and j, y_i and y_j are the respective economic sizes (GDP) of countries i and j, $y_w$is global income, t_{ij} represents the bilateral trade barriers, σ is the elasticity substitution parameter, and P_i and P_j are price indices or "multilateral resistance." According to eq. 2, the bilateral trade, considering economic size, depends on the bilateral trade barriers and the product of multilateral trade resistance in countries i and j.

The log-linearization of the gravity eq. (2) with an additive error term can be characterized by the following form (Anderson and van Wincoop, 2003),

$$lnX_{ijt} = k + lny_{it} + lny_{jt} - lny_{wt} + \rho(1-\sigma)lnd_{ij} + R_{ij} + \varepsilon_{ijt} \tag{3}$$

where X_{ijt} denotes the trade flow from country i to j; k is a positive constant; y_i and y_j are the respective economic sizes in countries i and j; d_{ij} is the geographic distance between countries i and j; ε_{ijt} is the error term; and R_{ij} measures the sum of multilateral resistance terms (explained in eq. 2) as follows:

$$R_{ij} = (1-\sigma)lnt_{ij} - (1-\sigma)lnP_{it} - (1-\sigma)lnP_{jt} \tag{4}$$

A theoretical gravity equation followed in this empirical analysis is based on Eq. (2).

The traditional gravity model given in Eq. (2) is typically estimated by using the ordinary least squares (OLS) approach following a logarithmic transformation. However, using the OLS approach introduces two drawbacks in estimates of the model. First, the incidence of zero trade flows (lnX_{ijt}) is a particular concern because it eliminates zero trade observations since the natural logarithm of zero is undefined. One can argue that it could be legitimate to discard zero trade values because they might not be economically meaningful (Anderson, 2011). In the case of forest trade flows, as in this study, zero trade flows are prevalent and could convey important information that potentially explains trade patterns under new policy changes, so the truncation of zero trade flows may cause standard sample selection bias in the model (Heckman, 1979). The second caveat is the presence of heteroskedasticity in the error term (ε_{ijt}); the estimated parameters and standard errors can be significantly biased and inconsistent (Silva and Tenreyro, 2006).

To overcome the estimation challenges presented above, Silva and Tenreyro (2006) proposed the Poisson Pseudo Maximum Likelihood (PPML) model, which has become a well-recognized estimation method of choice in empirical international trade studies. Silva and Tenreyro (2006) demonstrate that the PPML estimator accounts for zero trade flows because the error term in eq. 2 takes a multiplicative form and estimates the model in levels instead of taking the natural logarithm of trade flows. Also, an important assumption of the PPML estimator is that the conditional variance is proportional to the conditional mean. Hence, the PPML estimator generates unbiased and consistent parameter estimates. The PPML estimator given in eq. 2 can be expressed as follows:

$$X_{ijt} = exp\left[lny_{it} + lny_{jt} - lny_{wt} + \rho(1-\sigma)lnd_{ij} + R_{ij}\right]\varepsilon_{ijt} \tag{5}$$

Anderson and van Wincoop (2003) pointed out that the absence of a multilateral resistance term in the model estimation, as in eq. 5, can lead to two problems: omitted variable bias and incorrect comparative statics analysis. Because multilateral resistance terms (the price indices, P_i *and* P_j, given in eq. 2) are unobservable by the researcher, they should be accounted for in the correct specification of the model. Baldwin and Taglioni (2006) also referred to the omission of multilateral resistance terms as a "gold medal mistake" and presented a way of overcoming this issue. Using directional (exporter and importer) or pairwise fixed effects in the estimation can control for the multilateral resistance terms; hence, the omitted variable bias can be avoided (Anderson and van Wincoop, 2003; Baldwin and Taglioni, 2006; Feenstra, 2004; Piermartini and Yotov, 2016). The usual application in empirical research is to introduce both importer and exporter fixed effects to absorb both observable and unobservable country-specific characteristics that may impact trade flows.[3,4]

Following the previous literature, this study also includes fixed effects to capture multi-resistance terms. However, the introduction of directional (both importer and exporter) or pairwise fixed effects in this study presents a difficulty in estimation because our data set does not have the entire set of country pairs for both directions (exporter and importer) and it focuses on a trade measure of a single importing country. For this reason, inclusion of country-specific exporter fixed effects is suitable in this study. Using time fixed effects also is not feasible for this study because importer-specific variables such as aggregate GDP or production are constant across all exporters and would be perfectly collinear; hence, it is dropped in the estimation. Therefore, we employ an alternative approach and use only exporter fixed effects to

[3] In addition to fixed effects estimation, Baier and Bergstrand (2009) proposed an alternative strategy to estimate the model using a first-order Taylor's series expansion. See Baier and Bergstrand (2009) for further details.

[4] Westerlund and Wilhelmsson (2011) proposed the use of a Poisson fixed-effects estimator. However, implementing such a model has the drawback of not excluding time-invariant variables.

Table 1
Estimation results: Australia.

Forest Products	Sawnwood (C)	Sawnwood (NC)	Plywood (C)	Plywood (NC)
lnDist	−9.940***	−2.860***	−6.661***	−2.836***
	(3.216)	(0.774)	(1.931)	(0.661)
ComLan	−0.924	0.287	−4.239	−1.295
	(2.798)	(1.772)	(4.326)	(2.200)
Cont	–	–	–	–
	–	–	–	–
lnForEx	0.980***	−0.00603	0.409	−0.475***
	(0.356)	(0.255)	(0.429)	(0.133)
lnForIm	−0.0936	−0.136	−0.798***	0.358*
	(0.302)	(0.169)	(0.267)	(0.183)
lnGDPEx	0.770	0.151	1.070	−0.622
	(0.490)	(0.262)	(0.679)	(0.418)
lnGDPIm	−0.103	0.598*	−0.402	1.741***
	(0.441)	(0.343)	(0.651)	(0.515)
lnExRate	−0.339***	0.0230	−0.113	−0.306*
	(0.113)	(0.106)	(0.214)	(0.183)
lnProEx	0.923***	0.191	0.465	0.602***
	(0.292)	(0.240)	(0.306)	(0.219)
lnProIm	0.154	1.149**	0.00116	0.0994***
	(0.429)	(0.347)	(0.321)	(0.0327)
ILPA	−0.259***	−0.262	−0.566***	−0.148
	(0.0801)	(0.218)	(0.200)	(0.0907)
Restriction	0.679***	0.472**	2.062***	−0.0715
	(0.218)	(0.194)	(0.667)	(0.355)
Member_WTO	2.155***	1.533	3.109***	1.634**
	(0.726)	(0.436)	(0.441)	(0.351)
Constant	80.67***	8.001*	50.96***	13.77***
	(31.15)	(8.405)	(19.51)	(4.686)
Observations	1078	1977	820	641
R-squared	0.940	0.920	0.832	0.848
Reset(*p*-value)	0.0151	0.0927	0.9689	0.1382
Exporter FE	Yes	Yes	Yes	Yes

Robust standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.
C = coniferous sawnwood; NC = non-coniferous.

capture unobserved country heterogeneity that may stem from trade measures, and we exploit the advantage of estimating importer-specific variables in our model.[5]

The empirical specification of the PPML[6] equation in this study is[7]

$$X_{ijt}^{k} = \beta_0 + \beta_1 lnDist_{ij} + \beta_2 ComLan_{ij} + \beta_3 Cont_{ij} + \beta_4 lnForEx_{jt} + \beta_5 lnForIm_{it} + \beta_6 lnGDPEx_{jt} + \beta_7 lnGDPIm_{it} + \beta_8 lnExRate_{ijt} + \beta_9 lnProEx_{jt}^{k} + \beta_{10} lnProIm_{it}^{k} + \sum_{n=1}^{3} \gamma_m d_{ijt}^{m} + \pi_j + \varepsilon_{ijt} \quad (6)$$

where X_{ijt}^{k} denotes the nominal imports value of country i from country j at time t for forest product k[8]; $Dist_{ij}$ stands for the geographical distance between trading partners; $ComLan_{ij}$ is a dummy variable for whether country i and country j share a common language; $Conti_{ij}$ is a dummy variable equal to 1 if trading partners share a common border, $ForEx_{jt}$ represents the exporter's forest rent at time t,$ForIm_{it}$ is the forest rent in year t in the importing country; $GDPEx_{jt}$ stands for the exporter's GDP at time t; $GDPIm_{it}$ is the importer's GDP at time t; $ExRate_{ijt}$ is the ratio of the exporter's local currency per importer's local currency; $ProEx_{jt}^{k}$ is the production quantity of product k in year t in the exporting country; $lnProIm_{it}^{k}$ denotes the importer's production quantity for product k at time t; d_{ijt}^{m} is the mth dummy for destination i at time t; π_j represents the country-specific exporter fixed effects; and ε_{ijt} is the error term.

Other variables that were introduced in this study include: (1) a trade policy indicator (ILPA, EUTR, LAA, or JCWA),(2) a restriction on production of regulated commodities, and (3) WTO membership. More specifically, we use the first two variables to capture the impacts of their incidence at the product level.

Given the estimation issues raised by using a conventional OLS estimator, we implement the PPML fixed effects (PPML FE) to estimate the product level[9] ($k = 1 \ldots 4$) gravity model for each importing country as the preferred specification, because the PPML FE simultaneously addresses both issues of zero trade flows and heterogeneity in the estimates and it also controls for omitted variable bias. Several robustness checks also were conducted to investigate econometric issues discussed above (Appendix C). We also implemented the Reset specification test to evaluate evidence of model misspecification (Ramsey, 1969) and report the results in the tables.

2.2. Data

We use annual data on bilateral total import values (in US dollars) of four product commodity groups for Australia, the EU, Japan, and the US and their trading partners.[10] Our data set covers the period 1996–2019 for Australia, Japan, and the US. The EU data spans from 1999 to 2019.[11] For the EU analysis, we consider 10 major importing countries in the EU, using the average value of imports between 1999 and 2019.[12] Data on import values for Australia, the EU, and Japan were collected from the United Nations (UN) Comtrade data (United Nations Statistics Division, 2019), using both the Harmonized Tariff System (HTS) 6-digit codes and the Standard International Trade Classification (SITC) (Rev.3) 4- and 5-digit codes. The EU and Japan data were assembled using HTC classification while Australian data was combined using SITC codes because SITC is the primary classification used in Australia's international trade statistics. For the US import values, data was obtained from the United States International Trade Commission (USITC) database (U.S. International Trade Commission, 2019) using HTS 6-digit codes.

Four commodity groups that were considered in this study are: (1) coniferous sawnwood, (2) non-coniferous sawnwood, (3) coniferous plywood, and (4) non-coniferous plywood. Table 1 and 2 in Appendix A display how such product groups were assembled using both the HTS and SITC classification codes. We select these product categories because they are regulated timber products by their HTS and SITC codes and they also represent major product groups by import values between 1997 and 2017 in Australia, the EU, Japan, and the US, as previously mentioned. In contrast with previous empirical studies that used aggregate level HTS classification codes for timber products (Guan and Gong, 2015; Morland et al., 2020; Larson et al., 2018), this study employs disaggregated data at the HTS 6-digit and SITC 4- and 5-digit codes to empirically evaluate the impacts of trade measures on the global forest products market.

As previously mentioned, the SITC is the primary trade classification

[5] We also implemented the Reset specification test (Ramsey, 1969) and report the results for each product group.

[6] The coefficients represent the elasticities of the dependent variable with respect to the continuous independent variables.

[7] All covariates are transformed with the natural logarithm, except for dummy variables in the model. The dependent variable is import value and is measured in levels.

[8] We estimated the PPML estimator separately for each of the four product groups: $k = 1$ is coniferous sawnwood, $k = 2$ denotes non-coniferous sawnwood, $k = 3$ indicates coniferous plywood, and $k = 4$ is non-coniferous plywood.

[9] We run the model by product group for each country.

[10] Trading partners of the countries are listed in the Appendix tables B9 through B12, respectively.

[11] The EU adopted the euro as their currency in 1999, so we used data from 1999 through, 2019 in order to be consistent with the exchange rate.

[12] For the EU data, we selected 10 major importing countries based on average import values between 1999 and 2019. The selected countries are Austria, Belgium, Denmark, France, Germany, Italy, the Netherlands, Poland, Spain, and the United Kingdom.

Table 2
Estimation results: European Union.

Forest Products	Sawnwood (C)	Sawnwood (NC)	Plywood (C)	Plywood (NC)
lnDist	−1.035***	−2.068***	−1.472***	−1.052***
	(0.363)	(0.339)	(0.426)	(0.338)
ComLan	0.662**	0.177	0.927**	1.513***
	(0.263)	(0.209)	(0.377)	(0.519)
Cont	0.611	0.260	−0.278	0.338
	(0.415)	(0.288)	(0.455)	(0.313)
lnForEx	0.378**	0.414**	0.591***	−0.269
	(0.157)	(0.189)	(0.221)	(0.188)
lnForIm	−0.716***	−0.552***	−0.0299	0.0214
	(0.177)	(0.131)	(0.197)	(0.104)
lnGDPEx	0.125	0.259	0.00335	−0.312*
	(0.154)	(0.166)	(0.208)	(0.178)
lnGDPIm	0.377*	0.0505	0.984***	0.937***
	(0.177)	(0.168)	(0.305)	(0.179)
lnExRate	−0.126	0.0891	−0.334	−0.0634
	(0.0988)	(0.0801)	(0.337)	(0.114)
lnProEx	0.264	0.314***	0.424***	0.664***
	(0.211)	(0.108)	(0.0859)	(0.108)
lnProIm	0.328**	0.294**	−0.228**	−0.143*
	(0.131)	(0.0838)	(0.0986)	(0.0739)
EUTR	−0.477***	0.0774	−0.204	−0.302***
	(0.182)	(0.0859)	(0.160)	(0.111)
Restriction	−0.0220	1.258***	−0.890***	0.298
	(0.265)	(0.150)	(0.204)	(0.206)
Member_WTO	−0.150	1.450***	−0.157	0.518***
	(0.197)	(0.224)	(0.344)	(0.168)
Constant	−5.942	10.04***	7.728**	−2.250
	(3.810)	(3.492)	(3.613)	(2.984)
Observations	17,780	23,220	8088	7764
R-squared	0.720	0.455	0.590	0.592
Reset(p-value)	0.861	0.687	0.6709	0.7908
Exporter FE	Yes	Yes	Yes	Yes

Robust standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.
C = coniferous; NC = non-coniferous.

code for Australian trade statistics. For sawnwood trade flows, 4-digit SITC codes were used. To obtain import values of non-coniferous (hardwood) plywood, coniferous plywood (63439) was subtracted from total plywood (6343) (see Table A1). The HTS classification system was used to obtain trade flows for the US, EU, and Japan. To obtain import values of non-coniferous (hardwood) plywood, coniferous (softwood) plywood was subtracted from total plywood (4412). HTS codes were redefined after 2007, so 4412.19 and 4412.39 were used for periods of 1996–2006 and 2007–present, respectively, to obtain non-coniferous plywood import values[13] (see Table A2).

Independent variables used in this study include forest rent, gross domestic product (GDP), exchange rates, the quantity of timber production for selected wood products, gravity variables and three dummy variables. Data on forest rents, GDP, and exchange rates were obtained from the World Bank's World Development Indicators (WDIs) (The World Bank, 2019). Forest rents (%GDP) were included to be a proxy for both forest endowment resources and the contribution of the forest sector to economic outputs. Previous literature has used either the ratio of per capita forestland area between exporter and importer (Guan and Gong, 2015) or wood production per capita (Zhang and Li, 2009) to proxy for forest resource endowment in considering the importance of forest abundance in the countries. Forest rents can also be a proxy for forest sector capacity; for instance, Morland et al. (2020) used forest rents to account for forest sector production potential. As gravity theory suggests, GDP is the most commonly used variable to account for economic size of a country in the literature; therefore, GDP data were included as a proxy for economic size. The effect of exchange rates on forest products trade has been documented by previous studies (Buongiorno, 2015; Zhang and Li, 2009; Zhang et al., 2019) because movements in exchange rates and exchange rate volatility bring uncertainty in trade flows and could influence trade patterns. The exchange rate used in this study is the importing country's exchange rate per exporter's local currency.

Home bias, the phenomenon in which consumers favor domestic products over foreign alternatives, has been an important puzzle in the international trade literature along with the border puzzle, tariff and non-tariff barriers, and exchange rate risk (Obstfeld and Rogoff, 2000). We included both exporter's and importer's production data to control for multilateral trade resistance (Anderson and van Wincoop, 2003) and quantity if trade induces such bias in forest products flow. Further, countries may adjust their production capacity to control the trade balance and increase domestic production as well. However, many factors (such as heterogeneity in demand across countries) might contribute to home bias, and often it is hard to distinguish demand-side home bias from costs associated with trade. Although home-bias in forest products trade has little empirical support in the literature, accounting for this phenomenon has a low cost in terms of reduced degrees of freedom but large potential benefits if it leads to avoidance of statistical confounding. Timber production data for selected wood products were obtained from the International Tropical Timber Organization (ITTO) (International Tropical Timber Organization, 2019)[14]

Adding commonly used gravity variables such as distance, common language, contiguity, or colonial history usually accounts for differences in demand trade costs (Anderson, 2011). More specifically, distance and contiguity are the most commonly used variables to account for trade costs and market accessibility in the international trade literature (Anderson and van Wincoop, 2004). Distance, common language, contiguity, and WTO membership were added to consider both trade cost and market accessibility. Data on gravity variables were collected from USITC's gravity database (U.S. International Trade Commission, 2020) to proxy market accessibility because USITC gravity data is more detailed and addresses limitations from Centre d'Etudes Prospectives et d'Informations Internationales (CEIP).[15]

In addition, we introduce the following variables to our models: (1) trade measures, namely ILPA, EUTR, JCWA, and LAA, which capture the impact of trade policies imposed by the importing countries in this study and are equal to 1 in the effective year of the related policy; (2) a restriction that takes a value of 1 if the exporting country has a law that curbs illegal logging within the country at time *t*; and (3) WTO membership, which takes a value of 1 if the exporter is a member of WTO. A negative (and significant) coefficient of trade measure and a positive (and significant) coefficient of restriction suggest trade diversion toward the markets where policies are in place that encourage legality. Moreover, a positive (and significant) coefficient of WTO membership indicates that being a member of WTO facilitates trade.

Yotov et al. (2016) suggests that using panel data with intervals, instead of pooled over continuous years, may allow for adjustments in trade flows and trade costs after trade policies are enacted to estimate the full impact of such policy. We specifically employed pooled continuous year data to avoid any biases that might arise due to a reduction in sample size and averaged-out anticipation (pre-window) and delayed (post-window) effects (Egger et al., 2022). We employed continuous pooled data because the use of consecutive-year data avoids downward-bias effects in the estimates.

All monetary values and exchange rates are in current US dollars. We

[13] Coniferous plywood is described in the HTS code system as plywood in which both outer plies are coniferous wood.

[14] The ITTO has provided information about timber production and trade flows data for primary timber products since 1990. Data collection is based on data submitted by ITTO members countries through the Joint Forest Sector Questionnaire administered by the United Nations Food and Agricultural Organization and the Economic Commission for Europe. Historical data can be found at https://www.itto.int/biennal_review/.

[15] More details can be found at https://www.usitc.gov/data/gravity/dgd.htm.

particularly used nominal values because the incorrect deflation of monetary values might cause biases in the estimations (Baldwin and Taglioni, 2006). Data descriptions and sources as well as a summary statistic of all variables included in the countries are exhibited in Appendix B Tables B1 through B4 present the definition of variables used in this study and detailed information about data resources for each country. Summary statistics of country-specific variables are displayed in Tables B5 through B8.

3. Estimation results

The estimation results of how trade measures on illegal wood trafficking impact international trade of forest products are based on the estimates from the PPML FE model. First we present the estimation results for Australia; then we continue with the EU, Japan, and the United States.

3.1. Australia

The estimation results of PPML estimators (PPML FE) are reported in Table 1. As indicated earlier, the main variable of interest in this study is the dummy variable constructed for each trade measure mentioned earlier, because the purpose of this study is to quantify the impacts of trade measures on import values in each country. The estimated coefficient of ILPA is negative, as expected, and statistically significant for both coniferous sawnwood and coniferous plywood. In other words, implementation of such a policy would reduce the total value of imports of coniferous sawnwood by 22.81%[16] while it decreases the import values of coniferous plywood by 43.22%.[17]

The coefficient of the restriction is positive, economically large, and statistically significant for all product groups except non-coniferous plywood. More precisely, if the exporting country has domestic policies that encourage legality, imports of coniferous and non-coniferous sawnwood by Australia would increase by 97.19%[18] and 60.31%, respectively.[19] The impact of having a trade restriction in the exporting country is quite large on the import values of coniferous plywood. We interpret the combined effects of both findings (the impacts of ILPA and trade restriction) as suggesting evidence of trade diversion for both coniferous sawnwood and coniferous plywood import values in Australia and moving trade flows toward countries that have trade laws in place for these two product groups. By having a trade restriction, the exporting country has made itself a preferred source of coniferous sawnwood and plywood imports. Overall, the partner membership in the WTO *(Member WTO)* has a positive and statistically significant influence on import values of all forest products (except non-coniferous sawnwood), suggesting that being a WTO member facilitates trade.

3.2. The European Union

The estimation results of PPML estimators from the preferred specification (PPML FE) are reported in Table 2.

The estimated coefficient of the EUTR is negative and statistically significant for both coniferous sawnwood and non-coniferous plywood. Coefficient estimates imply that the implementation of EUTR would reduce coniferous sawnwood imports by 37.93%[20] while it decreases the import values of non-coniferous plywood by 26.06%.[21] The estimated coefficient of restriction is positive and statistically significant for non-coniferous sawnwood. This result suggests that EU trades more with the countries that have trade restrictions on illegal fiber sourcing—a possible indication of a trade diversion for non-coniferous sawnwood imports. As for coniferous plywood, the impact of whether the exporting country has trade restriction that discourages illegal logging is negative and statistically significant. We interpret this result as suggesting that the EUTR would not cause a trade diversion for coniferous plywood imports. The parameter estimate of WTO membership *(Member WTO)* is positive and statistically significant for non-coniferous sawnwood and non-coniferous plywood, but it is not statistically significant for coniferous sawnwood and coniferous plywood.

Table 3
Estimation results: Japan.

Forest Products	Sawnwood (C)	Sawnwood (NC)	Plywood (C)	Plywood (NC)
lnDist	−1.645	−1.634***	−0.794	−1.152**
	(1.276)	(0.167)	(0.770)	(0.525)
ComLan	–	–	–	–
	–	–	–	–
Cont	–	–	–	–
	–	–	–	–
lnForEx	0.546***	−0.212	1.941***	0.224
	(0.205)	(0.234)	(0.439)	(0.150)
lnForIm	0.0471	0.475***	0.0419	−0.508***
	(0.234)	(0.115)	(0.192)	(0.174)
lnGDPEx	0.621**	−1.014***	0.410	0.545***
	(0.295)	(0.175)	(0.283)	(0.137)
lnGDPIm	0.901**	1.275***	1.165**	−0.0640
	(0.445)	(0.222)	(0.538)	(0.195)
lnExRate	−0.0340	−0.104	0.496*	−0.202*
	(0.154)	(0.118)	(0.278)	(0.103)
lnProEx	0.345	0.182	0.944***	0.620***
	(0.384)	(0.161)	(0.244)	(0.115)
lnProIm	0.866***	0.196***	−0.531**	0.160***
	(0.265)	(0.0404)	(0.263)	(0.0547)
JCWA	−0.808***	−0.340***	−0.568***	−0.548
	(0.0741)	(0.111)	(0.130)	(0.365)
Restriction	0.225**	−0.0418	0.709**	−0.103
	(0.0931)	(0.0917)	(0.300)	(0.711)
Member_WTO	0.306	0.189**	0.500	0.808***
	(0.225)	(0.0890)	(0.620)	(0.268)
Constant	−7.577	4.710**	−3.317	−1.409
	(14.28)	(2.313)	(7.813)	(4.351)
Observations	1240	2472	615	618
R-squared	0.949	0.933	0.901	0.932
Reset(p-value)	0.0921	0.0013	0.031	0.4641
Exporter FE	Yes	Yes	Yes	Yes

Robust standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.
C = coniferous; NC = non-coniferous.

3.3. Japan

The estimation results from the preferred specification (PPML FE) are reported in Table 3. The estimated coefficient of the JCWA variable is negative and statistically significant for coniferous sawnwood, non-coniferous sawnwood and coniferous plywood. The negative sign implies that the implementation of JCWA would reduce imports values of coniferous sawnwood, non-coniferous sawnwood and coniferous plywood by 55.42%,[22] 28.82%[23] and 43.33%,[24] respectively. These findings suggest that the implementation of JCWA impedes trade and decreases import values of these commodity groups. The estimated coefficient of restriction is positive and statistically significant for both

[16] The coefficients on indicator variables are semi-elasticities that are equal to [exp(β)-1] *100), so the rest of paper follows this equation to interpret the impact of country-specific trade measures on import values. It is computed as [exp (−0.259)-1] *100.
[17] It is estimated as [exp (−0.566)-1]*100.
[18] Computed as [exp (−0.259)-1] *100.
[19] Computed as [exp (0.472)-1] *100.
[20] Computed as [exp (−0.477)-1] *100.
[21] Computed as [exp (−0.302)-1]*100.
[22] Computed as [exp (−0.808)-1] *100.
[23] Computed as [exp (−0.340)-1] *100.
[24] Computed as [exp (−0.568)-1] *100.

Table 4
Estimation results: United States.

Forest Products	Sawnwood (C)	Sawnwood (NC)	Plywood (C)	Plywood (NC)
lnDist	3.093**	1.273***	−1.388***	2.463***
	(1.207)	(0.355)	(0.198)	(0.491)
ComLan	1.747	9.996***	8.207***	−3.197***
	(2.385)	(1.081)	(0.198)	(1.139)
Cont	9.526**	−1.946	–	5.481***
	(3.854)	(1.503)	–	(1.171)
lnForEx	−0.0343	0.754**	−0.205	0.124
	(0.164)	(0.209)	(0.232)	(0.182)
lnForIm	−0.648***	−0.0939	0.279	0.334*
	(0.196)	(0.414)	(0.657)	(0.195)
lnGDPEx	−0.957***	0.200	−1.267***	0.0433
	(0.177)	(0.193)	(0.181)	(0.217)
lnGDPIm	1.495***	1.424*	4.886***	1.430***
	(0.291)	(0.615)	(0.862)	(0.399)
lnExRate	−0.367*	−0.132**	0.295	−0.0145
	(0.191)	(0.0597)	(0.761)	(0.126)
lnProEx	0.696**	0.200**	1.942***	0.865***
	(0.347)	(0.0995)	(0.249)	(0.115)
lnProIm	1.592**	0.411	1.875**	0.0955
	(0.259)	(0.350)	(0.823)	(0.779)
LAA	0.251**	−0.633***	−0.280	−0.551***
	(0.124)	(0.101)	(0.212)	(0.0938)
Restriction	−0.624**	0.524***	−1.199	0.888**
	(0.245)	(0.203)	(1.015)	(0.373)
Member_WTO	1.229**	1.410***	0.297	0.601
	(0.572)	(0.353)	(1.112)	(0.421)
Constant	−58.22***	−36.66***	−62.54**	−36.62***
	(11.19)	(3.492)	(14.71)	(7.556)
Observations	1699	2581	894	1028
R-squared	0.990	0.941	0.926	0.945
Reset(p-value)	0.0201	0.0019	0.0003	0.9107
Exporter FE	Yes	Yes	Yes	Yes

Robust standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.
C = coniferous; NC = non-coniferous.

coniferous sawnwood and coniferous plywood. If the combined effects of both JCWA and the restriction are considered, we find supporting evidence of import diversion toward countries that impose trade measures on illegal fiber sourcing for both coniferous sawnwood and coniferous plywood. The parameter estimate of WTO membership *(Member WTO)* is positive and statistically significant for both non-coniferous sawnwood and non-coniferous plywood.

3.4. The United States

The estimation results of PPML estimators from the preferred specification (PPML FE) are reported in Table 4. The introduction of the LAA has a negative and statistically significant impact on both non-coniferous sawnwood and non-coniferous plywood, as expected, implying that the LAA reduces non-coniferous sawnwood and non-coniferous plywood imports by 46.90[25] percent and 42.36%,[26] respectively. The estimated coefficients of the restriction are positive and statistically significant for both non-coniferous sawnwood and non-coniferous plywood. Considering both the impacts of the LAA and the restriction, the implementation of the LAA is associated with trade diversion with non-coniferous sawnwood and non-coniferous plywood. The parameter estimate of WTO membership *(Member WTO)* is positive and statistically significant for both coniferous sawnwood and non-coniferous sawnwood.

4. Discussion

Illegal wood trafficking is a global problem due to its detrimental environmental, economic and social impacts. Several countries have attempted to take proactive trade measures to address the problem and prevent illegally traded timber from coming to their markets. Trade measures in key consuming countries—-Australia, the EU, Japan, and the US—-have affected trade patterns of imported wood products. Our gravity model estimates identified a negative and significant effect of trade measures implemented by countries on the import of wood products. Nevertheless the effect varies by country and product group (Tables 5 and 6).

The national legislative efforts by countries also set an example for other countries to take initiatives, though perhaps not in identical fashion. ILPA is associated with a reduction in the import values of both coniferous sawnwood and plywood in Australia, but it also apparently induced significant trade diversion in the region, where the rate of illegal wood fiber sourcing is high (Forest Campaign, 2023). A similar finding from our analysis emerged for the EUTR; it is associated with a reduction in the import values of coniferous sawnwood and non-coniferous plywood and likely induced a diversion of imports of non-coniferous plywood toward unregulated countries, redirecting trade for non–coniferous plywood to regulated countries. The EUTR, a demand-side prohibition of illegally sourced wood, was designed to complement the supply-directed VPAs under FLEGT, toward an overall goal of shrinking the illegal sector and expanding the legal sector in global forest products markets. While the dummy variable on restrictions was intended to model the effects of current exporters to the EU, the positively signed effects indicate that export revenues are higher, other variables held constant. This finding hints that the laws that prohibit illegal logging may act as a promoter of greater legal trade with the EU. The pairing of such demand- and supply-side actions, which we modeled with the gravity equations, was a key recommendation by Chatham House (2020), who called for a redoubling of international efforts to pair supply- and demand-side actions, in addition to recommending strengthened programs countering agriculture-driven forest loss and putting more resources into promoting sustainability.

Indeed, the refocusing recommendations of Chatham House (2020) align with the new European Commission Regulation (EU) 2023/1115, commonly referred to as the European Union Deforestation Regulation (European Commission, 2003). The EUDR, in fact, supersedes the EUTR and expands the EU's scope of concern to now prohibit imports into the Union of forest and agricultural products which have been produced in the process of forest degradation or deforestation. While new research using market simulation approaches suggests the range of potential market and trade impacts of the EUDR, (Johnston et al., 2025), the specific empirical effects of the EUDR on global markets and trade are yet to be known; the natural forest loss provision could imply effects even larger than those that we and others have identified for the more narrowly designed EUTR.

Despite the JCWA's voluntary nature, we find that its effects are quite similar in magnitude to the effects of the compulsory schemes we analyzed for Australia, the United States, and the EU. The impacts of the

Table 5
The impact of trade measures on import values by forest product groups.

Policy	C Sawnwood	NC Sawnwood	C Plywood	NC Plywood
Australia (ILPA)	−22.80%	Negative impact but not significant	−43.22%	Negative impact but not significant
EU (EUTR)	−37.93%	Positive impact but not significant	Negative impact but not significant	−26.06
Japan (JCWA)	−55.42%	−40.49 Percent	−43.33%	Negative impact but not significant
US (LAA)	28.53 Percent	−46.90 Percent	Negative but not significant	−43.36 Percent

C = coniferous; NC = non-coniferous.

[25] Computed as [exp (−0.633)-1] *100.
[26] Computed as [exp (−0.551)-1] *100.

Table 6
The evidence trade diversion on forest product groups.

Policy	C Sawnwood	NC Sawnwood	C Plywood	NC Plywood
Australia (ILPA)	Positive	Positive impact but not significant	Positive	Positive
EU (EUTR)	Negative	Positive impact but not significant	Negative impact but not significant	Positive
Japan (JCWA)	Positive	Negative impact but not significant	Positive	Negative impact but not significant
US (LAA)	Negative	Positive	Negative but not significant	Positive

C = coniferous; NC = non-coniferous.

LAA on US imports show mixed results in our gravity model-based study. However, the LAA is associated with a reduction in the total value of US imports of non-coniferous sawnwood and non-coniferous plywood from the countries where laws promoting legality are in place, which is consistent the findings on quantities of these product imports found by Prestemon (2015), while the LAA was associated with an increase in the import values of coniferous sawnwood. Key regulations analyzed in this study show reductions in the import values of certain product groups. Although this study was based on empirical data analyzed with an expanded gravity model of trade in forest products, it is important to recognize that the statistical results identified statistical associations, not proven causal effects of the policies that we analyzed.

Overall, the impact of trade measures to remove illegally sourced wood, as measured by the statistical associations identified in this study, vary by selected product categories and individual countries possibly because of the technical and practical differences in policy structures and dynamics of the domestic forest industry in the affected countries. We find that the extent to which the efforts taken by countries to combat illegal wood trafficking are associated with a decrease in the import values and cause trade diversion depend on the product category in question. In particular, the majority of the world's illegal wood fiber sourcing is in non-coniferous wood products, not for coniferous products. One possible exception to the international flow of illegal coniferous wood may be from Russia to China (Forest Trends, 2021).

5. Conclusions

While our findings show the combined impacts of actions by multiple countries to have substantially altered global markets for wood, our approach is not without its limitations. First, although the gravity model has been parameterized to account for time-invariant factors affecting trade, trade flows may be impacted by various hidden time-varying factors that are not directly considered by the model, such as transportation costs, energy prices, market volatility, prices of product substitutes, and domestic policies creating changes within importing and exporting country markets over the span of the time series of data. Another source of modeling uncertainty derives from time-varying rates of trade law enforcement success, which is inherently unobservable, at deterring illegal wood imports. Furthermore, we were not able to model another inherently unobservable factor regarding illegal fiber supply, the variations over time and across countries in the strength of certification standards. While those standards may roughly be correlated with the Restriction dummy in our model, the sign and magnitude of that dummy shows only the average effect. Likewise, our analysis of the effects of the various policies on the imports of EU member states did not seek to model differences in import control intensities across the member states, which also might have been time-varying over the span of the data. New research that accounts for these differences would be helpful for fortifying the success of the EU framework.

A further weakness of the study extends to the input data themselves, the value of imports. The value of products that are nominally from the listed exporting country but instead are reexports of products from a different, original country, create additional uncertainty in our models and could potentially bias parameter estimates. Such values would lead to inconsistencies in these estimates if they are time-varying or otherwise created correlations between errors and other regressors in our models. Related to this, we also did not directly model intra-EU trade in forest products. Direct modeling of this trade could have helped to better understand how the EUTR, which applies for intra-EU trade as well as imports from outside the EU, has altered flows internally; we suggest that such modeling is an area for future research.

Finally, our analysis did not seek to directly model the effects of domestic laws seeking to more vigorously enforce laws on illegal harvesting that were enacted over the time span of our data or on the extent of forest and wood certification taking place within the borders of the trading partners of the EU, Australia, Japan, or the U.S. Indeed, a fruitful avenue for advancing understanding in illegal fiber sourcing would muster data on wood certification and model their effects jointly with trade measures. The effects of domestic legality enforcement and sustainability enhancing laws on the global flow of wood in conjunction with trade measures of importing countries may be possible with small sets of countries and products (e.g., Prestemon (2015)), but research is needed to assemble and model these laws in the context of trade measures by importers. The omission of unmodeled time-varying factors such as those mentioned here could generally lead to inflated standard errors and biased parameter estimates, so our empirical findings should be viewed in this context, even while we do not know the magnitude of these phenomena.

With the above caveats in mind, we conclude that efforts undertaken by Australia, Japan, the EU, and the United States designed to stem the flow of illegal wood are associated with economically meaningful impacts on trade, and in the manner expected. Although effects on trade are not proof of effects on illegal wood fiber flows, our results suggest that companion efforts to bolster legality in wood source countries, possibly in the form of VPAs but also through unilateral and bilateral efforts, are associated with expanded export opportunities to countries concerned with limiting the flow of illegal wood. Whether the new EUDR takes global markets a step further in bolstering legal and sustainable production remains to be seen, but that legislation, with its particular expanded focus on forest loss and degradation, merits new investigation because of its potential consequences across many countries not originally impacted by the EUTR.

CRediT authorship contribution statement

Elise T. Kaya: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Jeffrey P. Prestemon:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization. **Barry K. Goodwin:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization.

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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2026.103942.

Data availability

Data will be made available on request.

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