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Sustainable forest management through certification and wood products trade: Analyzing the role of the FSC across diverse economic and climatic contexts

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ABSTRACT

This study investigates the role of Forest Stewardship Council (FSC) certification in advancing sustainable forest management and influencing forest cover changes across 70 countries from 2000 to 2021. Using dynamic panel data model and Generalized Method of Moments (GMM) estimations, the analysis addresses endogeneity concerns, such as those stemming from lagged dependent variables, providing robust and unbiased estimates. Results indicate that FSC certification significantly enhances forest cover, with the most pronounced effects observed in low- and middle-income countries. Additionally, the study explores how FSC certification interacts with income levels and climatic conditions, revealing region-specific variations in its effects. These findings highlight the importance of market-based conservation tools, such as FSC certification, which align economic incentives with sustainability objectives. The analysis provides practical insights, recommending the integration of FSC certification into responsible trade practices and the development of regionally tailored forest management strategies to maximize conservation outcomes.

1. Introduction

Forests cover one-third of the Earth's habitable land and are vital for sustaining terrestrial biodiversity and regulating the planet's climate systems (Ritchie, 2021). These ecosystems serve as critical carbon sinks, absorbing greenhouse gases and mitigating climate change (IPCC, 2019). Beyond their environmental functions, forests support human livelihoods and contribute to global ecological stability. They provide essential ecosystem services, including soil conservation, water purification, and flood prevention, while also supplying timber and non-timber products critical to millions of people worldwide. Their importance transcends national boundaries, making them central to addressing global environmental challenges and promoting sustainable development.

Notwithstanding their ecological and economic importance, forests face persistent threats from deforestation and degradation, challenges that undermine their ability to support biodiversity, regulate climate systems (Anderegg et al., 2020), and contribute to sustainable development (Hoang and Kanemoto, 2021). The urgency of these threats is evident in the rapid decline of global forest cover. Between 2000 and 2021, global forest area decreased from 4146 million hectares to 4045 million hectares, driven by region-specific factors (World Bank, 2024). In tropical regions, agricultural expansion and logging are the primary drivers of forest loss (Hoang and Kanemoto, 2021). In contrast, temperate zones experience degradation largely due to unsustainable resource use (Blackman et al., 2018) and weak enforcement of management practices (Tritsch et al., 2020). Effective mitigation requires regionally tailored forest management strategies that address economic pressures, environmental challenges, as well as socio-political constraints. In response, policymakers and stakeholders have adopted a range of conservation strategies, broadly categorized into regulatory and market-based approaches. Traditional regulatory mechanisms, such as protected areas and land-use zoning, restrict access to forest resources to prevent overexploitation. In contrast, market-based approaches like forest certification programs aim to align economic incentives with sustainability objectives. Among these, the Forest Stewardship Council (FSC) has emerged as a leading certification system, covering 160 million hectares of forest globally as of 2023 (FSC, 2024). Established in 1993, FSC certification promotes compliance with social and environmental standards by linking sustainable forestry practices to market

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demand for certified products. Its dual focus[1] on conservation and economic viability has earned it international recognition as a powerful tool for sustainable forest management.

In tropical regions, empirical evidence indicates that certification improves compliance and forest management practices, thereby reducing deforestation (Blackman et al., 2018). However, challenges persist in temperate zones, where socio-economic factors, market volatility, and fragmented supply chains can hinder the effectiveness of certification (Tritsch et al., 2020). These findings lend support to the importance of context-specific approaches to certification systems.

Illustratively, while FSC certification has demonstrated potential in curbing deforestation and degradation, its impacts remain uneven across regions and contexts. For example, FSC's influence is particularly pronounced in tropical regions, where it strengthens forest governance and improves management practices. However, the effectiveness of certification approaches varies widely due to socio-economic factors, market conditions, and enforcement challenges. For instance, while FSC certification has gained traction in regions with high biodiversity and weak governance, other systems, such as the Programme for the Endorsement of Forest Certification (PEFC), dominate in temperate and boreal forests, often aligning more closely with national policies.

Despite existing insights, significant gaps remain in the literature regarding the effectiveness of FSC certification. In particular, there is limited empirical evidence on its differential impacts across countries with varying income levels and climatic zones. Furthermore, many studies overlook the dynamic nature of forest cover change, which is often shaped by lagged effects and issues of endogeneity—factors that complicate econometric analyses. To address these limitations, this study uses the Generalized Method of Moments (GMM), a robust dynamic panel data estimation technique that accounts for endogeneity and unobserved heterogeneity. GMM's ability to handle lagged dependent variables and complex interactions makes it particularly suitable for assessing the long-term effects of FSC certification on forest cover dynamics. Specifically, the objectives of this research are threefold:

i. To assess the global impact of FSC certification on forest cover changes.
ii. To examine the differential effects of FSC certification across income levels and climatic zones.
iii. To explore the role of sustainable wood product trade in promoting forest conservation.

This study makes several key contributions to the literature on sustainable forest management. First, it provides empirical evidence on FSC's effectiveness across diverse economic and ecological contexts, highlighting its differentiated impacts in tropical and temperate zones. Second, it enhances methodological rigor in forestry research by applying GMM to capture dynamic interactions and address endogeneity issues. Third, it situates FSC certification within broader sustainability frameworks, including the United Nations Sustainable Development Goals (SDGs) and the United Nation's Reducing Emissions from Deforestation and forest Degradation (REDD+) initiative, highlighting its relevance to global policy debates. Finally, the study provides actionable insights for policymakers and stakeholders, emphasizing the importance of certification programs tailored to specific regional socio-economic and environmental conditions.

To address these research questions, the paper begins with a brief review of relevant literature on sustainable forest management and certification systems. It then presents the data and methodology, followed by empirical results and a discussion of policy implications.

[1] Forest certification systems, particularly FSC, aim to reduce deforestation and degradation while enhancing the economic viability of forest enterprises through independent assessments based on predefined standards (Brashaw and Bergman, 2021; Malek and Abdul Rahim, 2022).

2. Literature review

The relationship between international trade, forest certification, and sustainable forest management has garnered increasing attention due to the economic and ecological benefits of forests. However, the effectiveness of these mechanisms in mitigating deforestation and promoting sustainable practices remains debatable. While some studies highlight successful outcomes in well-regulated regions, others emphasize the challenges posed by weak governance, economic incentives for illegal logging, and the displacement of deforestation to neighboring areas.

As Fig. 1 can reveal, international trade in forest products has grown significantly over recent decades, driven by globalization (Boubacar, 2024) and rising demand for timber and non-timber products (FAO, 2018).

According to the Heckscher-Ohlin theorem, countries with abundant forest resources tend to export forest-derived goods, whereas resource-scarce countries often rely on imports (Boubacar, 2024). This theoretical framework helps explain the dual role of trade in both driving deforestation and supporting sustainable forest management.

On one hand, several studies highlight the detrimental impacts of trade on forest resources, particularly in regions with weak regulatory frameworks and inadequate enforcement. This problem is especially acute in countries with high corruption levels, where unsustainable logging often goes unchecked. For instance, Abman and Lundberg (2020) find that increased exports of wood products often intensify deforestation, particularly in tropical countries with weak governance and high corruption. Similarly, Meyfroidt et al. (2010) argue that trade liberalization exacerbates deforestation by incentivizing forest exploitation to meet global demand.

On the other hand, some researchers content that trade can promote sustainable forestry practices. Kastner et al. (2011) posit that importing wood products helps countries facing high population pressure alleviate stress on their domestic forests, thereby reducing the need for extensive logging. This perspective aligns with the idea that well-regulated trade can enhance resource efficiency (Migliavacca et al., 2024) and reduce illegal logging (Hedemann-Robinson, 2024). However, a major limitation of this argument is its failure to adequately address the phenomenon of deforestation leakage, wherein conservation efforts in one country may lead to increased deforestation in neighboring countries to meet redirected demand (Pendrill et al., 2019). Addressing this dynamic requires coordinated policies targeting global supply chains, such as deforestation-free trade agreements and effective certification programs (Hedemann-Robinson, 2024).

The literature also examines how demographic and economic factors contribute to deforestation. Early studies highlighted the roles of population growth (Cropper and Griffiths, 1994) and economic development (Jha and Bawa, 2006). However, more recent research presents

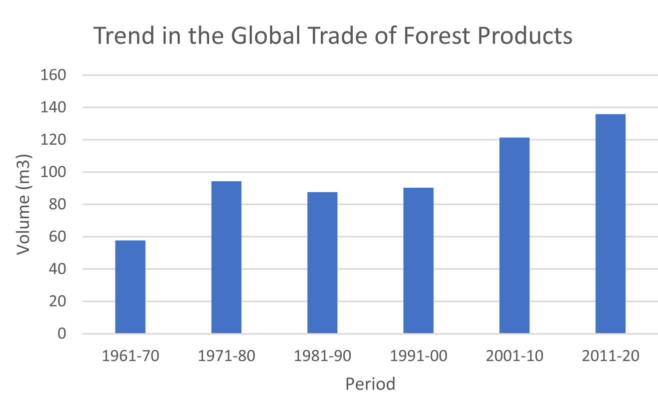

Fig. 1. Global trade of forest products.
Source: Food and Agriculture Organization of the United Nations Statistics (FAOSTAT)

mixed findings. For example, DeFries et al. (2010) and Panlasigui et al. (2018) argue that the relationship between economic development and deforestation is context-dependent: while development may reduce forest loss in some regions, it can accelerate it in others. In addition to these factors, deforestation has been linked to agricultural expansion, infrastructure development (Weatherley-Singh and Gupta, 2015), urbanization (Wilcove et al., 2013), and governance quality (Fischer et al., 2020). Notably, weak governance often facilitates illegal logging and other unsustainable practices (Fischer et al., 2020).

Though these studies offer valuable insights, they frequently lack a holistic perspective that integrates the dynamic interactions between socio-economic drivers and forest management strategies. Furthermore, most analyses are limited to national or regional contexts, overlooking the complex interconnections among international trade, governance structures, and global environmental policies.

Amid these challenges, forest certification has emerged as a key tool for promoting sustainable forest management. Certification frameworks, such as those under the Forest Stewardship Council (FSC), incentivize responsible forest management practices through market-based mechanisms. By linking certified products to environmentally conscious consumers, certification offers an alternative to traditional conservation approaches. For example, Auld et al. (2008) emphasize the role of certification in expanding environmentally sensitive markets, while Malek and Abdul Rahim (2022) link certification to the advancement of the Sustainable Development Goals (SDGs). Still, the effectiveness of certification approaches remains a topic of debate, with empirical evidence showing mixed results regarding their impact on forest cover change, adoption rates (Ehrenberg-Azcárate and Peña-Claros, 2020), and enforcement efficacy (Fischer et al., 2020).

Several certification systems exist, the most prominent being the Forest Stewardship Council (FSC) and those under the umbrella of the Programme for the Endorsement of Forest Certification (PEFC) (Auld et al., 2008). Established in 1993, the FSC is often regarded as the most rigorous and globally recognized standards (Taylor and Lindenmayer, 2021). As of June 2023, approximately 160 million hectares of global forest area were certified under the FSC (FSC, 2024), compared to 291 million hectares under the PEFC (PEFC, 2024). Together, these systems account for about 9 % of the world's forest area. However, a closer look at disaggregated statistics by countries, regions, and certification frameworks reveals significant variations in adoption rates (Fig. 2 and Table 1), motivating this study's focus on FSC[2] over PEFC.

From Fig. 2, it is evident that North America leads in PEFC certifications (55 %), followed by Europe (29 %), with South America and Africa contributing only 2.13 % and 0.45 % respectively. For FSC certifications, North America still leads the list with 38.25 % and closely followed by Europe with a rate of 37.45 %. Two major observations stand out from the analysis of Fig. 2. First, on average, Asia shows no significant difference in certification distribution between FSC and PEFC. Second, Africa, Europe, and South America have a higher share of FSC-certified land, whereas North America and Oceania favor PEFC. At the country level (Table 1), Canada tops both systems with 29 % (FSC) and 43 % (PEFC). While the top 10 PEFC-certified countries are concentrated in North America and Europe, the top 10 for FSC are more geographically diverse, spanning multiple continents. Illustratively, the two North American countries, namely Canada and USA, account for about 55 % forest land certified under the PEFC endorsed frameworks while up to four countries (Canada, Sweden, USA, and Brazil) account for the same rate of certification under FSC system.

Despite sharing similar goals, FSC and PEFC differ in structure and geographic focus. FSC operates in 89 countries (FSC, 2024), often in regions of high biodiversity and weak governance, thanks to its stricter social and environmental standards (Taylor and Lindenmayer, 2021). In contrast, PEFC, active in 56 countries (PEFC, 2024), aligns more closely with national forest management policies and is more prevalent in temperate and boreal zones.

The broader relevance of FSC becomes particularly evident when examined within the context of international frameworks like REDD + program and SDGs. FSC has the potential to enhance REDD + implementation by supporting its core objectives of reducing deforestation and promoting sustainable forest management. Moreover, integrating FSC into REDD + frameworks can provide tools for assessing co-benefits such as biodiversity conservation and poverty alleviation. For instance, FSC and other voluntary certification mechanisms are increasingly used to validate REDD + projects, helping ensure they meet both environmental and social sustainability criteria (Merger et al., 2011). This synergy enhances the credibility and on-the-ground effectiveness of REDD + initiatives. Nonetheless, a key limitation of FSC certification is its lack of explicit carbon quantification metrics, a hallmark of REDD+. Incorporating carbon accounting measures into FSC standards could strengthen its alignment with REDD + goals, attract climate financing, and reinforce its role in global climate change mitigation efforts (Fletcher et al., 2016).

Forest certification also contributes to the achievement of the SDGs by addressing interconnected targets including climate action (Goal 13), life on land (Goal 15), and poverty alleviation (Goal 1) (Malek and Abdul Rahim, 2022). Certification initiatives enforce sustainable practices that reduce environmental degradation while promoting economic fairness and social equity. For instance, certified forest projects often incorporate local and indigenous communities into forest governance, thereby ensuring equitable benefit-sharing and recognizing traditional knowledge (Teitelbaum and Wyatt, 2013). Moreover, empirical evidence shows that FSC-certified forests exhibit higher ecological integrity (Malek and Abdul Rahim, 2022), supporting SDG targets (van der Ven et al., 2018).

Despite progress, several challenges hinder broader certification adoption. Weak governance, limited enforcement, and insufficient demand for certified products (Damette and Delacote, 2011) continue to constrain effectiveness (Yamamoto and Matsumoto, 2022). Certification systems are also criticized for prioritizing commercial over environmental interests and for neglecting root causes of deforestation, such as insecure land tenure and weak governance failures (Fischer et al., 2020). These challenges highlight the need for robust methodologies to evaluate the effectiveness of certification programs. This study applies the Generalized Method of Moments (GMM) to analyze the dynamic impacts of FSC certification across diverse income levels and climatic zones. GMM accounts for lagged effects and endogeneity, providing a more rigorous assessment of certification outcomes and addressing key gaps in the literature.

3. Methodology

3.1. Model

This study aims to advance the scientific understanding of policy instruments for forest conservation by analyzing the reinforcing effects of forest certification and roundwood trade on sustainable forest management. To achieve this, we develop a dynamic panel data model, capturing the temporal and cross-sectional dimensions of forest cover changes across 70 countries from 2000 to 2021. We use the Generalized Method of Moments (GMM) estimation technique to address the challenges of endogeneity, unobserved heterogeneity, and dynamic relationships, ensuring robust and unbiased results. GMM is particularly suited for analyzing relationships in panel data with lagged dependent variables and endogeneity. The baseline model, which estimates the relationship between forest cover changes and key variables while accounting for temporal and spatial dynamic, is expressed as:

[2] Existing literature also suggests that the FSC has solidified its approach as the globally recognized certification system (Taylor and Lindenmayer, 2021).

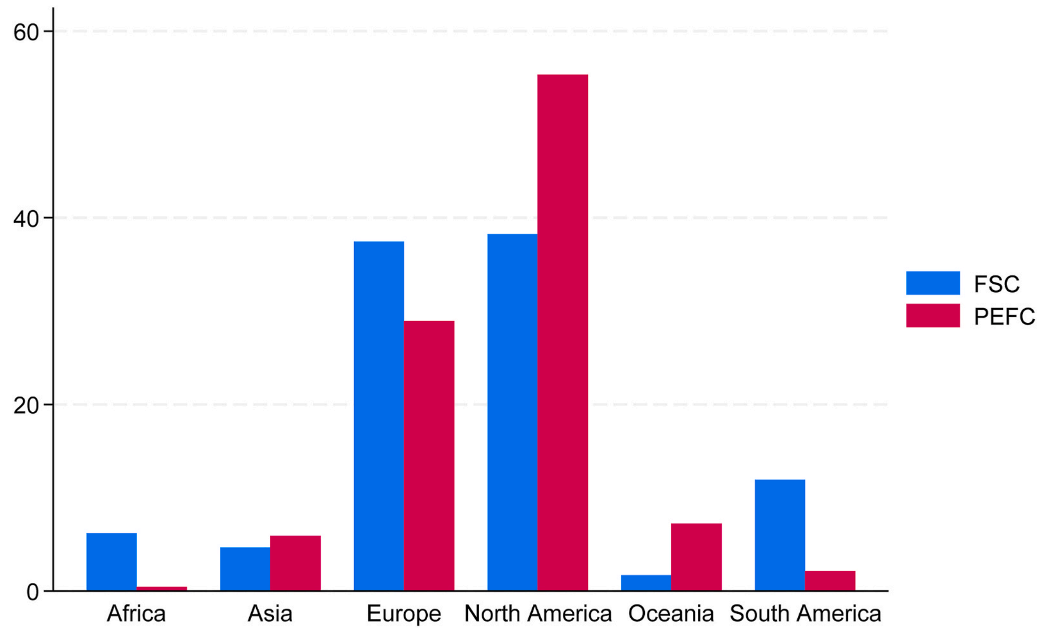

Fig. 2. Regional distribution of certified forest area: FSC vs PEFC (%).
Sources: FSC, 2024 and PEFC (2024).

Table 1
Top 10 countries in terms of certified areas.

FSC			PEFC		
Country	Region	% certification	Country	Region	% certification
Canada	North America	29.14	Canada	North America	43.49
Sweden	Europe	12.16	USA	North America	11.85
USA	North America	9.11	Australia	Oceania	7.01
Brazil	South America	5.88	Finland	Europe	6.55
Türkiye	Europe	5.22	Sweden	Europe	5.67
Ukraine	Europe	2.96	Germany	Europe	3.01
Indonesia	Asia	1.94	France	Europe	2.78
Congo	Africa	1.93	Norway	Europe	2.52
Romania	Europe	1.78	Poland	Europe	2.48
Poland	Europe	1.48	Malaysia	Asia	2.11

Sources: FSC, 2024 and PEFC (2024).

$$\text{Forest}_{it} = \beta_{10} + \beta_{11}\text{Forest}_{it-1} + \beta_{12}\text{FSC}_{it} + \beta_{13}\text{Agland}_{it} + \beta_{14}\text{Income}_{it} + \beta_{15}\text{GDP}_{it} + \beta_{16}\text{GDPsquare}_{it} + \beta_{17}\text{Population}_{it} + \beta_{18}\text{RoundwoodNX}_{it} + \theta_i + \zeta_t + \varepsilon_{it} \quad (1)$$

where the subscript i denotes country and t represents year. The inclusion of a lagged dependent variable captures the temporal autocorrelation inherent in forest dynamics. This approach acknowledges the persistence of inertia in deforestation and regrowth processes, reflecting the delayed responses of ecological systems to external drivers. For instance, past deforestation often catalyzes future losses by altering land-use patterns, advancing infrastructure development, or disrupting ecological thresholds (Metzger et al., 2009). Similarly, forest regrowth is influenced by gradual processes such as soil fertility recovery, seed dispersal, and climatic variability, which collectively introduce significant temporal delays in conservation outcomes (Ehrenberg-Azcárate and Peña-Claros, 2020). By integrating lagged variables into econometric models, researchers can better understand the nuanced interplay between deforestation drivers and restoration efforts, thereby informing more effective policy interventions (Metzger et al., 2009).

To account for potential heterogeneity in FSC impacts, we extend the model with interaction terms based on income levels and climatic zones. These factors are selected due to their significant influence on forest management outcomes and regional policy needs. The adjustments yield two additional models: The income-based interaction model (Equation (2)) and the climate-based interaction model (Equation (3)).

Using World Bank definitions, countries are categorized into low-income, lower-middle-income, upper-middle-income, and high-income groups. We created interaction terms between FSC and income levels to explore how certification effectiveness varies across socio-economic contexts, reflecting differences in institutional capacity, resource constraints, and market access (Leblois et al., 2017). This approach aligns with the Environmental Kuznets Curve (EKC) framework, which suggests that environmental performance improves as countries transition to higher income levels due to enhanced governance and resource availability (Tritsch et al., 2020). The income-based interaction model is expressed as follows:

$$\text{Forest}_{it} = \beta_{20} + \beta_{21}\text{Forest}_{it-1} + \beta_{22}\text{Agland}_{it} + \beta_{23}\text{Income}_{it} + \beta_{24}\text{GDP}_{it} + \beta_{25}\text{GDPsquare}_{it} + \beta_{26}\text{Population}_{it} + \beta_{27}\text{RoundwoodNX}_{it} + \beta_{28}\text{FSClowincome}_{it} + \beta_{29}\text{FSClowmidincome}_{it} + \beta_{210}\text{FSChighmidincome}_{it} + \beta_{211}\text{FSChighincome}_{it} + \theta_i + \zeta_t + \varepsilon_{it} \quad (2)$$

The interaction terms are: FSClowincome, the product of FSC forest certification and low-income countries; FSClowmidincome, the product of FSC forest certification and low-middle income countries; FSChighmidincome, the product of FSC forest certification and high-middle income countries; and FSChighincome, the product of FSC forest certification and high-income countries. By disaggregating FSC impacts by income level, this study offers insights for tailoring policy interventions to the specific challenges and opportunities in low-, middle, and high-income countries.

Likewise, the climate-based interaction model is expressed as follows:

$$\text{Forest}_{it} = \beta_{30} + \beta_{31}\text{Forest}_{it-1} + \beta_{32}\text{Agland}_{it} + \beta_{33}\text{Income}_{it} + \beta_{34}\text{GDP}_{it} + \beta_{35}\text{GDPsquare}_{it} + \beta_{36}\text{Population}_{it} + \beta_{37}\text{RoundwoodNX}_{it} + \beta_{38}\text{FSCtemperate}_{it} + \beta_{39}\text{FSCtropical}_{it} + \beta_{310}\text{FSCothers}_{it} + \theta_i + \zeta_t + \varepsilon_{it} \quad (3)$$

This extended model reflects climate differences using the Koppen-Geiger classification. This classification is widely recognized for its ecological relevance and ability to capture variations in climatic influences on forest dynamics (Abman and Lundberg, 2020). For the purpose of this study, we use three climate categories - temperate, tropical, and other climate type - to create the following interaction terms: FSCtemperate, FSCtropical, and FSCothers, which indicate countries that have adopted the FSC certification and are located in temperate, tropical, and other types of climate zones respectively. This classification captures critical variations in deforestation drivers, such as the dominance agricultural expansion in tropical regions versus logging and industrial activities in temperate zones (Taylor and Lindenmayer, 2021). While alternative metrics, such as regional land-use patterns or forest composition, could enhance robustness, these are often less standardized and more challenging to generalize across countries. By incorporating climate zones, this study bridges ecological diversity with practical policy considerations, providing a nuanced understanding of how FSC certification interacts with environmental conditions to influence forest cover outcomes.

3.2. Data description

The dataset includes a balanced panel of 70 countries over 22 years, sourced from FAOSTAT, the FSC certification database, and the World Bank. Variables were carefully selected to capture key drivers of forest cover changes. The key variables are:

- Forest: Net forest cover change (hectares).
- FSC: Percentage of forest area certified under FSC (%).
- Agland: Agricultural land as a percentage of total land area (%).
- Income: GDP per capita (constant 2015 US$).
- GDP: Gross Domestic Product (constant 2015 US$) and GDPsquare, the squared value of GDP
- Population: Population growth rate (%)
- RoundwoodNX: Net exports of roundwood, calculated as the difference between export and import quantities of roundwood (m^3).

Moreover, θ is a country fixed effect (to capture unobserved factors such as the demand for wood products, other forest management, and institutional quality in a country), ζ accounts for year fixed effect (to capture factors that affect change in forest cover across the country in each year), and ε is an error term assumed to be uncorrelated with the explanatory variables. $B_{10} \ldots \beta_{311}$ are coefficients to be estimated.

To ensure data accuracy and consistency, several verification and harmonization processes were conducted. First, FAOSTAT and FSC datasets were crossed-referenced with third party sources, such as national forestry reports and UNEP assessments, to identify and resolve discrepancies in forest cover reporting. Second, temporal scales were standardized to annual frequencies, ensuring consistency across all variables. Third, we used linear interpolation to impute missing values, but countries with three consecutive years of missing values were excluded from the sample. Finally, potential biases arising from national variations in forest cover definitions or measurement methods were mitigated by focusing on net forest change as the primary outcome variable and incorporating year and country fixed effects to account for systemic differences. These steps collectively enhanced the reliability and consistency of the dataset,[3] ensuring its suitability for analysis in this study.

Key variables and their sources are summarized in Table 2.

Moreover, we conducted several panel data unit root tests to check the degree of integration of the series. The tests confirm the stationarity of key variables, ensuring the validity of GMM estimations. The results of these tests are summarized in Table 3.

4. Results

We use the System Generalized Method of Moments (GMM) to estimate Equations (1)–(3). GMM is particularly effective in dynamic models because it addresses two critical issues, ensuring more reliable results: (1) endogeneity arising from the inclusion of lagged dependent variable and (2) unobserved heterogeneity across countries. Traditional panel estimators, such as fixed effects or random effects, yield biased estimates in the presence of endogenous regressors because they fail to account for the correlation between regressors and error terms (Arellano and Bond, 1991). GMM mitigates this issue by using internal instruments -lagged values of the dependent and explanatory variables-which are uncorrelated with the error term. Moreover, system GMM extends the approach by combining equations in levels and first differences, significantly improving estimator efficiency in cases where instruments are weak or when panel datasets are unbalanced (Arellano and Bover, 1995). Empirical studies validate the robustness of GMM in handling endogeneity and dynamic relationships, such as those seen in forest management contexts (Ahn and Schmidt, 1995). The dynamic nature of forest cover changes and the potential for feedback effects make GMM particularly suitable for this study.

4.1. Whole sample analyses

Table 4 summarizes the estimations of Eq. (1). We started the analysis by estimating a reduced version of Eq. (1) that includes a lagged value of the dependent variable and forest certification as the only regressors. The results are summarized under the column Model 1 in Table 4.

The coefficient of the lagged forest cover change is negative and statistically significant at the 1 % level. This negative value indicates that forest loss tends to persist over time, reflecting ecological inertia due to saturation effects or policy interventions. Specifically, saturation effects suggest that regions experiencing significant deforestation

Table 2
Data description and sources.

Variable	Description	Source
Forest	Net forest change observed (hectares)	FAOSTAT
FSC	Certified forest area as a percentage of total forest	Forest Stewardship Council (FSC)
Agland	Agricultural land as a percentage of total land area	FAOSTAT
Income	GDP per capita (constant 2015 US$)	World Bank
GDP	Gross Domestic Product (constant 2015 US$)	World Bank
GDPsquare	Squared value of GDP (constant 2015 US$)	Calculated based on GDP data
Population	Population growth rate (percentage)	World Bank
RoundwoodNX	Net exports of roundwood (quantities)	FAOSTAT

[3] The dataset used in this article is publicly available on figshare (https://doi.org/10.6084/m9.figshare.28454606).

Table 3
Panel unit root tests.

Variable	Level			First Difference		
	HT	IPS	LLC	HT	IPS	LLC
Forest	−0.002***	–	−1.1e+4***	0.0003***	−1.2e+4***	−8.5e+4**
FSC	0.84**	1.05	0.149	−0.13***	−23.19***	−23.23***
Agland	0.85	−3.94***	−2.02**	−0.12***	−21.83***	−20.63***
Income	1.01	3.54	−1.93**	0.02***	−21.98***	−21.17***
GDP	1.03	8.00	2.92	−0.13***	−22.45***	−20.97***
Population	0.779***	−1.041	3.52	0.08***	−12.86***	−7.24***
Roundwood NX	0.933	−0.972	−2.56***	0.14***	−22.81***	−21.68***

Notes: *, **, and *** indicate rejection of the unit root hypothesis at the 10 %, 5 %, and 1 % levels, respectively.
HT stands for Harris–Tzavalis, IPS for Im–Pesaran–Shin, and LLC for Levin–Lin–Chu.

Table 4
Whole sample results.

Variables	Model 1	Model 2	Model 3	Model 4
Lag Forest	−0.0022 *** (0.0001)	−0.0021*** (0.0001)	−0.0022*** (0.0001)	−0.0021*** (0.0001)
FSC	9730*** (515)	9111*** (554)		
Agland		−3186 (2991)	−3948 (3025)	−3031 (2987)
Income		17.59*** (3.81)	17.47*** (3.85)	17.84*** (3.80)
GDP		−9.71e-07*** (8.86e-08)	−9.69e-07*** (8.94e-08)	−9.83e-07 *** (8.85e-08)
GDPsquare		1.49e-20*** (2.52e-21)	1.50e-20*** (2.55e-21)	1.50e-20*** (2.02e-21)
Population		7070 (11071)	6392 (11174)	7085 (11053)
Roundwood NX		0.0011 (0.0021)	0.0008 (0.0021)	0.0012 (0.0021)
FSClowincome			8484* (4648)	
FSClowmidincome			13594*** (4174)	
FSChighmidincome			3763*** (1204)	
FSChighincome			10513*** (665)	
FSCtemperate				8789*** (568)
FSCtropical				2657 (3451)
FSCothers				12970*** (4656)
Intercept	−135608*** (6164)	−115912*** (6813)	−117830*** (6912)	−111438*** (7580)

Notes: *, **, and *** indicate statistical significance at 10 %, 5 % and 1 % respectively. Figures in parentheses are standard errors.

approach a threshold where forest clearing diminishes because of resource depletion or limited viable areas for conversion (Sant'Anna and Costa, 2021). Additionally, policy-driven interventions, such as conservation programs, mitigate further losses by enforcing stricter land-use practices and promoting sustainable forestry (Harding et al., 2021). Similarly, the coefficient of the variable FSC is positive and statistically significant at the 1 % level. This positive coefficient indicates that areas with Forest certification tend to experience an increase in forest cover, suggesting the effectiveness of forest certification in promoting forest conservation efforts. The finding echoes the conclusions of studies on sustainable forest management and certification programs.

To further ascertain the validity of these results, Eq. (1) is fully estimated after controlling for the characteristics of each country that potentially affect forest management as well as the other control covariates such as agricultural land, income, GDP, population growth, roundwood trade, and interaction terms between FSC and income levels on the one hand and FSC and climate type on the other hand. The results are shown in Table 4 under columns Model 2, Model 3, and Model 4.

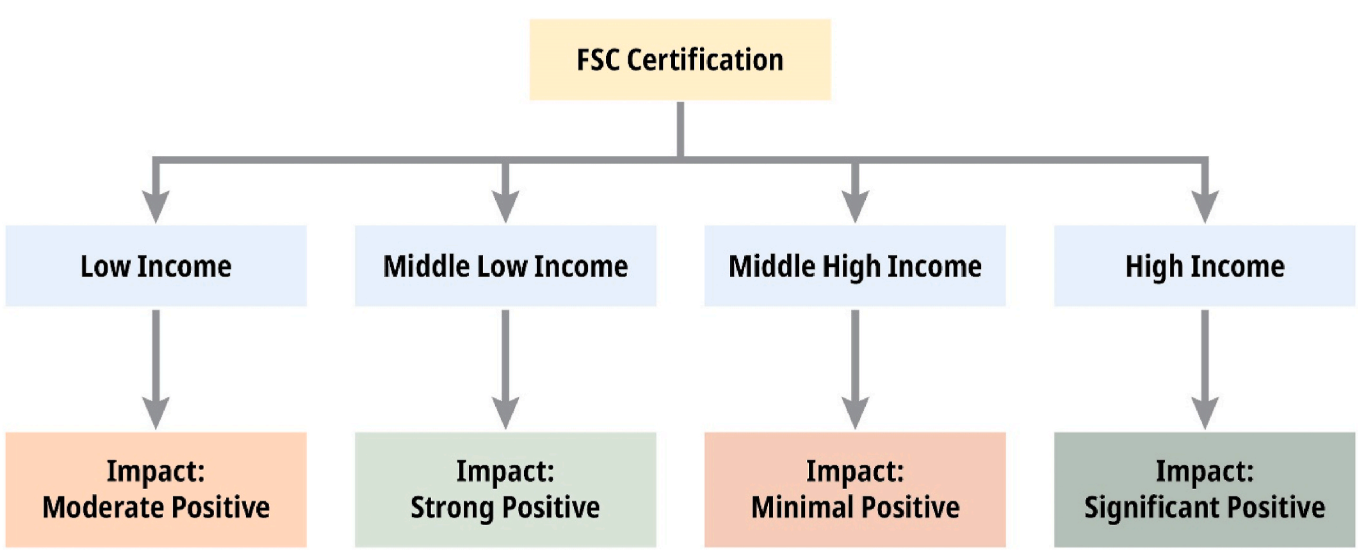

Fig. 3. Impacts of FSC certification by income levels.

The coefficients for the lagged value of the dependent variable and the FSC variable remain statistically significant and consistent across different models, indicating robustness in their impact estimates. Specifically, the lagged forest variable consistently exhibits a negative and significant coefficient, reflecting the persistent nature of forest cover dynamics over time. Similarly, the FSC variable displays positive and statistically significant coefficients even after controlling for the observed country characteristics, confirming its association with increased forest cover. However, the impact of FSC on change in forest cover appears to be more pronounced in low-middle income countries, while high-middle income countries exhibit the least impact. A visual summary of regional impacts by income levels is shown in Fig. 3.

The strong positive impact in low-middle countries may be attributed to limited pre-existing conservation mechanisms, making certification a relatively more effective tool. This finding aligns with the EKC framework, which posits that environmental degradation initially worsens with economic growth but improves as countries achieve income levels and institutional capacity. Our results echo the findings of Tritsch et al. (2020), among others. In contrast, Panlasigui et al. (2018) find FSC certification to exert minimal impact on forest cover changes in Cameroon, using data from 2000 to 2013.

Similarly, the coefficients of FSC by climate zones are positive for all three variables, but statistically significant in all but the variable FSCtropical, consistent with the literature on certification and deforestation in tropical countries (Blackman et al., 2018). Fig. 4 provides a graphical summary of the impacts of FSC certification by climate zones.

The lack of statistical significance of FSC certification in tropical climate zones contrasts with findings from much of the literature, which highlight the role of certification in mitigating tropical deforestation (Yamamoto and Matsumoto, 2022). One potential explanation is the high prevalence of informal or illegal logging in tropical regions, which may undermine the effectiveness of certification approaches. Another contributing factor could be weak institutional capacity, which hampers the enforcement and monitoring of certification standards in these areas (Taylor and Lindenmayer, 2021). These results lend support to the need for targeted policies to strengthen certification implementation in tropical zones, such as integrating certification efforts with REDD + initiatives or providing financial and technical support to local forest managers.

In all three models, agricultural land, population and roundwood NX are not statistically related to changes in forest cover at the global level. Moreover, while agricultural land has the expected negative sign, population and roundwood NX have an unexpected positive sign. One possible explanation is that our model controls for population and agricultural land, while higher population density might lead to increased demand for agriculture to satisfy intensive food needs. In the existing literature, the role of population in deforestation/forest degradation remains inconclusive (DeFries et al., 2010). For instance, Leblois et al. (2017) conclude that population is an important driver of deforestation while Damette and Delacote (2011) find its statistical significance to be dependent on the methodological framework. The relationship between population and change in forest cover is further complicated by the fact that the causality is bidirectional (Busch and Ferretti-Gallon, 2017). As for the agricultural land, the finding that its coefficient is not statistically significant contrasts with much of the existing literature, where agricultural expansion is frequently cited as a primary driver of deforestation, particularly in tropical regions. This unexpected result may be explained by broader land-use transition theories, such as Forest Transition Theory (FTT), which posits that countries undergoing economic development often experience a shift from deforestation to reforestation as agricultural practices intensify and marginal lands are abandoned (Pendrill et al., 2019). In contexts where agricultural productivity has increased through intensification, less land may be required for cultivation, potentially reducing pressure on forests. Additionally, the adoption of agroforestry practices in certain regions may blur the distinction between agricultural and forested land, mitigating the negative impacts of agricultural expansion on forest cover (Teo et al., 2025). Moreover, the lack of significance could also reflect regional variations in the relationship between agricultural land and deforestation. Policies promoting sustainable agriculture or reforestation programs could offset the deforestation typically associated with agricultural expansion. Alternatively, the interaction of agricultural land with other variables, such as FSC certification or trade, may dampen its direct effect on forest cover, suggesting the need for future analyses to incorporate interaction terms or subnational land-use data. This finding highlights the complexity of land-use dynamics and the importance of considering both regional heterogeneity and the evolving nature of agriculture-forest interactions in global deforestation analyses. In their assessment of agriculture-driven deforestation, Pendrill et al. (2022) acknowledge the existence of discrepancy that reflects the complex role of agriculture as a driver of deforestation and often lead to inconclusive results. The most startling result, however, is the estimated coefficient for roundwood net exports, which is unexpectedly positive but statistically insignificant in all three models. This result may reflect the complex interplay between trade and sustainable forestry practices. Previous studies (e.g., Busch and Ferretti-Gallon, 2017) suggest that

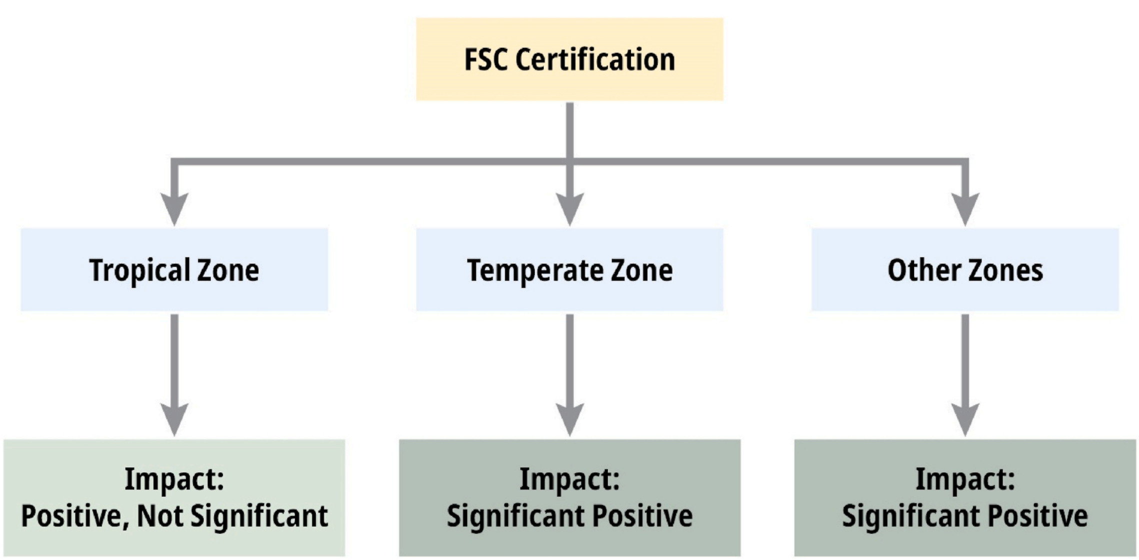

Fig. 4. Impacts of FSC certification by climate zones.

sustainable trade frameworks, like those supported by FSC certification, can decouple economic growth from deforestation. However, these findings also highlight the need for stricter enforcement of sustainable practices and global supply chain monitoring to prevent “leakage” effects, where conservation in one region leads to deforestation elsewhere (Hoang and Kanemoto, 2021). Another alternative explanation of this result, which points to potential dynamics differing from traditional assumptions about trade and deforestation, is that economic incentives tied to sustainable forestry practices, such as FSC certification, may enhance productivity and value addition, thereby supporting exports without intensifying deforestation.

4.2. Subsample analyses

Further analyses grouped countries by levels of FSC engagement (Tables 5 and 6) and compare them against the whole sample analysis (Table 4).

Consistent across all tables, the lagged dependent variable reflects the temporal autocorrelation characteristic of ecological data, capturing the inertia or momentum in forest cover changes. Its negative coefficient in high FSC countries (Table 6) aligns with ecological theories that suggest past deforestation leads to ongoing cover loss unless interventions (e.g., FSC certification) are effective.

With regards to the coefficients of FSC, our results from low FSC countries (Table 5) indicate an unexpectedly negative association with forest cover change, contradicting the presupposed benefits of certification. This could indicate ineffective implementation or insufficient enforcement of sustainable practices in these regions, a finding that deviates from typical expectations discussed in literature, such as those by Blackman et al. (2018). Conversely, in high FSC countries (Table 6), certification correlates strongly with increases in forest cover, supporting the certification’s intended role in promoting sustainable forest management and aligning with positive impacts documented by Tritsch et al. (2020) as well as Damette and Delacote (2011).

Table 5
Low FSC rates.

Variables	Model 1	Model 2	Model 3	Model 4
Lag Forest	0.0064*** (0.0009)	0.0051*** (0.0011)	0.0052*** (0.0011)	0.0058*** (0.0012)
FSC	−4374*** (281)	−3489*** (363.9)		
Agland		5261*** (1896)	5091*** (1902)	5035*** (1908)
Income		−29.14*** (2.48)	−29.07*** (2.48)	−29.35*** (2.49)
GDP		1.59e-06*** (5.60e-08)	1.59e-06*** (5.60e-08)	1.59e-06*** (5.64e-08)
GDPsquare		−5.53e-20*** (2.01e-21)	−5.53e-20*** (2.01e-21)	−5.53e-20*** (2.02e-21)
Population		17016** (6904)	17032** (6909)	16351** (6947)
RoundwoodNX		−0.0037*** (0.0013)	−0.0038*** (0.0013)	−0.0038*** (0.0014)
Certlowinc			−2400 (2925)	
Certlowmidinc			−4777** (2263)	
Certhighmidinc			−3864*** (777.6)	
Certighinc			−3277*** (431)	
Certemp				−3371*** (374)
Certrop				−8107*** (1788)
Certoc				−4925* (2951)
Intercept	58226*** (3341)	38036*** (4432)	36973*** (4429)	44213*** (4705)

Notes: *, **, and *** indicate statistical significance at 10 %, 5 % and 1 % respectively. Figures in parentheses are standard errors.

Furthermore, the impacts of agricultural land and roundwood trade vary starkly between high and low FSC countries. For instance, while agricultural expansion typically leads to deforestation, as supported by the ecological literature and seen in high FSC countries (where the coefficient of the agricultural land variable is negative), the positive relationship in low FSC countries suggests a possible prevalence of agroforestry or less intensive agricultural practices that integrate rather than displace forest landscapes. Forest transition theory offers another plausible explanation, whereby agriculture intensifies and becomes market oriented, a phase associated with a reversal in forest loss (Pendrill et al., 2019). Similarly, the coefficient estimate of roundwood trade is negative and statistically significant in low FSC countries, indicating that increases in net exports of roundwood are associated with decreases in forest cover, supporting the theory that timber extraction for export contributes to deforestation without appropriate remedial actions. However, these impacts become statistically not significant high FSC certification environments. These results are consistent with the purpose of forest certification that is to create barriers to those producers who use illegal timber, contribute to deforestation, forest degradation and disadvantage indigenous people.

Findings on GDP and income provide partial support for the EKC hypothesis. In high FSC countries, economic growth is linked with deforestation (negative GDP impact), possibly indicating that these countries are in the earlier, upward-sloping part of the EKC. The nonsignificant and mixed results on income further complicate the interpretation and suggest that other factors, such as government policies or international trade dynamics, might be influencing these relationships.

The seemingly startling positive coefficients in both low and high FSC countries suggest that population growth, contrary to leading to straightforward increases in deforestation pressure, may also drive forest cover expansion through urban and peri-urban forestry initiatives. This aligns with findings by Busch and Ferretti-Gallon (2017) but contrasts with traditional views where population growth strictly heightens deforestation risks.

The subsample analyses reveal divergent impacts of FSC certification between high- and low-engagement countries. The stronger positive association of FSC countries highlights the importance of certification adherence and enforcement mechanisms in realizing conservation outcomes. In contrast, the negative relationship in low FSC countries may point to implementation challenges or insufficient market incentives, as also observed by Panlasigui et al. (2018). These results advocate for targeted capacity-building programs in low FSC regions to enhance certification uptake and efficacy. Such programs could include technical training for forest managers on sustainable practices, financial support to offset certification costs, and the establishment of monitoring and enforcement mechanisms to ensure compliance with FSC standards. Additionally, initiatives to raise awareness among local communities and stakeholders about the benefits of FSC certification could help foster greater adoption and engagement.

5. Conclusion and policy implications

This study highlights the critical role of Forest Stewardship Council (FSC) certification in promoting sustainable forest management and mitigating deforestation across diverse economic and climatic contexts. The findings reveal the significance of FSC certification across different income levels, with varying degrees of effectiveness. Specifically, FSC certification has a moderate positive impact in low-income countries, a strong positive impact in lower-middle-income countries, a minimal positive impact in upper-middle-income countries, and a strong positive impact in high-income countries. This differential effectiveness lends support to the importance of tailoring certification programs to specific socio-economic and environmental conditions to maximize their

Table 6
High FSC rates.

Variables	Model 1	Model 2	Model 3	Model 4
Lag Forest	−0.0020*** (0.0004)	−0.0022*** (0.0005)	−0.0022*** (0.0005)	−0.0021*** (0.0005)
FSC	51673*** (3017)	47583*** (4155)		
Agland		−468369*** (140290)	−338526** (141846)	−472921*** (144100)
Income		−44.87 (49.09)	−53.06 (47.63)	−6.200 (51.21)
GDP		−4.37e-06*** (9.24e-07)	−4.04e-06*** (9.03e-07)	−4.82e-06*** (9.54e-07)
GDPsquare		1.39e-19*** (2.36e-20)	1.29e-19*** (2.30e-20)	1.51e-19*** (2.44e-20)
Population		851181** (220881)	705962*** (213679)	1028143*** (230561)
Roundwood NX		0.015 (0.0192)	0.017 (0.019)	0.016 (0.019)
Certhighmidinc			19931* (10378)	
Certighinc			53799*** (4541)	
Certemp				4 44183*** (4334)
Certrop				54959*** (12644)
Certoc				
Intercept	−1092327*** (43267)	−965259*** (65748)	−996403*** (64496)	−1042489*** (69868)

Notes: *, **, and *** indicate statistical significance at 10 %, 5 % and 1 % respectively. Figures in parentheses are standard errors.

benefits.

Given these income-based differences, a uniform policy approach is unlikely to be effective. In low-income countries, where financial and institutional capacity constraints hinder certification adoption, policies should prioritize financial incentives, capacity-building programs, and technical assistance to enhance the feasibility of sustainable forestry. Lower-middle-income countries, where FSC certification exhibits the strongest impact, would benefit from scaling up certification programs and integrating them into national forestry policies to reinforce their effectiveness. In upper-middle-income countries, aligning certification with domestic regulatory frameworks and strengthening market incentives could improve its adoption and influence. High-income countries, where FSC certification significantly enhances forest sustainability, should continue emphasizing market-driven approaches, such as consumer demand, corporate sustainability commitments, and trade agreements that favor certified products. These findings reaffirm the necessity of tailored policy strategies that consider the economic structures, governance capacities, and market conditions of different income groups.

In addition to its empirical contributions, the study draws on existing literature to provide a comparative perspective on FSC and other certification frameworks, such as the Programme for the Endorsement of Forest Certification (PEFC). While both systems contribute to sustainable forestry, prior research highlights that FSC's rigorous environmental and social standards make it particularly effective in biodiversity-rich tropical zones. In contrast, PEFC's broader alignment with national forestry policies facilitates its adoption in temperate and boreal regions, as highlighted by Wolff and Schweinle (2022). This adaptability supports widespread uptake of PEFC standards but may result in less stringent environmental outcomes compared to FSC. These insights provide valuable guidance for stakeholders seeking to enhance the effectiveness and reach of forest certification programs globally.

Building on these findings, the study offers actionable insights for integrating FSC certification into broader sustainability frameworks. Aligning FSC certification with international initiatives such as the Sustainable Development Goals (SDGs) and the Reducing Emissions from Deforestation and Forest Degradation (REDD+) initiatives can amplify its ecological and socio-economic benefits. For example, FSC certification has been successfully integrated into REDD + initiatives in the Congo Basin, where FSC-certified concessions have contributed to reduced illegal logging, improved governance, and enhanced biodiversity conservation efforts (Tritsch et al., 2020). Similarly, the forest industry is increasingly recognized for its role in achieving SDGs. The FSC certification plays a central role in supporting all 17 SDGs (Malek & Abdul Rahim, 2022). By linking certification efforts to these frameworks, policymakers can create synergistic strategies that address both local and global conservation objectives. Furthermore, FSC certification can enhance sustainable trade by ensuring that certified forest products meet rigorous standards, thereby incentivizing responsible forest management across global supply chains.

Despite its contributions, this research acknowledges certain limitations that warrant further exploration. One key challenge is the potential for self-selection bias, where countries with stronger governance and conservation policies are more likely to adopt FSC certification. This dynamic complicates the assessment of the true causal impact of certification on forest cover. Future studies could address this issue through alternative methodologies, such as propensity score matching or natural experiments to better isolate the effect of certification (Austin, 2011). Additionally, more in-depth qualitative research could shed light on the motivations behind certification adoption - whether driven by economic incentives, political pressure, or a genuine commitment to sustainability. Investigating compliance mechanisms and enforcement levels within FSC-certified regions could further clarify the conditions under which certification leads to positive ecological outcomes. Addressing these limitations would help refine our understanding of FSC certification's impact and inform more effective conservation strategies.

By positioning FSC certification within the evolving global framework of forest governance, this study demonstrates its significant role in advancing sustainable forest management. The findings emphasize the need for strengthened collaboration among policymakers, industry stakeholders, and international organizations to expand certification adoption and improve its implementation. Through targeted financial incentives, enhanced capacity-building initiatives, and integration into trade agreements, FSC certification can be leveraged more effectively to address the pressing challenges of deforestation and forest degradation. A concerted global effort to refine certification policies and align them with regional economic and governance conditions will be crucial in ensuring their long-term success. As the World seeks to balance environmental conservation with economic development, forest certification represents a powerful mechanism to align these objectives and promote ecological resilience for future generations.

CRediT authorship contribution statement

Inoussa Boubacar: Writing – review & editing, Writing – original draft, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Yaya Sissoko:** Writing – review & editing, Writing – original draft, Methodology, Data curation.

Declaration of competing interest

None.

Data availability

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