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Do environmental taxes improve environmental sustainability beyond net-zero emissions? Evidence from ecological footprint subcomponents in the EU

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Environmental degradation has manifested in various forms, including air and water pollution. Therefore, the impacts of environmental policies should be evaluated across all dimensions of environmental degradation. The European Union has targeted to stop CO_2 emissions by 2050. Accordingly, the literature has predominantly focused on the relationship between environmental taxation and CO_2 emissions. Even if the net-zero emissions target is achieved, this does not necessarily ensure the elimination of overall environmental degradation. This study investigates the impact of environmental taxation on environmental degradation in the European Union over the period 1995–2021 using the Driscoll-Kraay (1998) estimator. The study focuses on the impact of environmental tax on ecological footprint and its sub-components. The findings show that the ecological footprint and its subcomponents, except for built-up land and forest product footprints, can be mitigated by current environmental tax policies. However, in order to achieve net-zero environmental degradation, the European Union must reduce pressures arising from built-up land and forest product footprints. In addition to the Driscoll-Kraay (1998) estimator, the Feasible Generalized Least Squares (FGLS) estimator is employed as a robustness check, and the results remain broadly consistent across both methods. Moreover, Dumitrescu and Hurlin (2012) causality test states that strong and bidirectional causal relationships between environmental tax and ecological footprint components. This overall result confirms the existence of a green dividend within the double dividend hypothesis. It is suggested that renewable energy plants should be constructed in areas where built-up land and forest products footprint are not affected. For example, floating solar panels do not use land and also protect water bodies from evaporation.

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Introduction

Environmental degradation has reached alarming levels in recent decades and the world has faced an absolute ecological deficit since the 1970s. Although the European Union (EU) countries have played a leading role in environmental challenges by implementing policy frameworks, environmental problems in the EU have been escalating rapidly and have doubled on a global scale (European Environment Agency, 2025a). Copernicus Climate Change Service C3S (2025) has reported record-breaking events in 2024, such as the longest hot summer in southeastern Europe, the third warmest year in the Arctic region, and the third highest year of CO_2 emissions due to wildfires in the Arctic region. The cost of environment-related events has also been increasing. The same report indicated that the key environmental events in 2024 in the EU resulted in at least 335 lives lost, €18.2 billion in economic losses, and 455 million people affected. With an economic power of €17 trillion and as the largest exporter of manufactured goods and services, EU is promoting very ambitious environmental initiatives, such as becoming the first carbon-neutral continent by 2050 (European Commission, 2021).

During the last decade, EU has successfully decreased fossil energy consumption. However, biodiversity loss has been increasing due to general consumption patterns in the region (European Environment Agency, 2025b). EU has tightened its environmental regulations to stop environmental degradation and provide a balance between economic growth and environmental sustainability. At the same time, EU wants to change consumer behaviors while addressing ecological problems. Taxation is an important policy instrument for addressing negative externalities arising from economic activities and human behavior. This is because technological progress may, in some cases, be insufficient to prevent environmental degradation (Okoth et al., 2026). The report of the European Commission (2025a) has stated that environmental tax revenues have been decreasing since 1995, from their highest level of 2.7% of EU GDP to 2% in 2023. Although environmental quality appears to be improving at first glance, a significant biodiversity deficit persists within EU.

The existing literature has shown that environmental taxes can help to stop environmental degradation (Artan et al., 2025; Țibulcă, 2021; Wolde-Rufael and Mulat-Weldemeskel, 2023). However, the studies in the literature predominantly focused on specific environmental proxies. For example, Obobisa and Ahakwa (2024) have assessed the effect of environmental taxes on environmental quality by using CO_2 emissions. Similarly, Bozatli and Akca (2023) and Rafique et al. (2022) have focused on broader environmental quality indicators, ecological footprint (EF), to measure the impact of environmental taxes. Unlike CO_2 emissions, which capture only air pollution related to carbon output, EF provides a more comprehensive measure of environmental pressure by incorporating multiple dimensions of resource use and waste generation. EF is calculated based on the biologically productive land and water area required to sustain consumption patterns, including carbon absorption, food production, and resource extraction. Therefore, while CO_2 emissions reflect a single aspect of environmental degradation, EF captures broader ecological impacts and allows for a more multidimensional analysis. EF has six subcomponents, and each component may be influenced by different economic activities, including the carbon footprint representing pressure from fossil fuel consumption, cropland and grazing land footprints capturing agricultural impacts, and fishing grounds reflecting pressure on aquatic ecosystems. Figure 1 shows that each subcomponent of EF follows a different trend over the period 1995–2021 in the EU. While the total EF remains relatively stable during this period, the carbon footprint shows a slight downward trend, whereas the forest footprint has approximately doubled. Thus, analyzing each component separately can make the analysis pathway clearer and more precise. For example, the report of the European Environment Agency (2020) states that unsustainable farming activities cause pollution of water and soil. Although the pollution effect of farming has been measured by total EF, it mainly affects specific subcomponents of the EF, such as forest, fishing grounds, and grazing land footprints. Similarly, water pollution from plastics is measured by total EF, and the fishing grounds footprint more clearly reflects water-related pollution. Hence, identifying the sources of different pollution types and addressing them through specific methods can be more economical and environmentally friendly.

To ensure that the EU achieves its goal of becoming the first carbon-neutral continent by 2050 more rapidly, the effects of the pollution prevention policies developed need to be examined in greater detail. Thus, the purpose of the study is to examine the effects of environmental tax in the EU on EF and its subcomponents for the period of 1995–2021 using Driscoll-Kraay (1998) and FGLS estimators to reveal the impact of environmental tax on marginal pollution measurement types. These methods are particularly suitable for the EU panel data, as they account for cross-sectional dependence (CSD), heteroscedasticity, and autocorrelation arising from economic and policy interlinkages among countries, thereby providing more robust and reliable estimates compared to conventional panel estimators. In this way, the total effect of environmental degradation can be decomposed, the effectiveness of green taxes can be assessed, and policies can be adjusted based on the increase in the desirable effects. Accordingly, the study addresses the following research

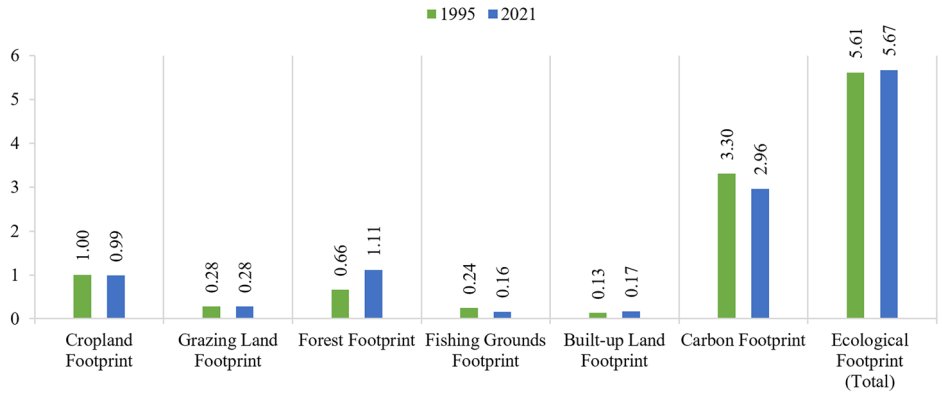


Fig. 1 Evolution of EF and its components in the European Union (Global Hectare (gha) per person).

questions. First, what is the impact of environmental tax on the overall EF in the EU? Second, does environmental tax exert heterogeneous effects across the subcomponents of the EF? For example, if the source of pollution is forest footprint and it is not affected by any existing green taxes, then increasing the current tax rates would not be an effective solution. Instead, introducing a new, specific tax targeting forest footprint would be more effective. In addition to environmental taxation, other macroeconomic factors also play a crucial role in shaping environmental outcomes. Economic growth may increase environmental pressure through scale effects, while also potentially reducing it through technological progress and structural transformation. Renewable energy consumption (REC) contributes to environmental improvement by reducing dependence on fossil fuels. In contrast, urbanization may intensify environmental degradation through increased energy demand, land-use change, and infrastructure expansion. Therefore, incorporating these variables allows for a more comprehensive understanding of the determinants of environmental degradation.

The contribution of this study is to fill the gap in the literature by addressing this deficiency. Beyond addressing this gap, the study contributes by providing a more detailed understanding of how environmental taxation affects different dimensions of environmental degradation through EF subcomponents. As noted above, previous studies consider EF in aggregate, limiting the ability to identify heterogeneous environmental responses. This limitation reduces the ability to identify heterogeneous environmental responses and may lead to misleading policy conclusions. Therefore, developing policies can affect one type of pollution while missing others. This highlights the importance of evaluating environmental policies at a disaggregated level to capture differential impacts across environmental dimensions. Overall, the study demonstrates that environmental taxation does not exert uniform effects across environmental dimensions, highlighting the need for more targeted and component-specific environmental policy design The main contributions of the study can be summarized as follows: (i) examining the impact of environmental taxation on EF, (ii) identifying heterogeneous effects of environmental taxation across EF subcomponents, and (iii) testing the validity of the double dividend hypothesis.

The study has been planned in five sections. Following the introduction section, related literature has been discussed, and a literature gap has been shown in section “Literature”. Data, methodology and findings have been explained and illustrated in section “Data, models and methodology”. Findings and their implications for the literature and policy have been discussed in section “Findings”. In section “Conclusion and policy recommendation”, the study has been concluded with conclusion and policy recommendations.

Literature

Theoretical background. Taxes represent one of the primary policy instruments for addressing market inefficiencies. Similar to their role in stabilizing economic fluctuations, environmental taxes can be designed to discourage environmentally harmful activities such as excessive energy consumption, carbon emissions, and resource exploitation. The political discussion started Pigou (1920) stated that pollution can be taxed. However, the concept of environmental taxes has gained prominence through the double dividend hypothesis. The hypothesis states that environmental taxes can be used to mitigate negative environmental externalities (Pearce, 1991). However, based on the double dividend hypothesis, policymakers have options of using environmental tax revenues to mitigate environmental degradation, which is called the green dividend, or policymakers can use environmental taxes to lessen other taxes such as income tax, which is called the blue dividend (Fullerton and Wu, 1998; Goulder, 1995; Wolde-Rufael and Mulat-Weldemeskel, 2023). Blue dividend also improves overall welfare by reducing taxes. Karydas and Zhang (2019) have mentioned adding a third dividend to the double dividend framework, suggesting that environmental taxes can also stimulate environmental technologies. However, allocating environmental tax revenues away from environmental improvement toward other objectives may reduce environmental effectiveness. Thus, environmental taxes may sometimes lead to environmental degradation or fail to produce the desired outcomes (Degirmenci and Aydin, 2023).

Building on these theoretical foundations, environmental taxes can be further understood through their transmission mechanisms affecting ecological outcomes. Environmental taxes can influence EF through several transmission channels. First, by increasing the cost of pollution-intensive production, environmental taxes incentivize firms and households to reduce fossil fuel consumption and shift toward cleaner production technologies (Amores et al., 2023). Second, environmental taxes promote energy efficiency improvements and renewable energy adoption, thereby reducing energy intensity (Nchofoung et al., 2023). Third, economic growth can play a dual role by increasing environmental pressure through scale effects and reducing environmental degradation through technological progress and structural change. REC directly reduces dependence on fossil fuels, while urbanization may increase environmental pressure through higher energy demand and land-use change, as described in the land sparing and land sharing framework (Chen et al., 2024; Degirmenci and Ünsal, 2026). In addition, increasing environmental quality helps to secure financial stability in the long run (Çakır and Ökte, 2026).

Empirical background. To mitigate negative externalities of economic activities, the EU has developed environmental taxes, including energy, pollution, and transport taxes. The topic has been commonly discussed in the literature, but studies have only focused on general pollution levels instead of each pollution type. For example, Silajdzic and Mehic (2018) have investigated the effectiveness of environmental taxes in the EU for the period of 1995–2015 using the fully modified ordinary least squares (FMOLS) method. The findings show that environmental tax does not mitigate CO_2 emissions. Although the study uses energy and transportation taxes as proxies for environmental taxation, environmental taxes are broader in scope than these categories alone. Moreover, the environmental impacts of economic activities are not limited to air pollution, as they may also extend to other forms of environmental degradation, including water pollution. Aydin and Esen (2018) have also used CO_2 emissions as an indicator of environmental degradation to assess the effectiveness of environmental taxes in EU for the period of 1995–2013. They state that after exceeding a threshold level, environmental taxes begin to mitigate CO_2 emissions. Although the study employs broader environmental tax proxies, it focuses exclusively on air pollution, and the effects of environmental taxes on other types of environmental degradation remain unexplored. Zioło et al. (2020) have focused on the impact of environmental tax on greenhouse gas (GHG) emissions in EU for the period of 2008–2017. The findings show that environmental tax reduces environmental degradation in countries with higher GHG emissions, but it has no significant effect in countries with lower GHG emissions. Likewise, Zioło et al. (2020), consistent with Aydin and Esen (2018), focus on air pollution as the primary proxy for environmental degradation. Wolde-Rufael and Mulat-Weldemeskel (2023) have examined the impact of environmental

tax on CO_2 emissions in EU from 1995 to 2012 using the FMOLS method. They state that an increase in environmental tax revenue leads to a decrease in CO_2 emissions. The study employs different types of environmental taxes and makes a significant contribution to the literature. However, the exclusive focus on CO_2 emissions as a proxy for environmental degradation leaves other forms of pollution unexamined. Gao and Fan (2023) have also examined the impact of environmental taxes on CO_2 emissions in EU for the period of 2000-2020 using panel quantile regression. However, the findings have not fully confirmed the study of Wolde-Rufael and Mulat-Weldemeskel (2023), and they still leave the broader effects of environmental taxes on other forms of environmental degradation, beyond air pollution, unexplored. Environmental tax has a negative effect on CO_2 emissions only in the fifth quantile, and the positive relationship has been identified in other quantiles. They explain this undesired outcome with the double dividend suggested by Pearce (1991). According to the double dividend concept, environmental tax revenues can be used either to improve environmental quality or to reduce the tax burden on others. Ullah et al. (2023) have utilized the Quantile-on-Quantile (QQ) regression method to examine the impact of environmental tax on EF in EU from 1995/Q1 to 2018/Q4. They also state that environmental tax has different effects on EF based on different quantiles. They suggested that environmental taxes should be imposed on environmentally damaging activities such as the use of fossil fuels to ensure homogeneous effects across all quantiles. Ullah et al. (2023) offer one of the most comprehensive analyzes of the impact of environmental taxes on environmental outcomes, employing broad tax measures and environmental degradation proxies. However, their study does not examine which subcomponents of EF are most affected, nor does it provide policy guidance on which pollution types should be prioritized for more effective mitigation strategies. Ali et al. (2023) have investigated the role of environmental tax on environmental degradation in EU for the period of 2000–2019 using cross-sectional auto-regressive distributed lag (CS-ARDL) and augmented mean group (AMG) models. The findings show that environmental tax mitigates CO_2 emissions. Youssef et al. (2023) have studied the link between environmental tax and CO_2 emissions in the European Economic Area for the period of 2000–2018 using CS-ARDL method. The findings confirm the negative relationship between variables. Dmytrenko et al. (2024) have investigated the impact of environmental tax on GHG emissions in EU for the period of 2000–2019 using a fixed-effects model. They reveal that environmental tax has a mitigating influence on GHG emissions. Adeshola et al. (2024) have focused on the impact of environmental tax on GHG emissions in EU from 2000 to 2017 and used Pooled Mean Group (PMG) estimation to explain the relationship. Their findings show that GHG emissions can be decreased by environmental tax. Akdag et al. (2025) have stated that environmental tax in the EU leads to mitigating GHG emissions for the period of 1995–2019. They have utilized the system generalized method of moments (GMM) method and indicated that a 1% increase in environmental tax leads to a decrease in GHG emissions by 0.18%. The studies above treat environmental degradation as either single-dimensional or aggregated, and are mostly centered on air pollution.

In addition to EU studies, some studies have focused on specific countries in EU. For example, Kirikkaleli (2023) has focused on the Netherlands for the period of 1990–2019 to explain the impact of environmental tax on environmental degradation using GHG emissions. The result of the Fourier ARDL test shows that environmental tax leads to mitigating environmental degradation. On the other hand, Ali and Kirikkaleli (2024) have focused on Germany for the period of 1994–2021. The outcome of the Fourier ARDL test demonstrates that environmental tax causes an increase in EF. In the case of France, Athari et al. (2025) have used the Fourier ARDL method to investigate the impact of environmental tax on environmental degradation. The findings show that environmental tax reduces GHG emissions and increases environmental quality in France for the period of 1995 to 2020. Likewise, Javed et al. (2023) have confirmed that environmental tax increases environmental quality in Italy for the period of 1994–2019. They have used the ARDL method and reached that environmental tax reduces EF. The effect of environmental tax on CO_2 emissions for the period of 1995–2020 in Denmark, Sweden, Norway, Finland and Iceland has been investigated by Sharif et al. (2023) using CS-ARDL method. They state that environmental tax reduces CO_2 emissions and increases environmental quality. Table 1 presents a summary of the studies examined in the empirical literature.

As a result, although there are a few studies showing environmental tax causes environmental degradation, the literature predominantly agrees that environmental tax mitigates environmental degradation. On the other hand, studies have mostly used CO_2, GHG emissions, and EF. Although these proxies have indicated pollution levels, they do not reflect specific pollution types and this creates a gap in the literature. For this reason, existing literature suffers from indicator bias, as it overwhelmingly relies on CO_2 emissions while ignoring multi-dimensional ecological degradation. Moreover, most studies treat EF as a homogeneous measure and ignore the distinct mechanisms driving each subcomponent. These biased proxies can create problems because policy instruments such as environmental taxes influence land-use decisions, agricultural output, and forest product substitution in different ways.

Literature gap. The serious scale of environmental degradation and the triggering of the climate crisis have accelerated the search for solutions. Environmental tax is one of the common policies to mitigate environmental degradation. However, the existence of many proxies for measuring environmental degradation has complicated the assessment of environmental tax effectiveness. The literature has mainly focused on common proxies: CO_2 emissions, GHG emissions and EF. It is logical to focus on the main proxies to have a general idea about the effectiveness of environmental tax. However, when addressing environmental degradation, policies based only on main proxy results can be misleading. For instance, using CO_2 emissions to assess environmental tax effectiveness can give similar results for GHG emissions and EF, as CO_2 emissions account for more than fifty percent of both indicators. Thus, examining each type of pollution provides more consistent results, especially for policy design, since there is a general consensus on the overall effectiveness of environmental taxes, but no studies focus on specific pollution types. As shown in Fig. 2, the existing literature generally agrees that environmental taxes reduce EF. However, the effects of environmental taxes on subcomponents of EF remain unknown, and this creates a gap in the literature. Thus, the purpose of the study is to fill the gap by investigating the impact of environmental taxes on each subcomponent of EF. The findings help the EU to mitigate and eliminate environmental degradation more effectively. While the decomposition of ecological footprint provides a more detailed perspective, the contribution of this study goes beyond simple disaggregation. Specifically, this study develops a mechanism-based framework linking environmental taxes to different ecological footprint components through economic growth, REC, and urbanization channels. In addition, by employing robust panel estimators such as Driscoll-Kraay (1998) and FGLS, the study provides more reliable and policy-relevant evidence on the heterogeneous effects of environmental taxes.

Table 1 Summary of empirical literature on environmental taxation and environmental outcomes.

Authors	Study Period	Sample	Econometric Methods	Main Findings
Silajdzic and Mehic (2018)	1995–2015	European Union	Fully modified ordinary least squares (FMOLS) method	Environmental tax does not mitigate CO_2 emissions
Aydin and Esen (2018)	1995–2013	European Union	Panel threshold regression (PTR) method	After exceeding a threshold level, environmental taxes begin to mitigate CO_2 emissions
Zioło et al. (2020)	2008–2017	European Union	Principal component analysis (PCA) method	Environmental tax reduces GHG emissions
Wolde-Rufael and Mulat-weldemeskel (2023)	1995–2012	European Union	FMOLS method	Environmental tax decreases in CO_2 emissions.
Gao and Fan (2023)	2000–2020	European Union	Panel quantile regression method	Enviromental taxes have both positive and negative influence on CO_2 emissions across quantiles
Ullah et al. (2023)	1995/Q1 to 2018/Q4	European Union	Quantile-on-Quantile (QQ) regression method	Environmental tax has different effects on EF based on different quantiles
Ali et al. (2023)	2000–2019	European Union	Cross-sectional auto-regressive distributed lag (CS-ARDL) and augmented mean group (AMG) methods	Environmental tax mitigates CO_2 emissions
Youssef et al. (2023)	2000–2018	European Union	CS-ARDL method	Environmental tax mitigates CO_2 emissions
Dmytrenko et al. (2024)	2000–2019	European Union	Fixed-effects method	Environmental tax has a mitigating influence on GHG emissions
Adeshola et al. (2024)	2000–2017	European Union	Pooled mean group (PMG) method	Environmental tax has a mitigating influence on GHG emissions
Akdag et al. (2025)	1995–2019	European Union	Generalized method of moments (GMM) method	Environmental tax has a mitigating influence on GHG emissions
Kirikkaleli (2023)	1990–2019	The Netherlands	Fourier ARDL method	Environmental tax reduces CO_2 emissions
Ali and Kirikkaleli (2024)	1994–2021	Germany	Fourier ARDL method	Environmental tax causes an increase in EF
Athari et al. (2025)	1995–2020	France	Fourier ARDL method	Environmental taxes are associated with a reduction in GHG emissions
Javed et al. (2023)	1994–2019	Italy	ARDL method	Environmental taxation is associated with lower EF
Sharif et al. (2023)	1995–2020	Denmark Sweden, Norway, Finland, and Iceland	CS-ARDL method	Environmental tax reduces CO_2 emissions

Data, models and methodology

Data and models. Static and dynamic panel data techniques have been used in the study, but the limitation of green tax data constrains the sample period to 1995–2021. Unlike the literature, the study has focused on the effect of green tax on sub-components of EF. Unfortunately, due to data limitations about the subcomponents of EF in EU member states, the sample size of the study has been restricted to 22 EU countries. Thus, the sample of the study consists of Austria, Belgium, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden. Driscoll-Kraay (1998) estimator, which is robust to heteroscedasticity, auto-correlation, and CSD, has been used in the study. In addition to Driscoll-Kraay (1998) estimator, the findings have also been tested using the FGLS estimator to check robustness and to avoid biased results. The study has used EF and its subcomponents as the dependent variable, while real per capita environmental tax (RETAX) has been used as the main explanatory variable. Also, the control variables have been used in all models are real income per capita (GDP), REC, and urban population (URB). All variables used in the study have been analyzed using their natural logarithms. Information regarding the variables is presented in Table 2.

The models tested by Driscoll-Kraay (1998) estimator in the study have been demonstrated in Eqs. 1 to 7. The same models have also been tested by FGLS estimator to avoid biased results.

$$lnEF_{it} = \alpha_0 + \beta_1 lnRETAX_{it} + \beta_2 lnGDP_{it} + \beta_3 lnREC_{it} + \beta_4 lnURB_{it} + \mu_{it} \quad (1)$$

$$lnCRF_{it} = \alpha_0 + \beta_1 lnRETAX_{it} + \beta_2 lnGDP_{it} + \beta_3 lnREC_{it} + \beta_4 lnURB_{it} + \mu_{it} \quad (2)$$

$$lnCLF_{it} = \alpha_0 + \beta_1 lnRETAX_{it} + \beta_2 lnGDP_{it} + \beta_3 lnREC_{it} + \beta_4 lnURB_{it} + \mu_{it} \quad (3)$$



Fig. 2 The literature gap.

$$lnGLF_{it} = \alpha_0 + \beta_1 lnRETAX_{it} + \beta_2 lnGDP_{it} + \beta_3 lnREC_{it} + \beta_4 lnURB_{it} + \mu_{it} \quad (4)$$

$$lnFGF_{it} = \alpha_0 + \beta_1 lnRETAX_{it} + \beta_2 lnGDP_{it} + \beta_3 lnREC_{it} + \beta_4 lnURB_{it} + \mu_{it} \quad (5)$$

$$lnFRF_{it} = \alpha_0 + \beta_1 lnRETAX_{it} + \beta_2 lnGDP_{it} + \beta_3 lnREC_{it} + \beta_4 lnURB_{it} + \mu_{it} \quad (6)$$

$$lnBLF_{it} = \alpha_0 + \beta_1 lnRETAX_{it} + \beta_2 lnGDP_{it} + \beta_3 lnREC_{it} + \beta_4 lnURB_{it} + \mu_{it} \quad (7)$$

In the models, i represents the countries and t denotes the time period. Additionally, while a_0 denotes the constant term, u_{it} and β represent the error terms and the coefficients of the variables, respectively. To simplify the monitoring of the methodology of the study and illustrate it visually, the sample and methods used in the study are shown in Fig. 3.

Methodology. The econometric framework of the study consists of five steps. First, CSD among the variables is examined, followed by unit root testing. The findings of these two steps allow the use Driscoll-Kraay (1998) estimator as the main technique in the third step. The findings of Driscoll-Kraay (1998) estimator have been retested in the fourth step by using FGLS estimator. In the last step, causality links among the variables have been tested by using Dumitrescu and Hurlin (2012) test.

The sample of the study consists of 22 EU countries. Therefore, these countries may have potential connections through economic integration and the EU framework. Hence, it is important to evaluate CSD among the variables before starting the main econometric method. The assessment of CSD in the study has been done by using CD and CDw+ tests developed by Pesaran (2015) and Fan et al. (2015). CD test developed by Pesaran (2015) is biased under heteroscedasticity and serial correlation and Monte Carlo simulation results show that the test is suitable for all cases of T and N (i.e., T>N, N>T ve N≈T). Similarly, CDw+ test has increased the power of the CD test and provides reliable results to find weak CSD under heteroscedastic errors. Besides, the evaluation of models for CSD has been conducted using the adjusted LM test. CD and LM tests have biased results when the average of the sample is zero, but the average of the unit is different from zero. Thus, the adjusted LM test has been developed by Pesaran et al. (2008). The test statistic has an asymptotically standard normal distribution and can be used in the case of T>N (Pesaran et al., 2008).

Table 2 Information of variables.

Variables	Add.	Unit of measurement	Source
Ecological Footprint (Total)	EF	Gha per person	Global Footprint Network (GFN) (2025)
Carbon Footprint	CRF	Gha per person	GFN (2025)
Cropland Footprint	CLF	Gha per person	GFN (2025)
Grazing Land Footprint	GLF	Gha per person	GFN (2025)
Fishing Grounds Footprint	FGF	Gha per person	GFN (2025)
Forest Footprint	FRF	Gha per person	GFN (2025)
Built-up Land Footprint	BLF	Gha per person	GFN (2025)
Real environmental taxes	RETAX	Real per capita environmental taxes (constant 2020 US$)	OECD (2026)
Economic Growth	GDP	GDP per capita (constant 2015 US$)	World Bank-WDI (2025)
Renewable Energy Consumption	REC	Renewable energy consumption (% of total final energy consumption)	World Bank-WDI (2025)
Urbanization	URB	Urban population	World Bank-WDI (2025)

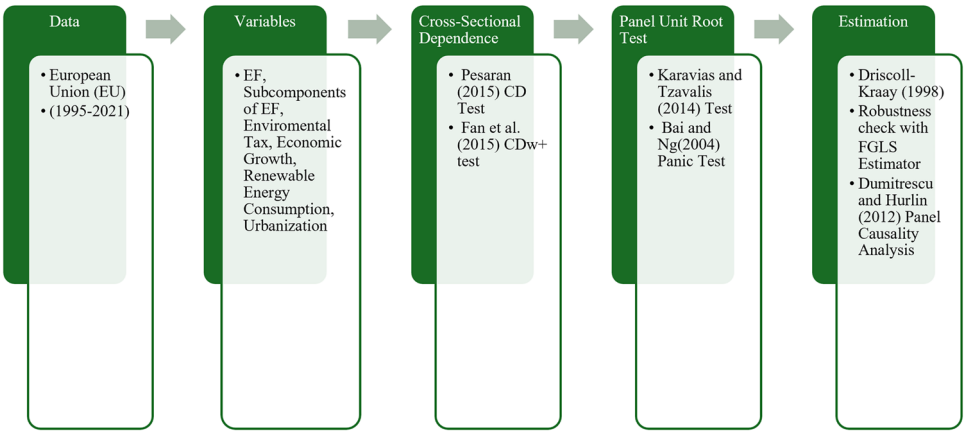


Fig. 3 Flowchart of analysis.

After evaluating CSD among the variables, the second step is to assess stationarity of the series. Since analyzing the series without accounting for CSD can lead to biased and inconsistent results. For this reason, second-generation unit root tests were preferred in this study. However, while standard second-generation tests can control for CSD, they do not directly incorporate structural breaks that can emerge over time into the model and evaluate the data without decomposing the common factors affecting the entire panel. In this case, the test can lead to the incorrect detection of a unit root, particularly in series that contain breaks or are exposed to strong common shock factors that appear to disrupt the series' stationarity. In particular, structural breaks (crises, policy changes, or regime shifts) cause sudden changes in the series' mean or trend, leading standard tests to interpret them as a permanent shock or stochastic trend. In this case, a series that is actually stationary around the break is incorrectly assessed as non-stationary. Similarly, common factors affecting the entire panel but not explicitly included in the model can cause simultaneous movements across all units, creating a false impression of persistence among the series. Standard second-generation tests may still be biased when they don't distinguish common factors or incorporate structural breaks. The approach by Karavias and Tzavalis (2014) reduces this bias by directly incorporating structural breaks, and PANIC method by Bai and Ng (2004) identifies the source of persistence by separating common and individual components.

Assessment of stationarity of series has been conducted by the test developed by Karavias and Tzavalis (2014). Thus, CSD and structural breaks have been captured, and the findings are unbiased compared to the other stationarity tests (Chen et al.,2022). More specifically, if point b is a structural break point, the function is divided as before and after b. I is the indicator function, and $\alpha_{1,i}$ and $\alpha_{2,i}$ indicate the fixed effects before and after the structural break. Eq. (8) shows the details of the test.

$$y_{it} = \varphi y_{it-1} + (1-\varphi)[\alpha_{1,i} I(t \le b) + \alpha_{2,i} I(t > b)] + \mu_{it} \quad (8)$$

Some or all of the time series in the panel are stationary as indicated by the alternative hypothesis, and all units are not stationary as indicated by the null hypothesis.

In addition to the unit root test by Karavias and Tzavalis (2014), which focuses on structural breaks, unit root tests that account for both the common and individual components of the series have also been developed. Bai and Ng (2004) developed PANIC (Panel Analysis of Nonstationarity in Idiosyncratic and Common Components) unit root test, which utilizes a panel's factor structure to decompose series into common and idiosyncratic components, determining whether the source of nonstationarity is common, variable-specific, or both. A key feature of the method is that it tests the unobservable components of the data rather than the directly observed series. Thanks to these features, the PANIC approach provides more reliable and detailed results, particularly in panel data analyzes where CSD and common shocks are noticeable. In this method, the null hypothesis is formulated such that the relevant component, common factors, or individual components contain a unit root, meaning that the series is non-stationary.

In the third step, the main econometric analysis of the study to investigate the effect of environmental tax on EF and subcomponents of EF has been conducted by using Driscoll-Kraay (1998) estimator. The estimator has consistent results under CSD, serial correlation and heteroscedasticity. Thus, Driscoll-Kraay (1998) has an advantage over OLS, fixed and random effects methods.

In the fourth step, the robustness of the findings of Driscoll-Kraay (1998) estimator has been checked using the FGLS estimator. Because the FGLS method explicitly accounts for the structure of the error term, it yields significantly more reliable and efficient estimates than classical OLS estimators, particularly in the presence of heteroscedasticity, autocorrelation, and CSD, similar to the Driscoll-Kraay estimator. In this regard, it provides a robust framework that not only improves estimation accuracy but also enhances the reliability of the empirical findings.

The causality relationships between environmental tax and ecological footprint variables have been analyzed using the panel causality test developed by Dumitrescu and Hurlin (2012). The biggest advantage of Dumitrescu and Hurlin (2012) test is considering CSD during estimation. The formulation of the test is illustrated in Eq. (9).

$$Y_{it} = a_i + \sum_{k=1}^{K} \gamma_i^{(k)} Y_{it-k} + \sum_{k=1}^{K} \beta_i^{(k)} X_{it-k} + \varepsilon_{it} \quad (9)$$

In Eq. (9), X and Y show the variables and k denotes lag length for each unit. The autoregressive parameter $\gamma_i^{(k)}$ and slope coefficient $\beta_i^{(k)}$ can vary across units. Dumitrescu and Hurlin (2012) method tests the causality relationship between and Y, and the null hypothesis states that there is no Granger causality from X to Y, whereas the alternative states that at least one unit has Granger causality. The formulations of the test are shown in Eqs. (10), (11) and (12).

$$W_{N,T}^{HNC} = \left(\frac{1}{N}\right) \sum_{i=1}^{N} W_{i,T} \quad (10)$$

$$Z_{N,T}^{HNC} = \sqrt{\frac{N}{2K}\left(W_{N,T}^{HNC} - K\right)} \quad (11)$$

Table 3 CD and CDw+ tests for CSD.

	Pesaran (2015) CD	Fan et al. (2015) CDw+
lnEF	17.14***	520.07***
lnCRF	36.17***	617.77***
lnCLF	5.76***	249.27***
lnGLF	−1.45	633.25***
lnFGF	6.20***	463.44***
lnFRF	5.82***	455.48***
lnBLF	16.90***	442.64***
lnRETAX	25.39***	612.85***
lnGDP	65.66***	1009.02***
lnREC	64.88***	999.07***
lnURB	6.56***	1045.04***

*** $p < 0.01$.

Table 4 Panel unit root tests.

	Karavias and Tzavalis (2014)		Bai and Ng(2004) Panic	
Değişkenler	Zmin-stat	5%bootstrap critical value	Test	Stat.
lnEF	−10.932***	7.836	$Z_{\hat{e}}^{c}$	5.841***
			$P_{\hat{e}}^{c}$	98.798***
lnCRF	−15.493***	9.598	$Z_{\hat{e}}^{c}$	4.160***
			$P_{\hat{e}}^{c}$	83.026***
lnCLF	−26.768***	18.390	$Z_{\hat{e}}^{c}$	6.088***
			$P_{\hat{e}}^{c}$	101.115***
lnGLF	−6.402***	3.479	$Z_{\hat{e}}^{c}$	3.179***
			$P_{\hat{e}}^{c}$	73.822***
lnFGF	−10.836***	3.041	$Z_{\hat{e}}^{c}$	3.854***
			$P_{\hat{e}}^{c}$	80.162***
lnFRF	−15.023***	9.742	$Z_{\hat{e}}^{c}$	4.580***
			$P_{\hat{e}}^{c}$	86.969***
lnBLF	−15.009***	11.643	$Z_{\hat{e}}^{c}$	4.394***
			$P_{\hat{e}}^{c}$	85.221***
lnRETAX	−14.303***	7.189	$Z_{\hat{e}}^{c}$	2.800***
			$P_{\hat{e}}^{c}$	70.273***
lnGDP	−21.429***	11.423	$Z_{\hat{e}}^{c}$	4.049***
			$P_{\hat{e}}^{c}$	81.989***
lnREC	−21.161***	6.853	$Z_{\hat{e}}^{c}$	2.885***
			$P_{\hat{e}}^{c}$	71.067***
lnURB	−2.242***	−1.765	$Z_{\hat{e}}^{c}$	4.328***
			$P_{\hat{e}}^{c}$	84.607***

$Z_{\hat{e}}^{c}$ represents the statistics proposed by Choi (2001), and $P_{\hat{e}}^{c}$ represents the statistics proposed by Maddala and Wu (1999). ***, represents 1% significance level. The lag length was automatically selected based on the Akaike Information Criterion (AIC).

$$Z_N^{HNC} = \frac{\sqrt{N\left[W_{N,T}^{HNC} - N^{-1}\sum_{i=1}^{N} E(W_{i,T})\right]}}{\sqrt{N^{-1}\sum_{i=1}^{N} \mathrm{var}(W_{i,T})}} \quad (12)$$

Testing for the null hypothesis, $W_{i,T}$ has been calculated for each unit and shows Wald statistics. On the other hand, $\left(W_{N,T}^{HNC}\right)$ denotes the average of each $W_{i,T}$ in Eq. (10). In the case of T>N, Dumitrescu and Hurlin (2012) suggests that using Eq. (11) and $\left(Z_{N,T}^{HNC}\right)$ statistics, but if N is bigger than T, it is suggested that using Eq. (12) and $\left(Z_{N}^{HNC}\right)$ statistics. In the study, T is bigger than N and Eq. (11) has been used. To determine optimal lag length, Akaike information criterion suggested by Lopez and Weber (2017) has been used.

Findings

Pesaran (2015) CD and Fan et al. (2015) CDw+ tests have been used to examine whether the variables exhibit CSD or not. The results guide the selection between first and second-generation unit root tests. The findings of the tests are shown in Table 3.

The findings in Table 3 show that variables have CSD. Hence, the second-generation unit root test needs to be applied. The results of the unit root tests are indicated in Table 4. The results of Karavias and Tzavalis (2014) test, which is a second-generation unit root test accounting for structural breaks, show that the null hypothesis is rejected and all series used in the study are stationary. Similarly, the results of the Bai and Ng (2004) PANIC unit root test, which separates common and individual components, indicate that the null hypothesis is rejected and all series are stationary at level. The consistency of the findings from these two tests, which differ from standard second-generation unit root tests in their characteristics and provide more reliable results, supports the conclusion that the series are I(0). In this case, it is suggested that Driscoll-Kraay (1998) estimator can be directly applied without checking cointegration. Thus, Driscoll-Kraay (1998) estimator has been applied, and the findings are shown in Table 5.

In Table 5, the *F*-test shows that all models are statistically significant in the study, and results of LMadj indicate the existence of CSD in all models. The findings show that lnGDP has positive effects on environmental degradation proxies in all models. lnREC has significant negative impacts on dependent variables in almost all models except for lnCLF in Model 3, lnFGF in Model 5, lnBLF in Model 7. In detail, 1% increase in lnGDP leads to an increase in EF by 0.552%, in lnCRF by 0.595%, in lnCLF by 0.274%, in lnGLF by 0.413%, in lnFGF by 0.598%, in lnFRF by 0.612%, and lnBLF by 0.548%. Basically, economic growth causes an increase in EF and subcomponents of EF. On the other hand, the effect of lnURB is statistically significant and negative effect in Model 1, Model 2, Model 3, Model 5, Model 6 and Model 7. However, lnURB has a positive effect on lnGLF in Model 4. While urbanization mitigates the effect of total EF, carbon, cropland, fishing grounds, forest and built-up land footprints, it causes an increase in grazing land footprint.

The findings show that lnRETAX has significantly negative effects on all dependent variables, including lnEF, lnCRF, lnCLF, lnGLF, and lnFGF, except for lnFRF and lnBLF. While it is indicated that lnRETAX has a significantly positive effect on lnFRF and lnBLF. The findings show that EF and its subcomponents such as cropland, grazing land, fishing grounds, and carbon footprints can be reduced by increasing real per capita environmental tax. However, an increase in real per capita environmental tax has the side effect that it raises forest product and built-up land footprint. The findings confirm the studies by Aydin and Esen (2018), Zioło et al. (2020), Wolde-Rufael and Mulat-Weldemeskel (2023), Ali et al. (2023), Youssef et al. (2023), Adeshola et al. (2024), and Akdag et al. (2025) in the literature. The overall findings are shown in Fig. 4.

More specifically, a 1% increase in real per capita environmental tax leads to a decrease in EF by 0.103%, carbon footprint by 0.231%, cropland footprint by 0.096%, grazing land footprint by 0.200%, and fishing grounds footprint by 0.807%, respectively. When examining the magnitude of the effect of environmental tax on pollution proxy types, environmental tax has the biggest effect on fishing grounds footprint, and followed by carbon footprint, grazing land footprint, total EF and cropland footprint. The magnitude of the effect of environmental tax on proxies has

Table 5 Driscoll-Kraay (1998) estimation.

	Model 1 lnEF	Model 2 lnCRF	Model 3 lnCLF	Model 4 lnGLF	Model 5 lnFGF	Model 6 lnFRF	Model 7 lnBLF
lnRETAX	−0.103**	−0.231***	−0.0960***	−0.200***	−0.807***	0.292**	0.212***
	(0.0442)	(0.0560)	(0.0280)	(0.0551)	(0.110)	(0.105)	(0.0424)
lnGDP	0.552***	0.595***	0.274***	0.413***	0.598***	0.612***	0.548***
	(0.0485)	(0.0988)	(0.0572)	(0.111)	(0.166)	(0.134)	(0.0925)
lnREC	−0.173***	−0.245***	−0.0252	−0.105***	−0.0247	−0.139***	0.0164
	(0.0130)	(0.0300)	(0.0190)	(0.0144)	(0.0590)	(0.0384)	(0.0288)
lnURB	−0.428***	−0.358**	−0.389**	0.304**	−1.584***	−0.624*	−0.731***
	(0.0836)	(0.137)	(0.168)	(0.146)	(0.382)	(0.342)	(0.0946)
Constant	2.639**	−0.161	2.704	−11.43***	11.26*	5.635	5.370***
	(1.103)	(2.626)	(2.654)	(1.996)	(6.455)	(6.086)	(1.706)
Obs.	594	594	594	594	594	594	594
Groups	22	22	22	22	22	22	22
F test	139.81***	48.48***	11.49***	23.05***	44.83***	81.80***	114.57***
LMadj	3.298***	34.54***	28.04***	14.24***	3.481***	2.701***	24.51***

Standard errors in parentheses *** p < 0.01, ** p < 0.05, * p < 0.1.

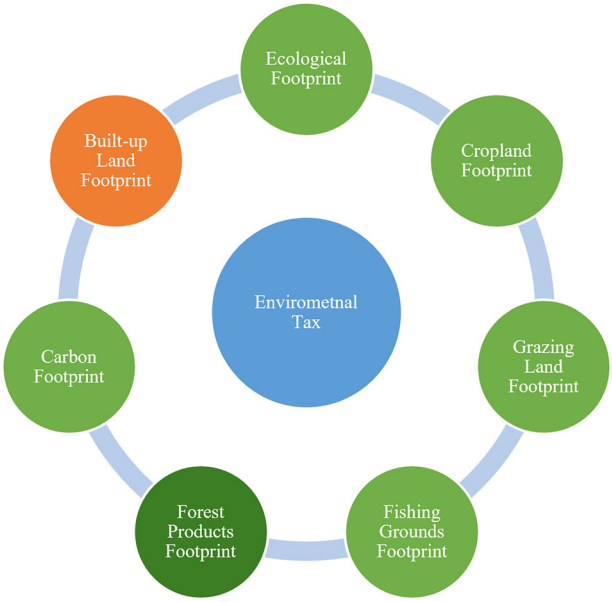


Fig. 4 The effect of environmental tax on ecological footprint components.

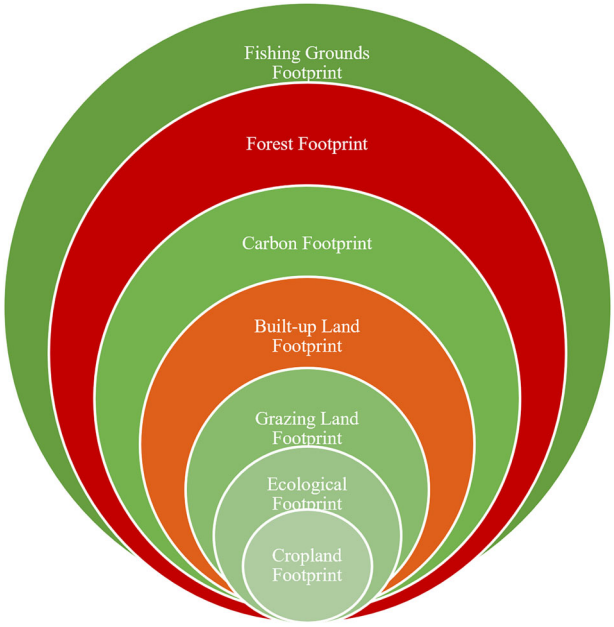


Fig. 5 The magnitude effect of environmental tax on ecological footprint components.

been illustrated in Fig. 5. In addition to the negative effects of real per capita environmental tax, a 1% increase in environmental tax causes an increase in forest product by 0.292% and built-up land footprint by 0.212%.

The findings of Driscoll-Kraay (1998) estimator have been verified using FGLS estimator and the findings of FGLS estimator confirm the findings of Driscoll-Kraay (1998) estimator. The robustness check results are seen in Table 6. The findings of FGLS estimator confirm the negative effects of lnRETAX on all dependent variables, including lnEF, lnCRF, lnCLF and lnFGF, except for lnGLF, lnFRF and lnBLF. In other words, real per capita environmental tax mitigates EF and its subcomponents such as cropland, fishing grounds, and carbon footprints and increases environmental quality. The positive effects of environmental tax on built-up land and forest product footprints have been confirmed.

The causal relationship between environmental tax and dependent variables has been checked, and the outcomes are shown in Table 7. The findings of Dumitrescu and Hurlin (2012) causality test indicate strong and bidirectional causal relationships between lnRETAX and lnEF, lnCRF, lnCLF, lnGLF, lnFGF, lnFRF, and lnBLF. These findings indicate that there are mutual interactions and feedback mechanisms between environmental taxes and related ecological pressure indicators and state that tax policies have an impact on environmental outcomes and that changes in environmental conditions play a role in shaping tax policies.

Economic activities have increased the pressure on the environment. Environmental taxes can be used as a policy tool to reduce pollution and mitigate environmental degradation. However, the impact of taxes is highly sensitive to the choice of pollution measurement. While focusing on a single type of pollution is understandable, it is not sufficient to fully address environmental degradation. Therefore, comprehensive tax studies targeting all known types of pollution are important. For example, European Commission (2023b) has targeted reducing CO_2 emissions by 2050. This goal is understandable and beneficial for addressing environmental problems. However, it will not completely eliminate environmental degradation. Thus, the effect of policies needs to be assessed on a broader scale. At first glance,

Table 6 Robustness check with FGLS estimator.

	Model 1: lnEF	Model 2: lnCRF	Model 3: lnCLF	Model 4: lnGLF	Model 5: lnFGF	Model 6: lnFRF	Model 7: lnBLF
lnRETAX	−0.046***	−0.041***	−0.045***	0.055***	−0.238***	0.033**	0.126***
	(0.010)	(0.009)	(0.011)	(0.018)	(0.033)	(0.016)	(0.020)
lnGDP	0.414***	0.505***	0.138***	0.577***	0.556***	0.541***	0.296***
	(0.011)	(0.011)	(0.011)	(0.026)	(0.036)	(0.027)	(0.027)
lnREC	−0.112***	−0.179***	−0.047***	−0.185***	0.066***	−0.008	0.036***
	(0.005)	(0.005)	(0.005)	(0.011)	(0.018)	(0.011)	(0.011)
lnURB	−0.123***	−0.109***	0.076***	−0.042***	0.298***	0.029***	−0.055***
	(0.004)	(0.003)	(0.005)	(0.006)	(0.019)	(0.009)	(0.015)
Constant	−0.551***	−2.086***	−2.838***	−5.667***	−14.18***	−6.023***	−3.231***
	(0.163)	(0.144)	(0.129)	(0.323)	(0.684)	(0.417)	(0.378)
Obs.	594	594	594	594	594	594	594
Gruops	22	22	22	22	22	22	22
Wald test	3035.14***	3335.10***	1403.64***	1884.56***	353.75***	1216.41***	327.43***

Standard errors in parentheses $^{***}p < 0.01$, $^{**}p < 0.05$.

Table 7 Dumitrescu and Hurlin (2012) panel causality analysis.

Direction of causality	W-bar	Z-bar	*p*-value
lnRETAX→lnEF	16.202	11.536	0.000
lnEF→lnRETAX	10.828	4.799	0.000
lnRETAX→lnCRF	13.031	7.561	0.000
lnCRF→lnRETAX	11.718	5.914	0.000
lnRETAX→lnCLF	12.103	6.397	0.000
lnCLF→lnRETAX	13.875	8.619	0.000
lnRETAX→lnGLF	18.008	13.799	0.000
lnGLF→lnRETAX	19.524	15.699	0.000
lnRETAX→lnFGF	15.338	10.45	0.000
lnFGF→lnRETAX	1.742	2.4625	0.014
lnRETAX→lnFRF	25.287	22.924	0.000
lnFRF→lnRETAX	21.576	18.272	0.000
lnRETAX→lnBLF	8.414	1.772	0.076
lnBLF→lnRETAX	14.067	8.859	0.000

The lag length was determined according to the Akaike information criterion.

this study indicates that environmental taxation mitigates environmental degradation by using EF as a measure of pollution. However, analyzing subcomponents of EF shows that not all components can be reduced by current environmental tax policies.

The results indicate that, based on the double dividend hypothesis, the green dividend effect is stronger than the blue dividend effect. Environmental taxation reduces the overall EF level. This finding suggests that environmental taxation improves environmental quality, implying that environmental tax revenues are primarily allocated toward environmental improvement. In addition to the reduction in the overall EF, environmental taxation reduces pollution levels across five models, including fishing grounds, carbon, grazing land, and cropland footprints. However, in two models with forest product and built-up land footprints, environmental taxation appears to increase pollution levels in these specific components of environmental degradation. These findings address our research questions. First, environmental taxation reduces the overall EF. Second, environmental taxation exhibits heterogeneous effects across EF subcomponents, as some components are negatively affected while others show a positive association with environmental taxation.

Among the subcomponents of EF, fishing grounds footprint has the largest negative coefficient. European Environment Agency (2019) states that industrial wastewater is a major threat to water quality in the EU. It is obvious that marine biodiversity is highly sensitive to pollution. Thus, environmental taxation improves water quality and protects marine biodiversity by reducing industrial pollution. Also, the energy demand in fisheries can be affected by environmental tax, and instead of fossil energy, renewable energy can be prioritized. These dual effects may make fishing grounds the most affected EF subcomponent from environmental taxation. More broadly, rising energy prices exert negative effects on agricultural activities, including fisheries, livestock production, and crop farming (European Environment Agency, 2022; Ma et al., 2022; Yanagida and Conway, 1981). Therefore, increased energy prices due to environmental taxes can reduce agricultural activities and related pollution types such as grazing land, fishing grounds and cropland footprints. Similarly, decreasing pollution thanks to environmental taxes can raise productivity in agricultural activities thanks to the feedback effect, and the need for energy can be eliminated (Recepoğlu et al., 2025). It is possible to produce the same amount of output using less energy due to efficiency improvements.

The large component of EF is carbon footprint with 60%, and it has a parallel trend with EF. The biggest source of carbon footprint in the EU is the transport sector, electricity and heat producers with 32% and 30%, respectively (IEA, 2024). IEA (2024) also states that 73% of the carbon footprint comes from oil and natural gas consumption. Energy dependency, especially on fossil fuels, in the transport sector and electricity and heat producers is still high. Thus, environmental taxation may have a limited effect on final consumption decisions, and its impact is relatively weaker compared to other components.

The only EF subcomponents positively affected by environmental taxation are built-up land and forest product footprints. Energy crises have affected EU economies and the environment, and REC has been increasing to reduce the negative effects of fossil fuels in line with the Green Deal (European Commission, 2023a). This approach is seen as the easiest and fastest way to achieve the net-zero CO_2 emissions target. However, increasing demand for REC leads to the need for new land use for renewable energy zones (Mongird et al., 2025). Moreover, to avoid environmental taxes, firms can use forest products as a low-carbon renewable energy source, which may lead to the reduction of forest areas. As is well known, forests play a key role in preserving ecosystems, species, and genetic diversity. The report of FAO (2022) states that 80% of amphibians, 75% of bird species, and 68% of mammal species live in forests. The same report also indicates that forests create green jobs around the world.

However, expanding economic activities put pressure on forests. For example, the tall forest of Europe has decreased by 2.25 million hectares and the average forest loss of Europe is around 0.85% (Carter, 2024). As a result, expanding renewable energy zones and decreasing forest areas due to higher environmental taxes can increase the built-up footprint. The findings show that net zero-CO_2 emissions by 2050 may be achievable, but net-zero pollution may not be achievable under current tax policies. In particular, the built-up footprint may reflect increasing land use associated with infrastructure development and renewable energy expansion. This expansion is largely driven by the transition toward cleaner energy systems, although it may also generate additional pressure on land resources. Therefore, it is necessary to redesign tax policies to cover all EF subcomponents.

Conclusion and policy recommendation

The world is making great efforts to stop environmental pollution, especially EU has strict policies and targets against environmental degradation. Particularly, net zero CO_2 emission by 2050 is the most challenging policy to reduce environmental degradation. Current EU environmental taxation policies are largely focused on carbon emissions and energy use. These policies are mainly implemented through instruments such as the EU Emissions Trading System (EU ETS) and energy taxation frameworks. While these tools have been effective in reducing carbon emissions, they may be insufficient to address land-use-related environmental pressures. However, to stop environmental degradation and pollution completely, policies need to target all types of pollution sources. Therefore, the study has investigated the impact of environmental tax on EF and subcomponents of EF in EU for the period of 1995–2021 using Driscoll-Kraay. The findings reveal that environmental taxes have significantly reduced EF and all of its subcomponents except for forest product and built-up land footprint. These findings have also been confirmed FGLS estimator method. The findings indicate that although environmental taxes are effective in reducing the overall EF, they do not significantly reduce built-up land and forest footprints. This suggests that current tax-based policies may not adequately address land-use and resource-based environmental pressures.

The policymakers should revise environmental taxes to cover all types of pollution. For this purpose, the policies should be updated based on the following suggestions. First, the EU has been accelerating renewable energy expansion and new energy plants cause an increase in built-up footprint. Therefore, energy facilities should be sited on idle or previously unused land to minimize land-use pressure. The EU should focus on floating solar panels. It has two positive effects on the environment. First, it reduces land-use pressure and does not contribute to new built-up land. Second, floating solar panels reduce evaporation and, if they are installed on freshwater, they help protect water resources. The revenue generated from environmental taxes could be allocated to floating solar panel technologies, as suggested by Karydas and Zhang (2019) under the "third dividend" framework. Idle or degraded lands, where floating solar panels are not suitable, should be used for renewable energy plants. Thus, agricultural and forest areas can be protected. The revenue generated from new development areas should be directed toward reducing built-up land and forest footprints, for example through investments that prevent deforestation. This recommendation is supported by Carter (2024), who reports that forest areas have been declining, and by European Commission (2025b), which states that the carbon-sink capacity of European forests has decreased by around 27%. More specifically, regarding country-level policy implications, Sweden, Finland, Poland, Spain, France, Latvia, Portugal, and Estonia account for approximately 80% of the total increase in forest harvested area in the EU, particularly driven by energy demand (Ceccherini et al., 2020; Migliavacca et al., 2025). EU policies should introduce stricter sustainable forest management standards and enforce harvesting quotas in Sweden, Finland, Poland, Spain, France, Latvia, Portugal, and Estonia to prevent excessive forest extraction. In addition, they should strengthen monitoring of biomass energy production and ensure that renewable energy targets do not unintentionally encourage over-reliance on forest-based fuels. Similarly, average net land-take increased by about 32% in the EU. However, in Croatia, Spain, Latvia, Estonia, Hungary, and Slovenia, this increase is at least five times higher than the EU average European Environment Agency, (2025b). Therefore, policymakers should implement urban growth boundaries to limit city expansion and protect agricultural and forest land. In addition, they should set land take reduction targets and provide incentives for brownfield redevelopment to encourage the reuse of existing urban areas instead of converting new land. For regional policy, renewable energy investments should be coordinated at the EU level and designed according to country-specific resource endowments. Southern European countries with high solar irradiation can prioritize solar energy development, while countries with strong hydropower potential can further expand hydro-based electricity generation. This resource-based specialization can enhance efficiency and support cross-border energy trade within the EU internal energy market.

The main limitation of this study is the relatively short time dimension of the data. As data availability increases, future studies can extend the sample period and apply more advanced econometric techniques. Since this study relies on static analysis, the use of dynamic panel models such as CS-ARDL may provide more robust results by capturing long-run relationships more effectively. In addition, when a longer time dimension is available, time-varying causality approaches can be applied to examine how relationships change over different periods, rather than relying on fixed causality results. Although it is beyond the scope of this study, future research may also consider asymmetric analysis by decomposing variables into positive and negative components. Finally, in line with our findings, future studies should further investigate the effectiveness of specific policy instruments aimed at reducing built-up land and forest product footprints. In addition, future research may examine the interaction between environmental taxes and renewable energy policies to better understand potential trade-offs, particularly in biomass use.

Data availability

The data used in this study were obtained from publicly available databases. The relevant data sources are cited in the manuscript. The compiled dataset used for the empirical analysis is available from the corresponding author upon reasonable request.

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Author contributions

MR: Writing – review & editing; Writing – original draft; Data curation. SCC: Writing – review & editing; Writing – original draft; Data curation. MAC: Writing – review & editing; Writing – original draft; Methodology. SA: Writing – review & editing; Writing – original draft; Supervision. PH: Writing – review & editing; Writing – original draft; Conceptualization. DK: Writing – review & editing; Writing – original draft; Investigation.

Competing interests

The authors declare no competing interests.

Ethical approval

This study did not involve human participants, biological materials, or any identifiable personal data. It was based solely on secondary data obtained from publicly accessible institutional sources. Accordingly, formal approval from an ethics committee or Institutional Review Board was not required.

Informed consent

Informed consent was not applicable because the study did not include human participants and did not use individual-level identifiable information.

Additional information

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