



Investigating the role of biomass energy consumption and forest products trade on the forest footprint in Finland: an environmental Kuznets curve analysis

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Abstract

Forests are essential in mitigating climate change by absorbing carbon dioxide and maintaining ecosystems, mainly through preserving biodiversity. For this reason, the sustainability of forests is essential for human life. This paper examines the role of biomass energy consumption, forest product trade, and economic growth on Finland's forest footprint from 1970 to 2018. By employing Fourier-based unit root and cointegration tests, we confirm the Environmental Kuznets Curve (EKC) hypothesis, demonstrating a long-term relationship in which economic growth first raises, then reduces the forest footprint. Biomass energy consumption and forest products trade show an insignificant long-term effect on the forest footprint. We found unidirectional causality from the forest footprint to biomass energy consumption and economic growth. This research fills a gap by focusing on the under-researched forest footprint within the EKC framework, particularly in Finland's context of stringent forestry policies. Our findings emphasize the need for interdisciplinary collaboration to enhance environmental policy and sustainability practices. We further contribute to the broader literature on sustainable forest management and offer actionable policy recommendations for enhancing Finland's environmental strategies.

Keywords Sustainability · Forest footprint · EKC hypothesis · Fourier · Biomass resources · Trade

Abbreviations

ADF	Augmented Dickey-Fuller
COE	Carbon dioxide emissions
EFP	Ecological footprint
EG	Economic growth
EKCH	Environmental Kuznets Curve hypothesis
EP	Environmental pollution
FADF	Fourier ADF
FDOLS	Fourier-based DOLS
FF	Forest footprint

Extended author information available on the last page of the article

NR	Natural resource
PHH	Pollution Haven Hypothesis
REN	Renewable energy
VAR	Vector Autoregressive

1 Introduction

In recent years, the academic discourse has witnessed a significant surge in research on environmental policy. In this field, scholarly investigations have primarily focused on two prominent concepts: the EKCH and the PHH. A crucial point of differentiation within the environmental literature lies in selecting specific pollution indicators. While the EFP has gained widespread usage in contemporary studies, a substantial body of literature demonstrates a distinct preference for COE as the primary environmental indicator. In response to this focus, scholars have developed diverse methodologies and techniques for quantifying both the productivity and utilization of NR. For instance, Wackernagel and Rees (1996) defined the EFP as a metric for assessing sustainability and sustainable development, and considered it a computational tool. There are different expressions if one checks the conceptual explanations of the EFP. Wackernagel and Yount (1996), Van den Bergh and Verbruggen (1999), Bartelmus (2008), Borucke et al. (2013), and Rudolph and Figge (2017) interpreted the inclusiveness and environmental effectiveness of the ecological footprint in their studies. Regarding the computation methods, the EFP comprises six distinct sub-components (Kitzes et al. 2007).

Examining the EKCH, frequently researched in environmental economics using ecological footprint indicators, provides comprehensive policy recommendations. The EKCH suggests an inverted U-shaped relationship between EP and EG. In other words, the hypothesis proposes that earlier stages of EG increase environmental pollution, and pollution decreases when income is sufficiently high. The EKCH was first proposed by Grossman and Krueger (1991), although they do not associate their curve with that of Kuznets. Many different factors determine the confirmation of the EKCH. Using various pollution indicators, methods, and samples can lead to varying findings while testing the hypothesis (Aslan et al., 2018; López-Menéndez et al., 2014; Shahbaz et al., 2013). However, these differences also impact the specific threshold within the national income range, often described as the turning point, at which, by the EKCH, a reduction in environmental pollution is anticipated to commence.

In this study, we aim to test the EKCH on the sub-components of the EFP. As stated, the ecological footprint, which consists of six different sub-components, stands out as an essential pollution indicator in forming an environmental policy specific to countries with characteristic production and consumption patterns that show the pollution level in different sectors. In this study, the FF, which is under-researched, is used, and it is aimed to test the validity of the EKCH over the forestry sector. The FF is calculated as the forest area needed for pulp, industrial wood, firewood, and timber. In this context, Finland, which has a large forestry sector, was chosen as the sample.

Forests account for more than 75% of Finland's total land area, making Finland the most forested country in Europe regarding the proportional share of forest lands. Besides, the country's forest area has consistently risen over the past 50 years. When we check the distribution of the forest area in terms of ownership, it is observed that private owners own 60%

of the existing regions, 26% are in the public sector, 9% are in companies, and the remaining 5% are in other entities. Comprehensive regulations and strategies are being developed to protect and ensure the sustainability of forestry in the country. In this context, the Forest Act (1996) stands out as the most fundamental law regulating the use of forest areas. The Forest Act promotes forest management that is economically, ecologically, and socially sustainable, with an emphasis on protecting biological diversity as a key outcome (Ministry of Agriculture and Forestry of Finland, 2022).

Also, Fig. 1 shows the course of Finland's forest footprint between 1961 and 2018. According to the impression obtained from Fig. 1, the sustainability and protection targets of the country, which have been implemented for many years, effectively reduce the FF. Moreover, Finland's National Forest Strategy 2025 draws a projection for an increase in welfare and sustainability aimed at climate sustainability and forest biodiversity. This strategy defines priorities and measures for developing forest-based businesses and activities (National Forest Strategy, 2025). From this motivation, this paper deals with the relationship between pollution in the forest environment and EG within the framework of the EKCH in Finland, which has a strict forestry policy, regulations, and future strategy. This approach aims to contribute to the literature on testing the EKCH with respect to the forest footprint and to provide original policy recommendations for the country's forest management. We also calculate the turning point to determine when the forest footprint shifts from increasing to decreasing in relation to economic growth. Our model incorporates the two related indicators: biomass energy consumption and trade of forest products. Biomass energy can mitigate the harmful impacts of climate change as a renewable energy resource. For instance, Shahbaz et al. (2016) suggest adopting biomass as the primary renewable resource to achieve sustainable development goals.

Furthermore, we also use the trade of forest products to explain its relationship with the FF. The paper differs from the studies in the literature in several points. First, we use the FF as an ecological indicator to test the EKCH. Second, we selected Finland as our sample since the country has one of the highest forest area densities in the world. Third, the paper uses new-generation econometric analyses. Last, we follow an interdisciplinary perspective while interpreting the findings with the theoretical and conceptual framework.

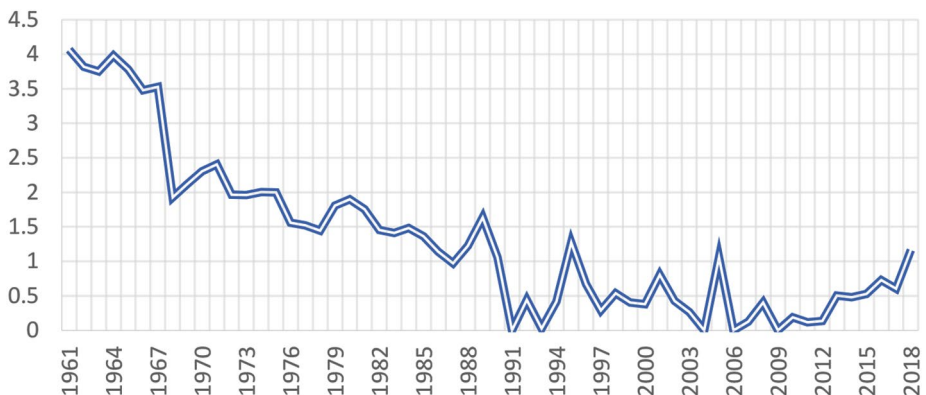


Fig. 1 Forest footprint in finland (1961–2018). Source Global footprint network

2 Literature review

A small but growing body of literature investigates the validity of the EKCH using the FF as an environmental indicator. In this paper, the literature review has been divided into two sections. We first review the papers that solely deal with the FF. After, we review the existing EKC literature, considering several environmental indicators. There are also multidisciplinary studies regarding the FF, such as Rannik et al. (2000), Leskinen et al. (2007), Oishi et al. (2008), Piao et al. (2009), Lier and Parviainen (2013), Qi et al. (2018), O'Brien and Bringezub (2018).

The existing literature does not present a consensus regarding the validity of the EKCH using the FF and deforestation. One may infer from the existing literature that deforestation is widely used as an ecological indicator rather than the FF. Nie et al. (2010) used an EFP model to measure the effect of FF on China's forest product imports between 1995 and 2007. The findings suggest that importing forest products does not seriously threaten the world's forest resources regarding the EFP. Choumert et al. (2013) investigate the relationship between deforestation and EG in 69 countries using a meta-analysis of the EKCH. The results conclude that the choice of econometric methodology was the primary reason for all variables and the EKC results for deforestation. Kayo et al. (2015) investigate the relationship between socioeconomic development and wood demand using a panel data analysis of the EKCH to examine the changes in wood demand over 33 OECD and BRICS countries and validate the EKCH. Joshi and Beck (2017) focus on the OECD and non-OECD Asian, African, and Latin American countries between 1990 and 2007. The results confirm the N-shaped EKCH for OECD and the inverted U-shaped EKCH for the African region. Also, an increase in trade openness and urbanization affects the regions differently. Andrée et al. (2019) supports the existence of consecutive inverted U-shapes in over 95 countries between 1999 and 2014. The analyses show a J-shaped link with EG within the COE per capita framework. In addition, the study concluded that structural changes are dominant in affecting EG. Usman and Makhдум (2021) examines the dynamic relationship various indicators in BRICS-T. The new-generation panel data techniques suggest that the added value in agriculture supports the country's EFP expectations. A 1% effect in agriculture increases the EFP level by 0.2201% in BRICS-T. A 1% increase in forestry and REN has been observed to create 0.7483% and 0.2248% reductions in the EFP, respectively. These indicators significantly decrease EP. Caglar et al. (2021) investigate the resistance of the EFP of the EU-5 against possible shocks (economic, political, epidemics) using annual data for the 1961–2006 period. The selected model includes the FF and is tested via modern unit roots methods. The findings suggest that all the EFP components, except the built-up land for Spain, grazing land, and FF for England, have unit roots in EU-5 countries. Cary and Bekun (2021) study the effects of deforestation on the EKCH, considering democracy and urbanization. According to the results, the EKCH regarding democracy and deforestation is rejected. Instead, democracy reduces deforestation rates. In addition, democracy and democratic expansion from neighboring countries reduce deforestation. Ajanaku and Collins (2021) test the EKCH over deforestation in Africa between 1990 and 2016. Using the panel GMM estimator, the validity of the EKCH is confirmed in Africa, where the turning point is estimated at \$3,000. Koondhar et al. (2021) analyzed the relationship between China's COE, REN consumption, forestry, and agricultural value. Based on the analysis of annual data from 1998 to 2018, it was found that COE decrease with an increase in forest

areas and REN consumption. Arto et al. (2022) propose a new calculation method to evaluate the FF of countries. Two hundred twenty-three countries and 20 forest products were used in the calculations. According to the results, 22 Mha of forest were harvested for global demand in 2014, and 42% of this amount was used to meet the foreign demand for forest products. Mamkhezri et al. (2022) investigated the spillover effect of economic freedom on cropland, forest area, and grazing land footprint in 17 Asia-Pacific countries from 2000 to 2017. The spreading effect in forest products and grazing areas was confirmed, while this effect was rejected in cultivated areas. In addition, energy use intensity significantly affects the EFP of all resource types. Last, the FF and the grazing land footprint validate the EKCH, but the cropland footprint does not. Caravaggio (2022) investigates the forest transition under the EKCH among 21 Latin American countries between 1982 and 2015. The findings reveal a U-shaped relationship between economic development and forest area, where the turning point is \$7,150. Farooq and Dar (2022) examine the validity of the EKCH for the FF in India. The findings show that India has an EKCH originating from an N-shaped FF. Rahman et al. (2024) examine the effect of the forestry sectors and renewable energy on COE in India. Using annual data from 1980 to 2021, the study concluded that the variables included in the analysis have a negative effect on the carbon footprint. Additionally, findings in the literature evaluating the carbon efficiency of forests are significant. For instance, Vais et al. (2023) found that the pine forests near Krasnoyarsk, a major industrial center in Russia, have a high carbon sequestration capacity, which is sustainable over time and could potentially increase with climate change. Many studies examine the validity of the EKCH using the EFP. Besides, several environmental indicators are also considered, such as CO₂, SO₂, NO_x, GHG, and water pollution rates. Using the ecological footprint, Destek et al. (2018), Altıntaş & Kassouri (2020), and Saqib and Benhmad (2021) report the validity of the EKCH. However, Bagliani et al. (2008), Hervieux and Darné (2015), Dogan et al. (2020), and Ansari et al. (2020) reject the hypothesis. Studies that employ CO₂ as the environmental indicator are reported by Chang (2009), Shahbaz et al. (2013), López Menéndez et al. (2014) and Kasman and Duman (2015) to validate the EKCH. Abid (2017) and Altıntaş & Kassouri (2020) reject the hypothesis. Markandya et al. (2006) use SO₂ as an environmental indicator, and Lee et al. (2010), on the other hand, use water pollution and results supporting the EKCH in both studies.

While the studies in the literature are discussed in different aspects, the main divergence is the selected method, country or country group, and the variables. This study aims to contribute to the EKCH literature using the FF as the environmental indicator. Moreover, we employ a set of control variables that might be related to the FF, such as biomass energy consumption and trade of forest products (exports+imports). Last but not least, investigating Finland's forest environment might be another contribution if one considers Finland has a large forest area in Europe. In that sense, providing empirical evidence on Finland's forest environment contributes to the related literature and provides insights to policy-makers regarding environmental policy.

3 Data and model

In this study, we investigated the impact of biomass energy consumption, EG, and trade of forest products on the forest footprint. We used data from Finland from 1970 to 2018 and considered the given period since the data regarding the environmental pollution indicator available between these years. The data description is as follows: GDP per capita (constant 2015 US\$), forest footprint (global hectares) (ff), per capita biomass energy consumption (domestic extraction, t) (bio), and trade of forest products (export/import) (trade). GDP data came from the World Bank database <https://data.worldbank.org/>. Food and agriculture statistics <https://www.fao.org/statistics/> were used to collect trade data. Biodata was obtained from the Global Material Flows Database (2023). Finally, ff data was obtained from the global footprint network database. All data series are expressed in logarithmic values. The following model was employed to test the EKCH:

$$\ln f f_t = \beta_0 + \beta_1 \ln gdp_t + \beta_2 \ln gdp_t^2 + \beta_3 \ln bio_t + \beta_4 \ln trade_t + \varepsilon_t \quad (1)$$

where β_0 , β_1 , β_2 , β_3 , and β_4 are the coefficients of constant, $\ln gdp$, $\ln gdp^2$, $\ln bio$, $\ln trade$, and ε_t is the error term. The EKCH must meet a few requirements before it can be verified. There must first be cointegration, followed by a statistically significant positive $\ln gdp$ coefficient and a negative $\ln gdp^2$ coefficient. If these criteria remain valid, the economy's growth will increase environmental pollution to a certain point, which will begin to decline. The threshold value can be determined using the following formula.

$$Y^* = e^{-\frac{\beta_1}{2\beta_2}} \quad (2)$$

4 Methodology and empirical findings

We calculated the descriptive statistics to reveal the data structure before moving on to the empirical analysis. Table 1 indicates the descriptive statistics, and the results show that forest footprint data have the most variation among other variables. The steps of the empirical analysis are shown in Figure A1 (in the Appendix). In the first stage, we investigated the integration degrees of our variables employing two different unit root tests.

Enders and Lee (2012) have developed a modification to the ADF test, introducing a model that incorporates Fourier terms to enable the detection of smooth structural breaks. They use the deterministic term, which is defined as follows, to account for structural breaks:

$$(t) = \alpha_0 + \alpha_1 \sin\left(\frac{2}{T} kt\right) + \alpha_2 \cos\left(\frac{2}{T} kt\right) \quad (3)$$

Table 1 Basic statistics

	FF	GDP	BIO	TRD
<i>Mean</i>	0.95	32481.57	5.70	9519798.96
<i>Std. Dev.</i>	0.70	9348.06	1.27	5057818.56
<i>Coefficient of Variation</i>	74.40	28.78	22.22	53.13

Table 2 Unit Root Test results

Variables	FADF				ADF			
	I(0)	p	F-Stat.	p	I(0)	p	I(1)	p
<i>lnff</i>	-3.779 (3)	1	5.209	3	-2.765	1	-8.713*	1
<i>lngdp</i>	-1.181 (3)	2	0.375	3	-2.623	1	-4.271*	0
<i>lngdp2</i>	-2.400 (3)	1	0.377	3	-2.606	1	-4.309*	0
<i>lnbio</i>	-3.597 (2)	1	1.440	3	-2.241	0	-7.165*	0
<i>lntrd</i>	-4.081 (1)	1	0.591	3	-2.120	0	-6.341*	0

Notes: * $p < 0.01$. Optimal frequency numbers are reported in parentheses

Table 3 The results of Cointegration

Tests	Values	k	F-Stat.
Fourier Shin	0.023	1	2.883
Shin	0.031	-	-
FDOLS long-run estimation results			
	Coefficient		P-value
<i>lngdp</i>	580.740*		0.005
<i>lngdp2</i>	-28.133*		0.005
<i>lntrd</i>	-1.631		0.221
<i>lnbio</i>	-1.245		0.525

Notes * $p < 0.01$. The critical values of the Fourier Shin test are 0.05 (1%), 0.038 (5%), and 0.034 (10%). Shin tests' critical values are 0.109 (1%), 0.073 (5%), and 0.056 (10%)

where t , k , and T denote the trend, the frequency of Fourier terms, and time, respectively; for the FADF test, the following model is recommended:

$$\Delta y_t = \alpha_0 + \alpha_1 t + \beta y_{t-1} + \alpha_2 \sin\left(\frac{2kt}{T}\right) + \alpha_3 \cos\left(\frac{2kt}{T}\right) + \sum_{i=1}^p \vartheta_i \Delta y_{t-i} + u_t \quad (4)$$

In the unit root test, the null hypothesis states that the series has a unit root, whereas the alternative hypothesis asserts that the series is stationary. The test results in Table 2 show that F statistics of all variables are not significant. Accordingly, we should use the ADF test results, not FADF. ADF test results show that all variables are stationary at first differences, i.e., $I(1)$.

Tsong et al. (2016) added to Fourier terms in Shin (1994) approach consider smooth structural breaks. The Fourier-Shin cointegration test was conducted using the following regression model:

$$y_t = d_t + x_t' \beta + \eta_t, \quad \eta_t = \gamma_t + v_{1t}, \quad \gamma_t = \gamma_{t-1} + u_t, \quad x_t = x_{t-1} + v_{2t} \quad (5)$$

where d_t denotes the deterministic term defined in Eq. 3, and the final model is defined as follows.

$$y_t = \sum_{i=0}^m \delta_i t^i + \alpha_k \sin(2\pi kt/T) + \beta_k \cos(2\pi kt/T) + x_t' \beta + v_{1t} \quad (6)$$

The null and alternative hypotheses are as follows: H_0 : Cointegration; H_1 : No Cointegration. The following definitions are for the test statistic used to examine these hypotheses.

$$CI_m^f = T^{-2} \hat{\omega}_1^{-2} \sum_{t=1}^T S_t^2 \quad S_t = \sum_{t=1}^T \hat{v}_{1t} \tag{7}$$

Tsong et al. (2016) use the F test to evaluate the significance of Fourier terms. If the Fourier components are not significant, it is suggested to use the cointegration test proposed by Shin (1994).

According to the cointegration test results reported in Table 3, the Fourier terms are insignificant. For this reason, we used the Shin cointegration test, and the results show a cointegration in Model 1. Furthermore, we used the FDOLS long-run estimator to estimate the long-run coefficients reported in Table 3. The results indicate that the EKCH is valid in Finland. Biomass energy consumption and forest products trade do not statistically significantly affect forest footprint. In EKCH analysis, the “turning point” refers to the level of income per capita at which the relationship between environmental degradation and EG changes direction. The EKCH suggests that as an economy grows, environmental degradation initially increases, reaches a peak, and then decreases as income continues to rise. This implies an inverted U-shaped curve when plotting environmental quality against income. We also compute the turning point as \$30373.65, where the FF is the maximum. Once the \$30373.65 GDP per capita level is reached, we expect improvements in environmental quality. This result also depicts the inverted U-shaped relationship between EP and EG in Finland. The estimated turning point in terms of GDP per capita was achieved between 2003 and 2004 in Finland. Other studies estimate the turning point of the forest environment for various samples, such as Ajanaku and Collins (2021), who estimated \$3000 in Africa, and Caravaggio (2022), who estimated \$7150 in Latin American countries.

Toda and Yamamoto (1995) (TY) developed a test for causality based on the VAR model, which involves using the maximum degree of series integration (dmax) and the appropriate length. However, the TY causality test does not consider structural breaks. To address this issue, Nazlioglu et al. (2016) incorporated the deterministic term into Eq. 3. Nazlioglu et al. (2016) improved the TY approach and proposed the following model:

$$y_t = \alpha_0 + \alpha_1 \sin\left(\frac{2kt}{T}\right) + \alpha_2 \cos\left(\frac{2kt}{T}\right) + \alpha_3 y_{t-1} + \dots + \alpha_{p+dmax} y_{t-(p+dmax)} + \epsilon_t \tag{8}$$

where *k* indicates the length of the frequency, the null hypothesis posits that no causality exists among the variables. The alternative hypothesis, however, demonstrates causality. Table 4 shows the causality results.

The result indicates a unidirectional causality from the forest footprint to EG. It implies that changes in the forest footprint significantly predict changes in economic growth. In other words, as the forest footprint varies, it notably impacts economic growth, suggesting

Table 4 The results of causality

Directions	Test Stats.	k	p	Bootstrap P-values
<i>lnff</i> – <i>lngdp</i>	6.157***	3	2	0.063
<i>lngdp</i> – <i>lnff</i>	2.625	3	2	0.277
<i>lnff</i> – <i>lntrd</i>	1.434	3	3	0.698
<i>lntrd</i> – <i>lnff</i>	2.744	3	3	0.447
<i>lnff</i> – <i>lnbio</i>	7.573***	1	3	0.081
<i>lnbio</i> – <i>lnff</i>	5.711	1	3	0.156

Note *** *p* < 0.10

that environmental factors are crucial in driving economic performance. There is also a significant unidirectional causality from the forest footprint to biomass energy consumption. This implies that changes in the forest footprint significantly predict changes in biomass energy consumption, highlighting the importance of forest resources in determining biomass energy use. Overall, the findings from Table 4 suggest that the forest footprint plays a crucial role in influencing EG and biomass energy consumption. However, the other economic and energy factors do not significantly impact the forest footprint. This asymmetry highlights the importance of ecological management in driving sustainable economic and energy practices.

Our analysis reveals several key insights into the relationship between forest footprint, EG, and bioenergy in Finland, though there are areas for improvement. The results confirmed the validity of the EKCH in Finland's forestry sector. This implies that EG initially increases the forest footprint, but further growth reduces the environmental impact after reaching a certain GDP per capita. The primary research problem addressed in this study is the dynamic relationship between economic activities and ecological sustainability, specifically in the forestry sector. The research fills a notable gap in the literature by using the FF as an environmental indicator, which is less commonly studied than deforestation. The significance of this research lies in its potential policy implications. By demonstrating the EKCH with FF in Finland, the study provides evidence for policymakers to design strategies that balance EG with ecological sustainability. The findings emphasize the importance of sustainable practices in forestry and the potential benefits of bioenergy in reducing the forest footprint.

5 Discussion

This paper approaches the environmental pollution issue using the FF in Finland. As theoretically stated, one of the most regarded explanations of the effect of EG on the environment is the EKCH, which has been frequently researched in recent years. A large body of literature uses the EFP and COE as ecological indicators while testing the EKCH. In this paper, we use the FF to test the EKCH in Finland from 1970 to 2018. Once we examine the Finnish economy, we can see that the service sector is at the forefront. Services such as the assembly and maintenance of paper machinery, forest products, and other capital goods produced in Finland are exported to a large extent. The forest industry, which uses renewable raw materials, remains the most crucial sector in Finland. In addition to paper production, other forest industry products produce new types of products. Energy consumption is high in Finland due to cold winters and intense industrial activities. In addition to imported energy sources such as oil and gas, the use of wood for energy is essential. Wood has become the most important renewable energy source. Wind and solar power also play a small but growing role.

This paper is the first attempt in the literature to analyze the validity of the FF within the scope of the EKCH through Finland. We checked the stationarities of the variables under the determined hypothesis and related literature. The FADF and ADF results show that the variables are not stationary at the level but become stationary at the $I(1)$ level when their first-order differences are considered. This poses the question of whether policy shocks to forest area footprints will contribute to reducing environmental pollution in the medium and

long term. In other words, in the case of expanding and implementing policies for environmental challenges to increase forest products and their added value, more economical and social returns from forest products can be achieved in Finland.

Following the unit root process, the Shin-Based Cointegration test was performed, and a long-term relationship exists between the FF, national income, bioenergy, and foreign trade of forest products. After the cointegration test, the Fourier-based DOLS test was performed as coefficient estimator analysis. Positive $\ln gdp$ and negative $\ln gdp2$ coefficients indicate that the EKCH is confirmed for the FF in Finland. In other words, as the EG increases in Finland, the FF primarily increases, and then the economy achieves a turning point, and the FF begins to decrease. We estimate the turning point to be \$30373.65, where the FF is maximum. Once the \$30373.65 GDP per capita level is reached, we expect improvements in environmental quality—the estimated turning point in terms of GDP per capita level achieved between 2003 and 2004 in Finland. Several papers estimate the forest environment's turning point for various samples. For instance, Ajanaku and Collins (2021) estimated \$3000 in Africa, and Caravaggio (2022) estimated \$7150 in Latin American countries. The validity of the EKCH is interpreted as EG reducing EP in the forest area in the medium and long term. When we look at the Finnish economy, we see that it has a welfare level far above the world average in terms of its per capita income. Since 75% of the country is covered with forests and an important industry in this area, the forest area footprint is essential in terms of human life and economic activities.

The last part of the analysis presents the causality test results. Accordingly, a unidirectional causality of 10% was observed from the FF to GDP and from the FF to bioenergy. The results are compatible with the theory and expectations because the FF is directly related to national income. Environmental improvements for forest lands are expected to impact Finland's national income, which generates \$50 billion in revenue from forestry products, and the total exports of forest products account for about 15% of the total. In addition, Finland, which defines forests as “green gold,” has a model country target for bio-economy in 2025. For this reason, changes and improvements in the FF will impact bioenergy due to the renewable raw material that can be converted into bio-economy products and the recycled product feature that can prevent climate change.

When the existing literature is compared with our findings, a direct comparison cannot be made due to the inadequacy of similar studies. Studies investigating the validity of the EKCH over the FF as an ecological indicator are limited. In the studies where the EKCH is tested, one may see that deforestation is mainly used as an ecological indicator. Therefore, in comparing the analysis findings with the literature, the EKCH studies carried out in forestry were taken as the basis. The results of this paper agree with those reported by Choumert et al. (2013), Kayo et al. (2015), Ajanaku and Collins (2021), Mamkhezri et al. (2022) and Caravaggio (2022). They are partially similar to those reported by Joshi and Beck (2017), Andrée et al. (2019), and Farooq and Dar (2022). However, we contradict the study of Cary and Bekun (2021). The contradiction might be reasonable due to the chosen model, method, variables, and sample. When examined through the perspective of renewable energy sources across different country groups, the literature underscores the contribution and novelty of this research. The findings of this study align with several works in the literature, such as Usman and Makhdum (2021), who analyzed non-renewable, and REN utilization in BRICS-TM countries; Rahman et al. (2024), who examined the impact of REN and forestry variables on the COE in India; Koondhar et al. (2021), who investigated

the relationship between COE, REN consumption, forestry, and agricultural value in China; and Sutherland et al. (2016), who explored the relationship between the environment, forestry, and renewable energy in Scotland using survey data. However, the study's findings do not align with those of Sikkema et al. (2021) and Mamkhezri et al. (2022).

Socioeconomic analyses and propositions carried out on the FF have yet to reach maturity. Besides, the fact that the empirical findings regarding Finland contribute to the literature and the forest industry sector is also essential. It also differs from other studies that analyze the EKCH since we use the FF as the EP.

6 Conclusion and policy implications

The mismanagement of production and consumption processes often increases environmental challenges. Addressing these challenges necessitates widespread environmental awareness and international cooperation. This study underscores the need for further environmental research and collaborative efforts to mitigate these risks.

Our findings validate the EKCH in the context of Finland's FF, suggesting that EG initially increases environmental degradation, which decreases after reaching a certain income level. Based on these insights, we propose several policy recommendations:

1. **Further Research and EKCH Validation:** Researchers should continue to test the EKCH across different countries and variables, using forest area footprint as a critical environmental indicator. Future studies could explore the impact of FF on various sectors, particularly forest product exports, to derive nuanced policy recommendations. Employing diverse methodological approaches based on the selected variables and country contexts will enrich the findings.
2. **Economic Growth Strategies:** Policymakers should focus on economic strategies that promote the production of high-value-added goods, thereby enhancing national income and welfare. Our study indicates that such growth can foster environmental awareness and reduce the forest footprint. Stable economic growth policies are essential for raising citizens' environmental consciousness and achieving sustainable development.
3. **Bioenergy and Renewable Resources:** Developing and promoting bioenergy resources is vital for addressing environmental challenges. Policies should encourage the use of alternative and REN sources, including organic wastes from the forest sector. Public support for these initiatives and sustainable forest management practices will improve forest productivity and longevity.
4. **Stakeholder Responsibilities:** Market actors and consumers within the forest products sector play crucial roles in sustainable development. Industry stakeholders should invest in the bio-economy, develop value-added forest products, and adopt environmentally friendly production technologies. Effective collaboration among stakeholders and adherence to policy decisions is imperative. Consumers should make informed choices, opting for renewable materials to drive continuous sectoral advancement.

Overall, while this study significantly contributes to understanding the EKCH in Finland's forestry sector, ongoing research is needed to refine these findings and explore additional

variables. Collaboration between policymakers, researchers, and industry stakeholders will be crucial in promoting sustainable economic growth.

Appendix

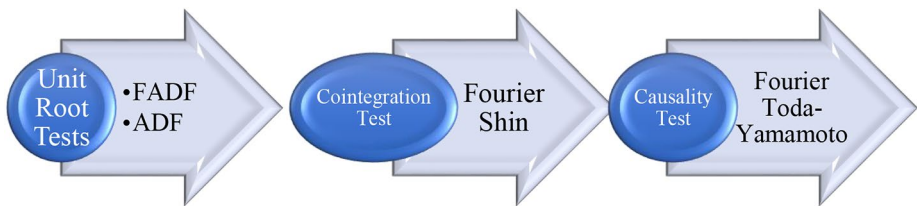


Fig. A1 The Steps of the Empirical Analysis Author contributions Mucahit Aydin: conceptualization, writing—review and editing, methodology, software, supervision, and formal analysis. Ibrahim Cutcu: conceptualization, writing—review and editing, Bilal Cayir: conceptualization, writing—review, and editing, Radulescu Magdalena: Data curation; Conceptualization; investigation; reviewing and editing.

Data availability Data are available on request from the corresponding author.

Declarations

Conflict of interest The authors declare no conflict of interests.

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