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Assessing forest ecological sustainability through wavelet decomposition and stationarity tests: a comparative analysis of major forest product producers

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Introduction: Forest ecosystems are central to environmental sustainability, yet the persistence of forest-specific ecological conditions remains insufficiently explored, particularly across different time horizons. Existing research has predominantly examined CO_2 emissions and aggregate ecological footprint indicators, while relatively limited attention has been devoted to the stochastic properties and frequency-dependent persistence of forest ecological balance (FEB). This study addresses this gap by examining the temporal persistence of FEB in nine major forest product-producing countries—Austria, Brazil, Canada, China, Finland, France, Germany, Sweden, and the United States—over the period 1990–2021.

Methods: The study combines wavelet decomposition with conventional and Fourier-based stationarity tests to investigate the persistence and dynamics of forest ecological balance across multiple time horizons. Specifically, the KPSS and Fourier KPSS tests are employed to assess whether FEB follows stationary or non-stationary processes, while frequency-domain decomposition is used to distinguish short-, medium-, and long-run dynamics. This framework enables the analysis to identify whether environmental and policy-related shocks generate temporary or persistent effects on forest sustainability.

Results: The empirical findings reveal substantial cross-country and frequency-dependent heterogeneity in the stochastic behavior of FEB. For the original series, the Fourier KPSS test identifies stationary FEB processes in China, Germany, and the United States, whereas Austria, Brazil, Canada, Finland, France, and Sweden exhibit non-stationary dynamics, indicating that shocks may have more persistent effects in these countries. The frequency-domain results further demonstrate that FEB persistence varies considerably across time horizons. Most countries exhibit non-stationary behavior in the short run, whereas broader evidence of stationarity emerges in the medium run. Long-run dynamics remain heterogeneous, with countries differing substantially in their responses to persistent environmental, economic, and policy-related disturbances.

Discussion and Conclusion: The findings indicate that forest ecological sustainability cannot be adequately characterized by a single time-invariant persistence process. The frequency-dependent nature of FEB suggests that the effects of forest-management interventions and external shocks may differ substantially

across temporal horizons and national contexts. Accordingly, uniform forest-policy frameworks may not generate comparable outcomes across major forest-producing economies. The study contributes to the literature by providing, to the best of our knowledge, the first frequency-domain assessment of forest ecological balance persistence among major forest product-producing countries and by integrating wavelet decomposition with Fourier-based stationarity testing. Rather than establishing causal relationships, the results provide evidence on the temporal persistence and reversibility of forest ecological dynamics, offering an empirical basis for developing country-specific and time-horizon-specific forest management strategies.

KEYWORDS

economic growth, energy economics, forest ecological sustainability, forest management, policy impact analysis, wavelet decomposition

Introduction

The 15th Sustainable Development Goal of the United Nations 2030 Sustainable Development Agenda, titled "Life on Land," aims to protect, restore, and sustainably manage terrestrial ecosystems. Forests provide essential ecosystem services such as biodiversity conservation, climate regulation, carbon sequestration, water filtration, and soil stabilization. Therefore, forest conservation is important not only for SDG 15 but also for other sustainable development goals such as Zero Hunger, Clean Water and Sanitation, and Climate Action.

Forests also support the livelihoods of billions of people and play a significant role in the economic and social structure of developing countries in particular. Approximately 1.6 billion people's livelihoods are directly or indirectly dependent on forests (Food and Agriculture Organization of the United Nations, 2016). Forest resources can account for approximately 22% of household income in tropical developing countries (Swamy et al., 2018). In addition, forests contribute to energy, health, food security, and production processes by providing firewood, medicinal plants, wild foods, and various raw materials. Therefore, a sustainable balance must be established between the economic use of forest resources and the preservation of their ecological integrity.

The development of effective forestry policies depends on understanding the behavior of forest-related environmental indicators in response to shocks. A stationary environmental indicator suggests that the effects of shocks disappear over time and the series returns to its long-term equilibrium. In contrast, in a non-stationary series containing a unit root, the effects of shocks can be persistent. This distinction is important for assessing whether policy interventions will produce temporary or long-term results (Dogan, 2016; Lee and Chang, 2008; Yilanci et al., 2019). Furthermore, convergence between countries indicates that differences in environmental indicators may decrease over time, while the absence of convergence highlights the need for country-specific policies (Borowiec and Papież, 2024).

In assessing the sustainability of forest ecosystems, it is necessary to consider not only the human pressure on forests but also the ecosystem's capacity to withstand this pressure and regenerate itself. While the forest footprint indicates the demand on forest areas from a country's annual forest product consumption, forest biocapacity expresses the capacity of existing forest resources to meet this demand (O'Brien and Bringezu, 2018; Ulucak and Lin, 2017; Yilanci, 2023). Forest ecological balance, calculated as the difference between forest biocapacity and forest footprint, evaluates both the supply and demand aspects of the forest ecosystem. A positive ecological balance indicates an ecological surplus and a more sustainable structure, while a negative value indicates an ecological deficit (Mancini et al., 2017; Pata, 2021; Pata and Yilanci, 2021; Yilanci and Pata, 2020).

Although there is a vast literature examining the stochastic properties of environmental indicators, a significant portion of previous studies has focused on carbon dioxide emissions and total ecological footprint. Studies examining the persistence of forest product footprint and forest ecological balance in the face of shocks across different time scales are limited. Furthermore, some existing research does not adequately consider structural changes, differences between short- and long-term trends, or heterogeneity between countries. This deficiency makes it difficult to assess the time frame in which forest policies can be effective and the persistence of policy shocks.

Accordingly, the fundamental question of this research is: Do forest footprint and forest ecological balance exhibit a stationary structure in the face of policy and environmental shocks in the selected major forest product producing countries, and does this structure change according to different time scales? The aim of the research is to reveal the temporary or permanent effects of shocks by examining the stochastic properties of these indicators in terms of both the original series and short, medium, and long-term components.

Research objectives

This study contributes to the existing literature by examining the stationarity characteristics of forest footprint and forest ecological balance in nine major forest product producing countries on a country-by-country basis and at different time scales. The use of Fourier-based tests together with the wavelet decomposition approach allows for the consideration of soft structural changes in the series and the separate evaluation of short, medium, and long-term dynamics. Thus, the study aims to determine whether the effects of shocks are temporary or permanent and to provide an empirical basis for revealing the differing policy requirements among countries.

In this context, the hypotheses of the research are formulated as follows:

> *H1*: The stationarity characteristics of forest footprint and forest ecological balance indicators in major forest product producing countries change according to different time scales.
>
> *H2*: In non-stationary forest sustainability indicators, the effects of policy, management, and environmental shocks are persistent.
>
> *H3*: In countries where forest sustainability indicators are stationary, the effects of shocks are temporary, and forest ecosystems tend to return to long-term equilibrium levels.

Testing these hypotheses will contribute to the development of differentiated policy recommendations based on the dynamics of forest ecosystems and the persistence characteristics of shocks in different countries, instead of uniform environmental policies.

For this purpose, forest footprint and forest ecological balance data from nine countries prominent in timber production are used. The stationarity properties of the series are examined using the traditional KPSS test and the Fourier KPSS test, which flexibly takes into account an unknown number and type of structural changes. Then, using the discrete wavelet transform, the series are decomposed into short, medium, and long-term components, and whether the stationarity properties change over time scales is evaluated. Due to the differences in governance structures and environmental conditions of the countries, the analyses are carried out on a country-by-country basis, and restrictive homogeneity assumptions are avoided.

The following section includes a literature review. After the literature discussion, the research gap is identified. Then, the contributions of the study are summarized and the research hypotheses are presented. Finally, the empirical methodology, results, discussion, and conclusions are presented, thus concluding the study.

Literature review

Limiting environmental degradation and promoting sustainable development requires both national policies and international cooperation. In this context, examining the convergence and persistence characteristics of environmental indicators contributes to evaluating whether policy interventions are effective and whether common policies can be implemented among countries (Bilgili and Ulucak, 2018; Hassoun, 2025). A return of an environmental indicator to its mean after a shock indicates that policy effects are temporary; the presence of a unit root suggests that the shocks may have permanent consequences.

Early studies on the stochastic properties of environmental indicators focused primarily on CO_2 emissions. While Strazicich and List (2003) obtained evidence of stochastic and conditional convergence in industrialized countries, Aldy (2006) identified divergence in a global sample and convergence in OECD countries. Similarly, Solarin (2014) presented findings supporting beta convergence in some African countries, and Ozcan and Gultekin (2016) presented findings supporting the stationarity of CO_2 emissions in various OECD countries. These results show that the findings of convergence and persistence can vary depending on the group of countries studied and the econometric method used.

The fact that CO_2 emissions reflect only a certain dimension of environmental pressure has increased interest in more comprehensive indicators. Solarin and Bello (2018), examining the ecological footprint of 96 countries, determined that shocks persisted in a large part of the sample. Studies investigating country and club convergence in ecological footprints have shown different clusters of convergence and divergence in Latin American and African countries (Tillaguango et al., 2021; Belloc and Molina, 2023).

Studies examining the subcomponents of the ecological footprint and ecological balance also reveal that the results vary depending on the indicator, income group and method. Solarin (2020) determined that the forest products footprint in 89 countries largely exhibits a non-mean-reverting structure. Studies examining built land and fishing area footprints have also shown that the persistence of shocks is heterogeneous across countries and income groups (Solarin et al., 2021a,b). Pata and Yilanci (2021) revealed that the stochastic properties of ecological balance differ between G10 and N11 countries with traditional and quantile-based unit root tests. Çelik et al. (2023) by Bahmani-Oskooee et al. (2014) approach supports ecological footprint convergence in ECCAS and ECOWAS countries, Adalı et al. (2024) reached similar results for the ecological balance of African countries. Adali et al. (2025) determined that the grazing land footprints of leading dairy and meat producers showed country-specific responses to shocks.

Recent research has begun to consider that the stochastic properties of environmental indicators can change across different time scales. Yilanci et al. (2023a,b), by examining the ecological footprint of the EU-15 countries using wavelet decomposition and Fourier unit root tests, showed that the persistence of shocks can differ in the short, medium, and long term. Ursavaş and Yilanci (2023), focusing on the Southern Common Market countries, also concluded that convergence trends vary according to time scale. Similarly, Yilanci and Abbas (2023) determined that convergence results in BASIC countries differ between the short term and the medium and long term. These findings indicate that analyses based solely on original series may overlook temporal differences.

Another branch of the literature on forests focuses on the economic determinants of forest product footprint and deforestation. Yilanci (2023) showed that economic growth and energy consumption are determinants of forest-based environmental quality in Brazil and China. Studies on Sub-Saharan Africa and Nigeria have revealed that economic growth, agricultural production, trade openness, energy consumption, urbanization, and population are among the main factors affecting deforestation (Ogundari et al., 2017; Maji et al., 2017; Nathaniel and Bekun, 2019). Farooq and Dar (2022), on the other hand, obtained findings supporting the Environmental Kuznets Curve hypothesis in terms of forest product footprint in India.

A review of the existing literature reveals three key gaps. First, while the majority of studies focus on CO_2 emissions or the total ecological footprint, the relationship between forest product footprint and forest ecological balance has been examined to a limited extent. Second, research that addresses both the consumption pressures and the bioregeneration capacity of forest ecosystems is insufficient. Third, frequency-based evidence regarding whether the responses of forest-related indicators to shocks vary across short, medium, and long-term

TABLE 1 Descriptive analysis.

Countries	AUSTRIA	BRAZIL	CANADA	CHINA	FINDLAND	FRANCE	GERMANY	SWEDEN	USA
Mean	1.485709	1.58E-14	9.926788	0.074634	7.994061	0.380198	0.162063	5.351281	0.833861
Median	1.553761	−0.006019	9.623059	0.051977	8.079386	0.408404	0.155054	5.489644	0.688498
Maximum	1.755284	5.377611	14.86428	0.246358	9.328109	0.486023	0.337953	6.617904	1.681057
Minimum	0.980225	−3.807312	6.926820	−0.019430	5.644119	0.144423	−0.272653	3.412145	0.411384
Std. Dev.	0.206171	1.257695	2.128837	0.065970	0.905769	0.098359	0.085556	0.689167	0.348214
Skewness	−0.975826	1.499561	0.592352	1.146745	−1.097957	−0.892798	−1.762001	−0.533444	0.875564
Kurtosis	3.059946	11.58355	2.460095	3.493905	3.803289	2.510290	12.41246	2.708888	2.553738
Jarque-Bera	9.849059	213.5695	4.378811	14.21877	14.12389	8.856105	260.9500	3.159408	8.436132
Probability	0.007266	0.000000	0.111983	0.000817	0.000857	0.011938	0.000000	0.206036	0.014727
Sum	92.11393	9.82E-13	615.4608	4.627321	495.6318	23.57225	10.04792	331.7794	51.69938
Sum Sq. Dev.	2.592892	96.48964	276.4488	0.265471	50.04548	0.590147	0.446508	28.97200	7.396413
Observations	62	62	62	62	62	62	62	62	62

periods is quite limited. These shortcomings necessitate a country-specific and time-scale assessment of policies concerning forest ecosystems.

Research gap

The current literature presents significant findings regarding the stationarity and convergence properties of environmental indicators such as CO_2 emissions and ecological footprint. However, the majority of studies focus on specific environmental indicators and country groups; indicators reflecting both the supply and demand aspects of forest ecosystems are examined more limitedly. In particular, empirical evidence regarding the stochastic properties of forest ecological balance, showing the relationship between forest product footprint and forest biocapacity, is insufficient.

Another limitation in the literature is that the stationarity properties of environmental indicators are mostly evaluated on a single time scale. This approach may overlook the fact that indicators can exhibit different behaviors in the short, medium, and long term, and that the effects of policy or environmental shocks can vary across time scales. Furthermore, aggregated results based on country groups may not adequately reflect the differences in forest resources, production structures, policy implementations, and resilience to shocks among countries (see Table 1).

Accordingly, the main research question of this study is as follows:

Do forest footprint and forest ecological balance exhibit a stationary structure in the face of policy and environmental shocks in selected major forest product producing countries, and does this structure change according to different time scales?

Data and methodology

The study focuses on the Major Forest Product Producers: Austria, Brazil, Canada, China, Finland, France, Germany, Sweden, and the USA, which are among the top ten within the context of data availability. Employing stationary and wavelet decomposition analysis, the time interval study spans a time interval from 1961 to 2022. The study employs the forest ecological balance, and its objectives address the persistent shocks of policies on the forest EB at varied frequencies for the top nine forest product producers. The forest EB is a comprehensive indicator reflecting the supply and demand side of the forests, and hence, the study reveals evidence based on forest sustainability. The forest product footprint per capita and the forest biocapacity per capita are used variables for achieving forest ecological balance, calculated as the forest biocapacity minus the forest products footprint. The variables considered are obtained from the Global Footprint Network's (2024) data stream. The availability of the series for each country determines the time interval of the series. The dataset was screened for completeness and consistency prior to estimation. Because the selected countries provided continuous observations throughout the sample period, no interpolation, extrapolation, or missing-value imputation was required as shown Table 2. The related series are shown in the Appendix. According to Appendix Figure 1, the maximum value of the forest EB is attributed to Canada, with Finland and Sweden following closely behind. Canada, Finland, and Sweden also have the largest mean values of the forest ecological balance, and Austria also possesses positive values of the forest ecological balance. These four countries contain a forest EB surplus, and the

TABLE 2 Analysis and characteristics of the dataset.

Item	Description
Data source	Global Footprint Network (GFN)
Sample period	1961–2022
Countries	Austria, Brazil, Canada, China, Finland, France, Germany, Sweden, USA
Total observations	62 annual observations per country
Missing observations	None
Missing-data treatment	Not required
Data consistency check	Completed before estimation
Wavelet filter	Daubechies Least Asymmetric (LA8)
Boundary condition	Reflection boundary
Software	Eviews-12

current production pattern of forest products does not seem to threaten forest sustainability. However, Brazil has encountered serious ecological deficits in its forests as a result of the Appendix Figure 1.

The study will begin by introducing Wavelet Decomposition, a powerful tool for analyzing time series data. This approach, with its practical applications in understanding complex economic and environmental indicators, provides a more detailed understanding of the data's underlying patterns. Moreover, the wavelet decomposition of the forest ecological balance, consisting of short-run, medium-un, and long-run components for each country, is also presented in Appendix Figure 2. Appendix Figure 1 presents the result of the descriptive analysis of the forest EB for major forest products countries. The primary aim of this study is to examine the stationarity and continuity characteristics of forest ecological balance at different frequencies, rather than estimating causal relationships. For this purpose, the traditional KPSS test is used in combination with the FKPSS test, which considers structural changes via Fourier terms. Thus, the stationarity of the series is evaluated under both linear trends and possible structural breaks.

The MODWT method was applied to determine the dynamics at different time scales; short, medium, and long-term components were separated. The LA8 wavelet filter, which preserves sample size and reduces information loss, and the reflection method, which limits boundary effects, were used in the separation. The combined evaluation of KPSS and FKPSS results at different frequencies shows that the findings are based on the temporal characteristics of forest ecological balance, not on model selection. Future studies could test the robustness of the results with alternative wavelet filters, different levels of separation, and tests considering multiple structural breaks. Both the KPSS and FKPSS tests assume covariance-stationary residuals under the null hypothesis; therefore, automatic lag-length selection based on the Newey–West bandwidth and the Bartlett kernel was used to address residual serial correlation and heteroskedasticity. By employing this dualmethod strategy, the study aims to thoroughly analyze the stationarity characteristics of the data under investigation. Eviews-12 software program is performed to apply the KPSS, FKPSS and Wavelet decompostion of the series.

Wavelet decomposition

The success and intended impact of policies are largely determined by the evidence gathered on the stochastic properties of the examined series. Recently, there has been a growing interest in the literature in exploring the stochastic patterns of series across different frequencies, though this area remains underdeveloped, with few studies focusing on ecological economic issues. As anticipated, the effectiveness of scales. Identifying and distinguishing policies at various time scales is crucial for mitigating environmental degradation and enhancing biocapacity. Policymakers can reduce the risk of policy failure by considering the stochastic properties of the series at different time scales. For this purpose, the series have been decomposed into short, medium, and long-term components. The wavelet-based method is based on the studies of Gençay et al. (2001), Andersson (2016), and Ha et al. (2018). In practice, the Maximal Overlap Discrete Wavelet Transform (MODWT) was preferred over the classical DWT because it is phase-independent and provides greater flexibility regarding data length. Furthermore, MODWT allows for transformation without losing outlying observations, making it more suitable for short samples. Furthermore, another transformation technique available in the literature, the Continuous Wavelet Transform (CWT), stands out for its high resolution (Daubechies, 1992; Percival and Walden, 2000). However, this method can reduce the interpretability of the results and is limited in its direct integration with the empirical analyses within the scope of this study. Therefore, for the reasons mentioned, MODWT was preferred. Within this framework, the forest EB is decomposed into different frequencies using the equation provided below:

$$EB(t) = \sum_k s_{\{j,k\}}\phi_{\{j,k\}}(t) + \sum_k d_{\{j,k\}}\psi_{\{j,k\}}(t) + \sum_k d_{\{j-1,k\}}\psi_{\{j-1,k\}}(t) + \cdots + \sum_k d_{\{1,k\}}\psi_{\{1,k\}}(t) \quad (1)$$

In Equation 1, $\phi_{\{j,k\}}$ and $\psi_{\{j,k\}}$ represent the scaling and wavelet functions, respectively. While the former captures long-run behavior, the latter captures short run behavior. The smoothing and detail coefficients, represented by $s_{\{j,k\}}$ and $d_{\{j,k\}}$, respectively, provide information about the trend and short-term components (Yilanci and Abbas, 2023; Yilanci et al., 2023a,b, 2024).

The wavelet transform method allows for the extraction of both local spectral and temporal information from a series. There are two main types of wavelet approximations: CWT and MODWT (Oliveira et al., 2019). Due to the CWT approach's issues with information redundancy and computational inefficiency, the MODWT approach is preferred for decomposing the series and examining its behavior at different frequencies (Yilanci and Abbas, 2023).

In this study, we opt for the MODWT because the traditional discrete wavelet transform (DWT) can limit the use of statistical analysis when the number of wavelet and scaling coefficients is reduced. The MODWT method allows for the presentation of wavelet ($w_{j,t}$) and scaling ($v_{j,t}$) coefficients as shown in Equations 2, 3: In this study, we use the MODWT because DWT restricts the use of statistical analysis when the number of wavelets and scaling coefficients are reduced. We can present the wavelet ($w_{j,t}$) and scaling ($v_{j,t}$) coefficients of MODWT as in Equations 2, 3:

$$w_{j,t} = \sum_{l=0}^{L-1} \frac{\psi_{j,l}}{2^{\frac{j}{2}}} EB_{t-l} \bmod N \quad (2)$$

$$v_{j,t} = \sum_{l=0}^{L-1} \frac{\phi_{j,l}}{2^{\frac{j}{2}}} EB_{t-l} \bmod N \quad (3)$$

The Daubechies Least Asymmetric, i.e., wavelet filter with length of eight wavelets, proposed by Gençay et al. (2001) is implemented and Equation 4 is used to detect the largest scale:

$$J = \log_2(T) \quad (4)$$

In this study, T represents the number of observations. We define the maximum scale as five, and we break down the original series into three components: short-term (spanning 2 to 8 years), medium-term (8 to 32 years), and long-term (over 32 years) (Ursavaş and Yilanci, 2023; Yilanci and Abbas, 2023; Yilanci et al., 2023a,b, 2024).

Consequently, both FKPSS and KPSS unit root tests are applied to the original and decomposed series. This approach helps to uncover

the impact of policy shocks at various frequencies and assess the stochastic behavior of the forest EB across different time scales.

KPSS and FKPSS stationarity tests

In this study, stationarity resulting from the applied transformations is examined using the KPSS and FKPSS stationarity tests. In these tests, the null hypothesis assumes stationarity. The KPSS unit root test was introduced by Kwiatkowski et al. (1992), who decompose the series into the sum of a deterministic trend, a random walk, and a stationary error. In the KPSS unit root test, the lag is determined automatically by the Newey-West method, and the Bartlett Kernel is used as the spectral estimation method. However, the error terms are independent and identically distributed random variables, which means they have a mean of zero and are normally distributed. The KPSS unit root test provides more consistent and resilient results in the case of the high moving average. On the other hand, the KPSS unit root test ignores the structural breaks, and the result of the KPSS unit root tests biasly reject the null hypothesis in the case of the structural breaks; therefore, the FKPSS unit root tests are also performed because the FKPSS unit root tests allow for considering smooth, unknown, and multiple structural breaks (Koçak and Özbek, 2020; Naimoğlu and Özbek, 2022). The FKPSS test is an extension of the KPSS test, originally proposed by Kwiatkowski et al. (1992), to include Fourier functions. Developed by Becker et al. (2006), the FKPSS test accounts for both sudden and gradual shocks. Fourier functions are effective in capturing changes within the series.

The model in question is as follows:

$$y_t = X_t'\beta + Z_t' + r_t + \varepsilon_t \tag{5}$$

$$r_t = r_{t-1} + u_t \tag{6}$$

In Equations 5, 6, the error term is expressed by ε_t. ε_t is a stationary process. u_t is a constant variance iid. Process. The Z_t term in (5) is shown in Equation 7

$$Z_t = \left[\sin\left(\frac{2\pi kt}{T}\right), \cos\left(\frac{2\pi kt}{T}\right)\right] \tag{7}$$

The Z_t term consists of sine and cosine functions. In Equation 7, t indicates the trend, T indicates the time dimension, and k indicates the frequency value. The appropriate preference of frequency (k) to minimizethe sum of squared residuals is imperative when utilizing OLS estimation for this equation, Becker et al. (2006) consider Becker et al. (2006) consider Equations 8, 9 to test stationarity against the unit root alternative hypothesis:

$$y_t = a_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + e_t \tag{8}$$

$$y_t = a_0 + \beta_t + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_1 \cos\left(\frac{2\pi kt}{T}\right) + e_t \tag{9}$$

Equations 8, 9 indicate the fixed and fixed&trend models, respectively. The relevant models are estimated by the Least Squares method and the residuals are obtained. The standard KPSS test is applied to the obtained residuals. Here, regression results where the residual sum of squares is minimum are taken into account. Test statistics are obtained with the model given in Equation 10. Test statistics of the model with constant $\tau_u(k)$ and trend $\tau_t(k)$ are given in Equation 10.

$$\tau_\mu(k) \text{ or } \tau_t(k) = \frac{1}{T^2}\frac{\sum_{t=1}^{T}\breve{S}_t(k)^2}{\breve{\sigma}^2} \tag{10}$$

In Equation 10, it is expressed as $\breve{S}_t(k) = \sum_{t=1}^{T}\breve{e}_j$. If the obtained test statistic is smaller than the critical value calculated by Becker et al. (2006), the null hypothesis cannot be rejected. In this case, it is concluded that the series does not contain a unit root process. In other words, the existence of stationarity is reached. If the null hypothesis cannot be rejected, the significance of the trigonometric functions must be tested. Equation 11 is used to test the significance of the trigonometric functions:

$$F_i(k) = \frac{KKT_0 - KKT_1}{\frac{KKT_1}{T-q}} \tag{11}$$

In the F test described in Equation 11, SSR_1 represents the residual sum of squares from Equations 8, 9, while SSR_0 represents the residual sum of squares from the model that excludes trigonometric functions. In Equation 11, q denotes the number of independent variables. To assess the significance of the F test, the critical values calculated by Becker et al. (2006) are used. If the F test statistic is smaller than the corresponding critical values, the null hypothesis cannot be rejected, indicating that the trigonometric functions in Equations 8, 9 are not statistically significant. In this case, the standard KPSS test results should be reported. However, if the F test statistic exceeds the critical values, it indicates that the trigonometric terms in Equations 8, 9 are statistically significant, and the FKPSS results should be reported.

Results

In the econometric analysis, the original series of countries' forest ecological balance is first examined. KPSS and FKPSS unit root tests are applied to assess whether any policy-induced shocks will have a lasting impact on the series. The results of these tests on the original series are presented in Table 2. The null hypothesis for both tests suggests that the series is stationary, with a constant mean and a mean-reverting pattern. Your understanding of the significance of the trigonometric terms is crucial for interpreting the results. If the FKPSS

F-statistics are statistically significant, it indicates that structural breaks are present in the forest balance series, and policy recommendations are provided accordingly. However, the KPSS unit root test results are evaluated regardless of the significance of the trigonometric terms. According to the KPSS unit root test findings, the null hypothesis of stationarity cannot be confirmed for the series of all the countries considered, as the KPSS-LM statistics exceed the critical values at a 5% significance level. This evidence suggests that the forest EB in these countries is susceptible to environmental policies, as any policy-induced shocks will have a lasting effect on the series. Regarding the FKPSS unit root test, the significance of the trigonometric terms is assessed by comparing the series' *F*-test statistics with the critical values. The *F*-test statistics indicate that the trigonometric terms are significant for all series, and structural breaks are relevant in the data generation process (Plots of the forest EB of the considered countries and fitted nonlinearities are disclosed in the Appendix). The null hypothesis of the Fourier KPSS unit root test holds for China, Germany, and the USA, while the series for the remaining countries contains a unit root and is not stationary. Based on the FKPSS unit root test results, policies aimed at reducing forest degradation and improving forest biocapacity will have a lasting impact on the countries studied, except for China, Germany, and the USA.

The success of policies designed to mitigate environmental degradation and enhance biocapacity depends on accurately understanding the stochastic pattern of the series under investigation. The KPSS and FKPSS unit root tests provide insight into the series' stochastic properties over time. However, the behavior of the series may vary across different frequencies.

Your analysis of the series at different frequencies is also essential for determining the appropriate policy mix over different time horizons. This underscores the importance of your role in policy planning. To decompose the forest EB into various frequencies, the maximal overlap discrete wavelet transform (MODWT) approach is applied, allowing for the identification of short-term, medium-term, and long-term components. The stochastic properties of each frequency component are then examined using the KPSS and FKPSS unit root tests. The results of these tests for the different frequencies are presented in Table 3.

TABLE 3 Unit root test finding for original series.

Country	*F*-test	Optimal Frequency	FKPSS	KPSS
Austria	39.09256	1	0.060579	0.210848
Brazil	118.5495	1	0.081304	0.238870
Canada	107.2946	1	0.064415	0.208318
China	916.8998	1	0.035232	0.197749
Findland	46.05112	1	0.070053	0.221458
France	99.89828	1	0.055480	0.217627
Germany	9.867206	1	0.046054	0.2066717
Sweeden	20.64411	1	0.060708	0.247104
USA	135.4319	1	0.035613	0.236120

The critical values of the KPSS unit root test at 1, 5, and 10% significance levels are 0.216000, 0.146000, and 0.119000, respectively. The critical values of the FKPSS unit root test at 1, 5, and 10% significance levels are 0.0716, 0.0546, and 0.0471, respectively. The critical values of the *F*-test at significance levels are 6.873, 4.972, and 4.162, respectively (Becker et al., 2006).

The original series is decomposed into short-term, medium-term, and long-term components to assess the persistence of the forest EB across different frequencies. For this purpose, the discrete wavelet transform method is applied. The procedures for this method are based on the recommendations of Andersson (2016) and Ha et al. (2018), with additional guidance drawn from empirical steps in pioneering studies utilizing wavelet methods (Yilanci and Abbas, 2023; Aydin and Pata, 2020; Pata et al., 2023a,b,c; Sun et al., 2023). The findings for all decomposed components of the forest EB are presented in Table 4.

The second and third columns of Table 4 display the results of the FKPSS and KPSS unit root tests for the short-term components. Initially, the significance of the trigonometric terms is examined. Comparing the *F*-statistics with the critical values at the 5% level reveals that the trigonometric terms are not statistically significant. This outcome suggests that the FKPSS unit root tests are not applicable, so only the KPSS unit root tests are considered. The KPSS unit root test results confirm the null hypothesis for Finland and France but reject it for the remaining countries' series in the short term. This indicates that forest-related policies will have a lasting impact on all series except those of France and Finland in the short term.

The fourth and fifth columns of Table 3 present the unit root test results for the medium-term components. The Fourier function is found to be statistically significant for all series, indicating a stable forest EB over time. The results of the KPSS unit root tests validate the null hypothesis for all series in the medium term, suggesting that the forest EB of all series exhibits a constant mean and mean reverting pattern. This means that the mean and variance of the series do not change over time and fluctuate around their mean values, implying that any shocks will not have a lasting effect. Unlike the short significance is confirmed for the medium-term components, as the *F*-statistics for all series exceed the critical values at the 5% level. Therefore, the FKPSS unit root test results are considered valid for interpretation. The comparison of test statistics with critical values shows that the null hypothesis of the FKPSS unit root tests is accepted for the medium-term components of the forest EB across all countries. This suggests that medium-term components are resistant to persistent shocks from policies due to their stationarity.

For the long-term components of the forest ecological balance, the KPSS unit root test results indicate that the series for China, Finland, France, and Germany are stationary and do not contain a unit root. However, the null hypothesis is not accepted for the other countries. Since the Fourier function is statistically significant, the FKPSS unit root test is also applied to the long-term components. The FKPSS test results indicate that the forest EB of China and Finland contains a unit root, meaning these series lack a mean-reverting pattern and constant mean, making them susceptible to persistent shocks in the long run. In contrast, for the remaining countries' long-term components, the null hypothesis cannot be rejected, confirming their stationarity. As a result, any shocks from policies will have only a temporary impact on 7 out of the 9 countries series, highlighting the potential long-term effects of forest-related policies.

Discussion and conclusion

General overview

Regarding the importance and scope of the policies, employing sufficient indicators and gaining insight into their impact on

TABLE 4 Unit root test finding for short-run components.

Country	Short-run components		Medium-run components		Long-run components	
	FKPSS	KPSS	FKPSS	KPSS	FKPSS	KPSS
Austria	0.50000 [5,0.578205]	00.50000	0.033725 [5,17.53914]	0.028569	0.063124 [1,55.17470]	0.150185
Brazil	0.50000 [5,0.413228]	0.409986	0.037008 [4,9.689071]	0.030524	0.049769 [1,59.09769]	0.195158
Canada	0.500000 [5,0.262762]	0.399799	0.039249 [4,11.41200]	0.031405	0.052433 [1,46.99510]	0.182873
China	0.448706 [5,0.284806]	0.314945	0.035520 [4,9.091264]	0.030709	0.169109 [2,29.87620]	0.124818
Finland	0.094191 [5,0.305128]	0.094872	0.037531 [5,9.504157]	0.032166	0.1376700 [2,25.59950]	0.107608
sFrance	0.175056 [5,0.330696]	0.097466	0.028103 [5,6.375327]	0.030449	0.054595 [1,90.23508]	0.118563
Germany	0.265144 [4,0.056089]	0.297702	0.047974 [4,10.61337]	0.028476	0.062406 [2,30.66611]	0.058215
Sweden	0.30000 [5,0.033328]	0.302182	0.036506 [4,11.08504]	0.029149	0.066702 [1,69.91206]	0.186501
USA	0.476848 [4,0.442213]	0.288968	0.031894 [4,31.02313]	0.029533	0.045816 [1,43.15849]	0.187596

Values in brackets are related to the FKPSS unit root test donate frequency and *F*-test statistics. The critical values of the KPSS unit root test at 1, 5, and 10% significance levels are 0.216000, 0.146000 and 0.119000, respectively. The critical values of the FKPSS unit root test at 1, 5 and 10% significance levels are 0.0716, 0.0546 and 0.0471, respectively, regarding one frequency. The critical values of the FKPSS unit root test at 1, 5, and 10% significance levels are 0.2177, 0.1478 and 0.1189, respectively, regarding four frequencies. The critical values of the FKPSS unit root test at 1, 5, and 10% significance levels are 0.2177, 0.1484 and 0.1210, respectively, regarding five frequencies. The critical values of the Ftest at significance levels are 6.873, 4.972 and 4.162, respectively (Becker et al., 2006).

the forest are pivotal to ensuring forest sustainability. Within this scope, the study first endeavours to identify more comprehensive indicators; hence, forest ecological balance is employed as an indicator. The forest ecological balance comprehensively reveals the demand and supply sides of the forest environment and calculates the forest's biocapacity with respect to the footprint of forest products. The forest biocapacity represents the forest's regenerative capacity, i.e., the supply side. In contrast, the forest products footprint reflects anthropogenic demand for forest area, presenting the demand side. Within this scope, another essential point in the policies' effectiveness is considered cases, and the Major Forest Product Producers: Austria, Brazil, Canada, China, Finland, France, Germany, Sweden, and the USA are considered cases, which are among the top ten within the context of data availability. The final step in the study is to determine whether the policy will promote effective and persistent outcomes, ensuring forest biocapacity and mitigating forest degradation. Moreover, determining policies according to their time dimension is also another final objective of the study. Investigating the stochastic properties of forest ecology using balanced responses addresses the study's final objectives. This study examined the stochastic properties of forest ecological balance (FEB) in nine major forest product-producing countries by combining wavelet decomposition with KPSS and Fourier KPSS stationarity tests. Unlike previous studies that primarily focused on aggregate ecological footprint or CO_2 emissions, the analysis concentrated on a forest-specific sustainability indicator that simultaneously reflects forest biocapacity and forest product demand. The main objective was to determine whether the persistence of FEB differs across frequency domains and whether these dynamics vary among countries with distinct forest governance structures and production systems. The empirical strategy provided two complementary contributions. First, the simultaneous use of KPSS and FKPSS tests allowed the study to evaluate stationarity both under conventional conditions and in the presence of smooth structural changes. Second, MODWT decomposition made it possible to distinguish short-, medium-, and long-run persistence patterns rather than relying solely on aggregate time-series behavior. This frequency-domain perspective is important because forest policies operate over different temporal horizons and ecosystem responses are rarely uniform across time scales. In other words, the study examines the persistence of forest ecological balance across various time scales, acknowledging that policies operate on different time frames. Disaggregating environmental policies by time dimension is essential for achieving more effective results, as ecosystems have varying recovery periods. Accordingly, the study does not attempt to establish causal relationships between policy interventions and forest outcomes. Instead, it provides evidence on the temporal persistence of FEB and on the extent to which disturbances tend to dissipate or persist at different frequencies. By focusing on the world's major forest-product producers, the analysis contributes new evidence to the literature on forest sustainability, frequency-domain persistence, and time-specific forest governance.

Main findings and interpretation

The results provide a clear answer to the central research question: the persistence of forest ecological balance is not uniform across either countries or frequency domains. Evidence from the original series, short-run, medium-run, and long-run components reveals substantial heterogeneity in the temporal behavior of FEB. For the original series, the conventional KPSS test suggests non-stationarity for all countries, whereas the FKPSS test identifies stationary behavior for China, Germany, and the United States after accounting for smooth structural changes. The remaining countries continue to exhibit non-stationary dynamics. This result indicates that the statistical persistence of FEB depends critically on whether structural breaks are incorporated into the analysis. A key implication of these findings is that stationarity should not be interpreted as direct evidence of ecological resilience, policy success, or superior forest

quality. Stationarity only indicates that the statistical properties of the series tend to revert toward their historical path following disturbances. Conversely, non-stationarity suggests that shocks may have more persistent effects on the observed FEB series. Therefore, the results provide evidence on temporal persistence rather than definitive proof of ecosystem resilience. The frequency-domain results further demonstrate that persistence is horizon-specific. The short-run analysis indicates that most countries remain non-stationary, while Finland and France exhibit stationary behavior. This pattern suggests that short-term disturbances in FEB tend to dissipate more rapidly in these two countries than in the rest of the sample. Medium-run components. The medium-run findings are the most consistent across the sample. Both KPSS and FKPSS results support stationarity for all countries once structural breaks are considered. This suggests that medium-term FEB dynamics are generally characterised by mean-reverting behavior, regardless of differences in national forest governance systems. Long-run dynamics are considerably more heterogeneous. The FKPSS results indicate persistent behavior for China and Finland, while Austria, Brazil, Canada, France, Germany, Sweden, and the United States display stationary long-run components. Consequently, the long-term persistence of FEB varies substantially across countries and cannot be represented by a single global pattern. These results also provide a robustness perspective on the apparent differences between KPSS and FKPSS outcomes. The divergence does not necessarily indicate contradictory evidence. Rather, it reflects the sensitivity of conventional stationarity tests to structural changes. Because the Fourier terms are statistically significant for the original, medium-run, and long-run components, the FKPSS results provide a more conservative basis for interpretation in those cases. This approach reduces the risk of overstating persistence when the underlying series contains smooth or multiple structural breaks. Overall, the findings support Hypothesis 1, which proposed that forest sustainability indicators exhibit non-uniform stability across different time scales. The evidence also partially supports Hypothesis 2, since persistent behavior is observed for several country-frequency combinations. However, the results provide only indirect and statistical evidence regarding persistence and should not be interpreted as proof that specific policy interventions caused the observed outcomes. Finally, the analysis highlights meaningful cross-country heterogeneity. Countries with long-established forest institutions, extensive monitoring systems, or large-scale ecological restoration programs often display different persistence patterns from countries facing stronger pressures from land-use change, wildfire risk, or resource extraction. Nevertheless, these differences should be interpreted as associations with observed stochastic behavior rather than as direct causal effects of any single policy regime.

These results are believed to be driven by the long-term reforestation and ecological restoration programs implemented in China over the last 30–35 years. In Germany, the importance of institutionalization in sustainable forest management is believed to have been highlighted. Indeed, Germany has established this institutional structure for a long time. It also implements programs highly aligned with the European Union's environmental sustainability goals. In this context, Germany has placed significant emphasis on a multifunctional forest management approach to reduce environmental degradation since the 1990s. The stability achieved by the US stems from its development of pioneering policies to reduce environmental pollution, despite occasional differences in perspective. In this context, advanced forest monitoring systems, environmental policies implemented with diverse implementation examples in many regions, and the use of the ecosystem services approach contribute to this outcome. It is believed that the implementation of the Forest Inventory and Analysis program, in particular, will contribute to reducing carbon intensity and achieving sustainable development goals.

When considering outcomes across different frequencies, the conventional KPSS unit root test should be evaluated for the short-run components of the forest ecological balance, given the insignificance of the Fourier function. In contrast, the FKPSS unit root test is available for the medium- and long-run components. In the short term, forest-related policies will have a lasting impact on all series except those for France and Finland. However, medium-term components are resistant to persistent policy shocks due to their stationarity. The forest ecological balance of China, France, Germany, and Finland exhibits a unit root, indicating that these series lack a mean-reverting pattern and a constant mean, making them susceptible to persistent shocks in the long run. When evaluating evidence across four time dimensions, policymakers have been able to implement both short- and long-term policies. For example, enforcement of existing forest laws, cracking down on illegal logging and land encroachment, deploying forest rangers, drones, and satellite monitoring for surveillance, a moratorium on logging in Critical Areas, rapid reforestation initiatives, and Fire Management and Prevention. In the long run, it is recommended for countries other than China, France, Germany, and Finland to adopt policies with the following goals: restoring degraded areas, building institutional capacity, and incentivising conservation. All in all, the evidence from the study suggests that policymakers in the countries considered may enact policies with short-term goals that mitigate forest degradation, thereby promoting a persistent influence. However, the ultimate targets should contain systemic change and biocapacity enrichment as a result of the estimation over the entire time dimension. Within this scope, it is recommended for all countries' policymakers to implement the policies aimed at achieving ecological resilience, sustainable forest economy, and biocapacity enhancement, such as the integration of forests into National Development Planning, Permanent Legal Protections, green Economy Transition,climate-resilient forest Management, agroforestry, and sustainable Land Use and Forest Landscape Restoration. Moreover, some further policy recommendations for the countries are shown in Table 5.

Study limitations and future research

All in all, the study has been conducted under some limitations that can be considered for further research. Firstly, the study focuses solely on the question of the persistence of forest ecological balance at different frequencies. Further research can employ the same methodology on other

TABLE 5 Specific policy implications.

Country	Specific policy implications
Austria	Future policy should prioritize mixed-species forest restoration, climate-adaptive silviculture, and biodiversity-oriented management in response to increasing climate-related disturbances.
Brazil:	The persistence of shocks suggests that stricter enforcement against illegal logging, expansion of satellite monitoring, protection of Indigenous land rights, and restoration of degraded Amazon ecosystems remain high priorities.
Canada	Forest governance should increasingly focus on wildfire prevention, climate-adaptive planning, carbon sequestration projects, and the integration of Indigenous forest governance with scientific management practices.
China	Given the relatively stable original series after accounting for structural changes, future policy should emphasize forest quality, biodiversity, ecosystem connectivity, and natural forest restoration rather than afforestation quantity alone.
Finland	Long-run non-stationary dynamics suggest greater attention to biodiversity-oriented harvesting, protection of old-growth forests, continuous-cover forestry, and landscape-scale ecological connectivity.
France	Long-term policy should strengthen ecological restoration, climate-resilient reforestation with native species, and adaptation to drought and wildfire risks within multifunctional forest landscapes.
Germany	Rather than introducing entirely new instruments, Germany should reinforce its existing sustainable forest governance framework through mixed-species forests, digital monitoring systems, and stronger integration of carbon and biodiversity objectives.
Sweden:	Future policy should reduce intensive clear-cutting in sensitive areas, protect high-conservation-value forests, and expand climate-adaptive ecosystem-based forestry.
United States	Continued investment in prescribed burning, fuel-reduction programs, restoration of fire-adapted ecosystems, and FIA-based monitoring systems will remain important as wildfire and drought risks intensify.

forest-related indicators, such as the Forest Load Capacity Factor (Siche et al., 2010), which measures load capacity as the biocapacity divided by the ecological footprint, using time-series unit root tests. Moreover, the convergence hypothesis, which discloses that joint action will be implemented to sustain sustainability among countries as a result of the panel unit root tests, is another option for further research. In addition, the Environmental Kuznet Curve (Grossman and Krueger, 1991, 1995) and the Load capacity curve Dogan and Pata (2022) and Pata et al. (2023a,b,c), are tested to determine the degree to which economic development matters for forest sustainability. The existing literature has considered the same objectives using different environmental indicators (Dogan and Pata, 2022; Karimi et al., 2022; Mamkhezri et al., 2022; Pata et al., 2023a,b,c, 2024; Shobande and Ogbeifun, 2023; Trofimov, 2024). The forest products footprint is used to test the EKC hypothesis, while the forest-load capacity factors are used to test the LCC hypothesis. The EKC hypothesis implies that forest degradation worsens with the initial stages of economic development, while it is mitigated with advanced economic development. However, the LCC hypothesis presents a pattern relationship between forest quality and economic development (Güler et al., 2025). However, the effect of FDI on forest indicators is examined to determine whether FDI harms the forest environment, supporting the pollution haven hypothesis, or whether FDI improves the forest environment, supporting the pollution halo hypothesis. Besides, some studies in the literature focus on the determinants of forest products, such as human capital, urbanization, and clean energy (Yilanci, 2023; Yilanci et al., 2023a,b), and they are utilized for further research. However, the democracy, freedom of press, corruption and rule of law have been recieved attention in the literature (Atta and Sharifi, 2024; Uzar, 2024; Eyuboglu and Uzar, 2025) and they are used in the research on the forest sustainablity.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

İG: Software, Conceptualization, Writing – original draft, Methodology, Validation, Visualization, Data curation, Supervision, Investigation, Funding acquisition, Resources, Formal analysis, Writing – review & editing, Project administration. MN: Resources, Visualization, Project administration, Funding acquisition, Validation, Formal analysis, Writing – review & editing, Investigation, Supervision, Data curation, Writing – original draft, Methodology, Software, Conceptualization. SÖ: Project administration, Formal analysis, Methodology, Writing – original draft, Supervision, Data curation, Conceptualization, Visualization, Software, Writing – review & editing, Funding acquisition, Investigation, Validation, Resources. ZA: Validation, Resources, Visualization, Formal analysis, Project administration, Conceptualization, Data curation, Methodology, Writing – review & editing, Software, Investigation, Supervision, Writing – original draft, Funding acquisition. OŞ: Project administration, Formal analysis, Supervision, Data curation, Validation, Methodology, Visualization, Software, Investigation, Conceptualization, Funding acquisition, Writing – review & editing, Resources, Writing – original draft.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2026.1622811/full#supplementary-material

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