Environmental Management (2023) 72:741–753
https://doi.org/10.1007/s00267-023-01867-0

Testing the Short, Medium, and Long-Term Effects of Shocks on Ecological Balance

Veli Yilanci[1] · Zafer Adali[2] · Orkun Çelik[3] · Bilgin Bari[4]

Received: 17 May 2023 / Accepted: 28 July 2023 / Published online: 4 August 2023

Abstract
Ecological balance is an indicator of environmental degradation, which is computed as the difference between biocapacity and ecological footprint. In this study, we examine whether the effect of shocks on the ecological balance is permanent or temporary in the EU-15 countries, considering the period from 1961 to 2018. The application of unit root tests, with and without a Fourier function, indicates that the effects of shocks are temporary in only four countries. To reveal the persistence of shocks at different frequencies, that is, the short-, medium-, and long-run, we decomposed the ecological balance series by using the Discrete Wavelet Transform method. The unit root test results show that the effects of shocks are temporary in all countries in the short-run. However, the results also show that the shocks are temporary in nine countries in the medium-run and ten countries in the long-run. Thus, the implemented policies to balance ecology are not effective in the short-run but are effective in only six countries in the medium-term and in only five countries in the long-term. These findings demonstrate the importance of considering different frequencies when testing the effectiveness of empirically implemented policies. Regarding policy implications, this study suggests focusing on medium- and long-term environmental policies rather than short-term ones.

Keywords Ecological balance · Ecological deficit · Ecological surplus · Sustainability · Fourier functions

JEL Classification N54 · Q57 · Q56

Introduction

The industrial revolution has been one of the breaking points in human history in terms of all aspects; production, consumption, transformations, and lifestyle. However, the world has also encountered severe environmental problems since the industrial revolution, and environmental degradation has persisted with diversified and heightened forms in the current century (Ozcan et al. 2021). Some scientific reports have strived to document the effects of human activities on plants. The Intergovernmental Panel on Climate (IPCC) (2018) is one of the leading documents highlighting the human cause-effect of environmental degradation. The report confirmed that the average temperature of the world's surface warned ~1 °C before the pre-industrial age, and the warming is also expected to reach 1.5 °C between 2030 and 2052 regarding the current rate. Another significant report by the United Nations (UN) projections alleges that we will need two earths to meet human beings' needs by the late 2030s because the demand for resources dramatically expands faster than the world's regenerating capacity (Global Footprint Network GFN 2010; Ozcan et al. 2021). Within the same context, Sustainable Development Goals (SDGs) have been among the most important agendas for sustainability and show the importance of the relationship between prosperity and ecology. Six of the seventeen SDG goals directly relate to environmental quality (United Nations Development Program UNDP 2022).

Determining comprehensive and sufficient environmental indicators is important because the effectiveness of selecting

✉ Veli Yilanci
veli.yilanci@comu.edu.tr

1 Department of Econometrics, Çanakkale Onsekiz Mart University, Çanakkale, Türkiye

2 Department of Economics, Artvin Çoruh University, Artvin, Türkiye

3 Department of Management and Organization, Vocational School of Social Science, Gümüşhane University, Gümüşhane, Türkiye

4 Department of Economics, Anadolu University, Eskişehir, Türkiye

and implementing policy actions and targets and improving socioeconomic strategies depends on these indicators. In this context, most of the studies in environmental economics literature have used carbon dioxide (CO_2) emissions as an indicator of environmental degradation. CO_2 emissions cause climate change by increasing the greenhouse gas effect, and global warming is primarily caused by greenhouse gas (GHG) emissions. However, environmental degradation is not only related to the atmosphere; in contrast, environmental degradation or pollution can also be observed in other parts of the planet. For example, acid rain, water scarcity, deforestation, and disappearing of plant and animal species are some important environmental issues. Therefore, CO_2 emissions reflect air pollution, while CO_2 emissions do not include soil, mining, forestry, and water stock information (Ulucak and Lin 2017). Additionally, human activities have not just produced atmospheric carbon accumulation; in contrast, all ecosystems are affected by human activities (Charfeddine and Mrabet 2017). Focusing only on fixed areas and ignoring other environmental problems does not provide sufficient knowledge to evaluate environmental degradation (Solarin and Bell 2018). Hence, a comprehensive and integrated approach that covers multiple criteria based on environmental issues has become an essential topic in the literature. The ecological footprint (EF) has been acknowledged as one of the most extensive indices indicating human demand for natural resources. Rees (1992), Wackernagel (1994), and Wackernagel and Rees (1998) presented a measure that considered the EF. The researchers have developed the EF to define the outcomes of human pressure on water, land, and air. The EF comprises six subcomponents: built-up land, carbon, cropland, fishing grounds, forest products, and grazing-land footprints (Galli et al. 2012). The six subcomponents induce EF to mirror the prevailing situation of human resource use and general anthropogenic pressures on the environment (Bilgili and Ulucak 2018a). Besides, the EF shows the amount of land and water area for meeting human consumption and the waste generated from consumption required to absorb (Bartelmus 2008; Yilanci and Pata 2020b). Furthermore, the EF is also an all-around indicator of global warming. The carbon footprint accounts for more than half of the EF index. Thus, EF further firmly images the impacts of GHG emissions (Yilanci and Pata 2020a). Moreover, the EF is one of the most critical indicators of sustainability because it determines how much of the renewable ability of the biosphere is utilized by human actions, representing humans' stress on the environment and revealing the ecological cost of goods and services furnished to humans (Rudolf and Figge 2017). In other words, the EF represents environmental boundaries, and how humans exceed these boundaries (McDonald and Patterson 2004; Galli et al. 2012; Solarin et al. 2019; Yilanci and Pata 2020a).

The EF provides a general picture of the pressure caused by human activities, and it represents the demand side, which explains the productive land and sea areas required to generate goods and services utilized by a population. Biocapacity (BIO) is a vital indicator of the supply side, as it measures the ability of known ecological assets belonging to a country, region, or worldwide (Mancini et al. 2018; Yilanci and Pata 2020b). In another explanation, BIO presents the level of natural resources supplied by a region and is employed to detect whether the natural resources are adequate to fulfill human needs (Niccolucci et al. 2007; Yilanci and Pata 2020b). In addition, BIO represents the ability of an ecosystem to reproduce itself (Yilanci and Pata 2020b). Therefore, the relationship between EF and BIO plays a vital role in achieving knowledge about sustainability since the EF and BIO can provide the limit and sustainability of natural resources employed worldwide (Bastianoni et al. 2012; Borucke et al. 2013; Miao et al. 2016). Sustainability indicators can be generated within this objective by comparing the EF and BIO. This new measure, achieved by comparison between EF and BIO, is called the ecological balance and can be calculated as global hectares (GHA) on a global scale (Torras 2003; Wackernagel 2014; He et al. 2016). Therefore, the ecological balance considering these two aspects exhibits a connection between human consumption and natural resources (Yilanci and Pata 2020b). Moreover, two cases emerge from the comparison of EF and BIO. If the EF is higher than the BIO, then the ecological deficit occurs. An ecological deficit means that human consumption is achieved beyond the limits of nature, and the existing system is not sustainable. On the other hand, if BIO is greater than the EF, the ecological surplus is revealed in which human activities do not generate pressure on the environment, and the existing system is sustainable (Hopton and White 2012; Rugani et al. 2014; Geng et al. 2014). Furthermore, if a country struggles with an ecological deficit, the country becomes an ecological debtor, while an ecological surplus leads the country to become an ecological creditor (Rugani et al. 2014; Yilanci and Pata 2020b).

The EF and BIO values are measured to determine sustainability. Both are exhibited in units of the average world bio-productive named GHA. Each GHA defines an equal part of the biological efficiency (Monfreda et al. 2004; Galli et al. 2012; Yilanci and Pata 2020a). The first ecological deficit occurred in the middle of the 1970s and has increasingly continued daily. For more than 40 years, the EF has exceeded the BIO, indicating that regenerating natural resources is insufficient to meet human activities (McLellan et al. 2014; Toth and Szigeti 2016; Bilgili et al. 2019; Yilanci and Pata 2020a). According to the Global Footprint Network GFN (2022), the trend of EF has been steadily rising at ~2.1 percent per year since 1961; on the other hand, BIO has been growing at an average of 0.5 percent per year.

The EF began to surpass the BIO in the 1970s; in other words, humanity's demand for natural resources has exceeded the planet's BIO. Today, humans employ the equivalent of 1.75 planets to supply the resources and absorb the generated waste. Therefore, it can be said that current human debt resources can regenerate in one year and eight months. It also demonstrates that more than 80 percent of the world's population lives in areas exposed to ecological deficits and utilizes more resources than their environment provides. The primary reason for the ecological deficit is CO_2 emissions because the human demand for energy is driven chiefly by non-renewable energy resources. Another reason for the ecological deficit beginning in the 1970s is globalization, which increased global trade and foreign direct investment and transformed the global consumption pattern, leading to excessive demand for natural resources around the world. These economic transformations have caused the effects of human activities to become more visible because provoking an upsurge in polluting waste in the environment has become a matter of unprecedented scale along with increasing destruction and overexploitation of natural resources (Panayotou 1993; Figge et al. 2017; Ahmad et al. 2020; and Tillaguango et al. 2021).

The sensitivity to the environment and the implementation of concrete steps for tackling environmental degradation have varied across countries, even though environmental degradation is an accurate and global fate. While intergovernmental organizations and international environmental agreements have promoted cooperative actions for nations, the effectiveness, willingness, and concentration of pro-environmental policies have not reached a consensus worldwide. Within this context, it can be claimed that the European Union's (EU) countries have been in the leading position regarding environmental regulations. The EU's environmental policy is extensively accepted as a success story 50 years after appropriating the first part of its environmental regulations (Lenschow and Sprungk 2010; Deters 2019). On the other hand, environmental degradation is still an outstanding issue in the region, although various ecological policies have been resolutely implemented. Ironically, researchers also ignore these countries, although they are among the few countries in the field of environmental progress.

According to the report of European Sustainable Development (2021), although it has legislative and policy tools in place or in preparation for addressing most SDG issues, it remains unclear how the EU plans to achieve the SDGs. The European Commission appears to have significant leadership over SDGs, and the European Green Agreement is the cornerstone of SDG enforcement in Europe. Nevertheless, this agreement directly contributes to only 12 of the 17 SDGs. The Green Deal does not fully represent many social dimensions of the SDGs. Therefore, these experiences obtained by EU countries, each with a similar level of development and common energy and environmental policies, can provide essential ideas for ensuring environmental quality (Esen et al. 2021). The EU-15 countries with similar development levels and policy structures are considered to obtain a homogeneous country group, as in Aydin et al. (2022)'s study. Figure 1 indicates the trends of the BIO and EF in the EU-15 countries over the period 1961–2018.

All graphs demonstrate that EF is higher than BIO, except in Finland and Sweden. In these countries, EF exceeds BIO (EF > BIO), which induces an Ecological Deficit (ED). Moreover, for Finland and Sweden, BIO is greater than EF (BIO > EF), therefore Ecological Reserve (ER) occurs in these countries. The reason why Finland and Sweden are different from other European countries can be explained by the fact that these Nordic countries have notably the same institutional, ideological, and political characteristics, as stated in Tunkrova (2008).

Based on all this preliminary information, we aim to reveal whether environmental policies have a permanent or temporary effect because the ecological balance in the region continues to deteriorate despite comprehensive environmental regulations. To this end, using unit root tests, we investigate the stationarity of the ecological balance for the EU-15 countries over the period 1961–2018. This study seeks to answer two research questions. One of the research questions is to determine the unit root behavior of the ecological balance series. The second is to observe whether this behavior is affected by decomposing the ecological balance series into different frequencies by employing wavelet transformations.

This study is thought to contribute to the literature in several ways. Firstly, this study applies a new time series analysis by considering different time scales, unlike previous studies. Secondly, it considers the EU countries as a group of developed countries which have an important role in sustainable environmental policies worldwide. Finally, it uses a wide time range, considering the 1961–2018 period. The rest of the study is organized as follows. Section 2 reviews the literature and Section 3 provides information on the data and methodology. Sections 4 and 5 present the empirical findings and a discussion. Section 6 concludes the study and provides policy recommendations.

Literature Review

The stochastic properties of variables have been one of the leading research topics for checking various theories or determining policy implementations regarding variables. Testing the environmental indicators' stochastic properties has attracted enormous attention for several reasons. These studies can be classified into two groups, stationarity and convergence. Essentially, stationarity is closely linked to the

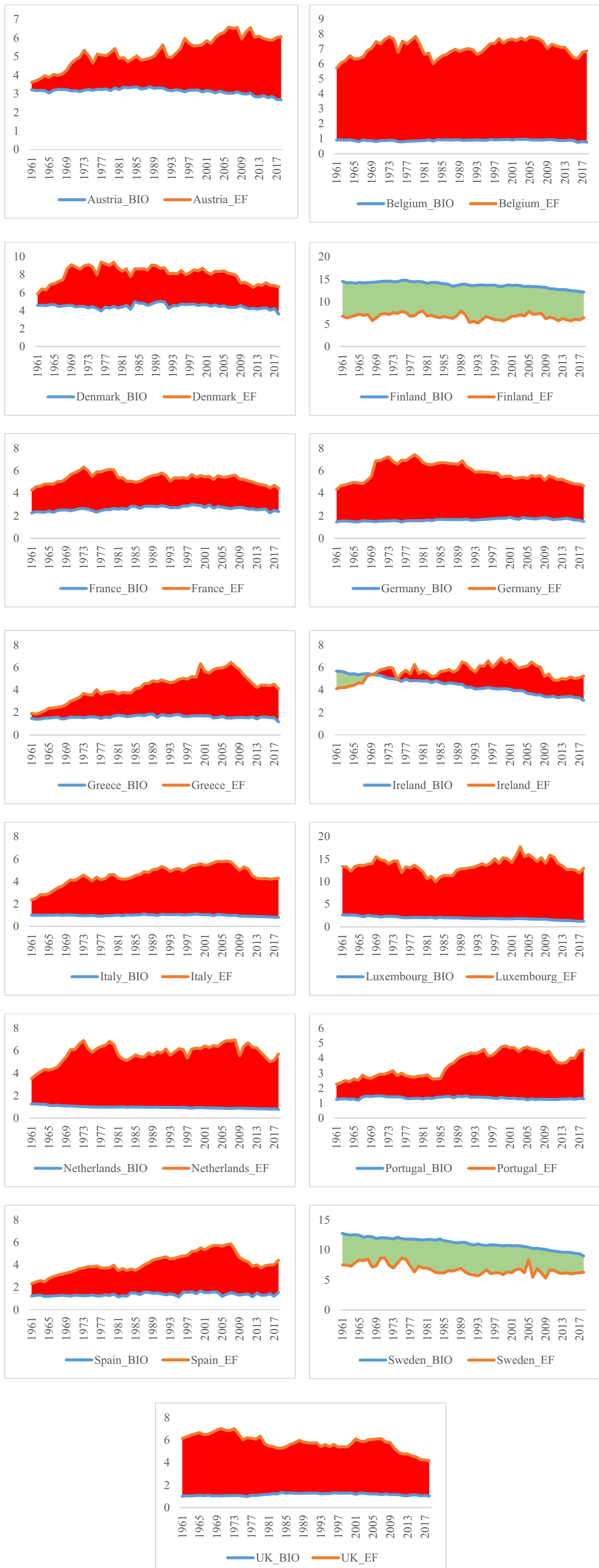

Fig. 1 Time trends of Biocapacity and Ecological Footprint in the EU-15 Countries. Source: Own graph. Notes: BIO Biocapacity, EF Ecological Footprint; Red and green areas denote ecological deficit and ecological reserve, respectively

concept of convergence (Christidou et al. 2013). For example, suppose that an environmental indicator is stationary. In that case, any shocks caused by the energy management policies induce the environmental indicator to transitory depart from its long-run trend path; that is, the effects of the shocks on the environmental indicator will be temporary. The stationarity of the environmental indicators shows that these indicators have a constant mean and variance over time, which exhibit a mean-reverting behavior; in other words, the mean and variance of a stationary variable exhibit persistent behavior. Although the power of the energy-environmental policies cannot create a power deviating a stationary series from its long-run trend, the future situations of the environmental indicators can be forecasted as they follow a trend path. On the other hand, if the environmental indicator contains a unit root that is not stationary, the energy and environmental policies will generate a power persistently deviating the environmental indicator from its long-run trend path. The policies perpetually impact the indicators, and the government can adopt a necessary target through environmental and sustainability objectives (McKitrick 2007).

Another investigation of the environmental indicators' stochastic properties is conducted by considering the ratio of the environmental degradation indicator of a country to the average indicator for the considered sample. If this ratio contains a unit root, any implication for convergence becomes nonbinding (Gil-Alana and Solarin 2018; Ozcan et al. 2021). On the other hand, if the ratio is stationary, the stochastic convergence for the considered country cannot be rejected. The validity of the convergence hypothesis implies that; the countries are generating a sample with similar environmental degradation, and a common strategy can be implemented across the sample (Barassi et al. 2011). Additionally, the validity of the convergence shows that the distinction in countries' ecological quality will diminish over time (Yilanci and Pata 2020a).

Various researchers have employed different environmental degradation indicators to investigate the stochastic properties of environmental indicators and the convergence hypothesis across the countries. CO_2 emissions have been the most dominant indicator in the literature because CO_2 emissions drive climate change and global warming. Within this scope, plenty of the literature studies have employed CO_2 emissions to test the convergence hypothesis across the countries. As for understanding the findings of the studies, it can be viewed that the current studies reflect an inharmony argument about CO_2 emissions convergence. For example, some researchers provided evidence supporting the validity of CO_2 emission convergence (Brock and Taylor 2010; Herrerias 2013; Li and Lin 2013; Sun et al. 2016). In contrast, various studies have also confirmed the existence of CO_2 emissions divergence (Aldy 2007; Barassi et al.

2008; Nourry 2009; Kounetas 2018). Some studies have also found that CO_2 emissions have converged in some countries (Li et al. 2014; Tiwari et al. 2016; Burnett 2016; Ahmed et al. 2017; Apergis and Payne 2017; Lin et al. 2018). Recently, the EF has been one of the most employed environmental indicators because it is a more comprehensive environmental variable involving air, sea, and soil pollution. The findings of studies that employ EF are contrevelsial. For example, some studies affirm that environmental policies will have a persistent impact on EF (Ulucak and Lin 2017; Solarin and Bell 2018; Yilanci et al. 2022b), whereas others confirm the opposite conclusion (Ozcan et al. 2019; Yilanci et al. 2019; Yilanci et al. 2022c). Besides, the testing of EF convergence has received enormous attention in the literature. The validity of the convergence is approved by Ulucak and Apergis (2018), Bilgili and Ulucak (2018b), Yilanci and Pata (2020a), Yilanci et al. (2022a) and Çelik et al. (2022). However, the different convergence clubs or the divergence of the EF have been claimed by Solarin et al. (2019), Bilgili et al. (2019), Haider and Akram (2019), Solarin et al. (2021), Tillaguango et al. (2021), Işık et al. (2021) and Erdogan and Okumus (2021).

There are a limited number of studies on the ecological balance. Yilanci and Pata (2020b) conducted the first study to investigate whether shocks have a permanent or temporary impact on the ecological balance in the G7 and E7 countries. The period of 1961–2016 is considered, and the Lagrange Multiplier (LM) unit root test, LM unit root test allowing for structural breaks, and Fourier LM unit root test are applied to examine the significance of policies considering EF and biocapacity. The evidence from unit root tests indicates that the ecological balance does not contain a unit root in Germany, Italy, Japan, Turkey, Mexico, Indonesia, India, and the US. By contrast, the ecological balance in the remaining countries is not stationary. The overall results also imply that shocks to ecological balance in G7 countries are more permanent than those in E7 countries. Hence, environmental protection policies can provide more powerful outcomes in G7 countries than E7 countries. Pata and Yilanci (2021) analyzed the stochastic properties of the ecological balance in the G10 and the N11 countries to determine the persistence of shocks to the ecological balance from 1961 to 2016. They employed various unit root techniques involving conventional unit root tests, a quantile unit root test, and a recently introduced quantile unit root test accounting for smooth breaks. Their empirical evidence shows that ecological balance permanently responds to shocks in Nigeria, the USA, the United Kingdom, Japan, Italy, and the Philippines. In contrast, the ecological balance is stationary in the remaining countries. The findings imply that any shocks to the ecological balance result in a more persistent impact in G10 countries than in N11 countries. Ozcan et al. (2021) examined whether the per capita ecological balance is sustainable in OECD countries. A quantile unit root test regarding nonlinearities and asymmetries is applied to data covering the period of 1961–2016. The results suggest that the sustainability of the ecological balance holds only for Mexico, Germany, and Israel, while the unsustainability of the ecological balance is valid for the remaining 24 countries.

Regarding the literature review, various studies have tested the stochastic properties of environmental indicators to determine whether the shocks of environmental management policies have a permanent or temporary impact. The pioneer studies employed CO_2 emissions, and the recent studies have considered the ecological footprint because of its comprehensive explanation power in environmental degradation. However, the ecological balance has received attention recently because it exhibits the limit and sustainability of natural resources. Therefore, we adopt the ecological balance as the environmental degradation indicator. Within this scope, EU-15 countries are the sample considered in this study. The European Union countries have been in the leading position in the application of environmental regulations. The EU's environmental policy has been accepted as a sensation report for the last 50 years. However, these countries are still exposed to the ecological deficit. More comprehensive knowledge is needed to implement robust environmental policies for EU countries. For this reason, to the best of our knowledge, for the first time in the study, we test the stochastic properties of the ecological balance for the EU-15 countries using the Fourier augmented Dickey–Fuller (FADF) and augmented Dickey–Fuller (ADF) unit root tests on both the original and the decomposed series to examine the impact of shocks at different frequencies.

Data and Methodology

Data

To compute the ecological balance, we use the following formula: $EB_{i,t} = BIO_{i,t} - EF_{i,t}$. EB is the ecological balance, and BIO and EF show the biocapacity and ecological footprint, respectively. The subscript i indicates the country index, while t is the time. The case $BIO_{i,t} > EF_{i,t}$ shows the ecological surplus, while the $EF_{i,t} > BIO_{i,t}$ indicates the ecological deficit.

We gathered both BIO and EF series for EU-15 countries between 1961 and 2018 from the Global Footprint Network website. We first present the descriptive statistics of the EB series of the EU-15 countries in Table 1.

As shown in Table 1, only the mean values of EB for Finland and Sweden are positive, while the remaining is negative; that is, there is an ecological reserve only in Finland and Sweden on average. Besides, the maximum

Table 1 Descriptive statistics

Countries	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	Jarque–Bera	Probability
Austria	−2.121	−1.974	−0.401	−3.554	0.882	0.037	2.020	2.333	0.311
Belgium	−6.171	−6.171	−4.811	−6.991	0.525	0.383	2.366	2.394	0.302
Denmark	−3.565	−3.742	−1.261	−5.427	0.850	0.487	3.034	2.295	0.317
Finland	7.065	7.120	8.486	5.599	0.653	−0.155	2.754	0.378	0.828
France	−2.687	−2.580	−2.027	−3.688	0.421	−0.785	2.859	6.003**	0.050
Germany	−4.241	−4.009	−2.881	−5.865	0.858	−0.314	1.664	5.266***	0.072
Greece	−2.652	−2.829	−0.446	−4.954	1.154	0.077	2.406	0.911	0.634
Ireland	−1.157	−1.437	1.557	−2.832	1.141	0.766	2.816	5.748***	0.056
Italy	−3.559	−3.597	−1.358	−4.821	0.828	0.811	3.355	6.665**	0.036
Luxembourg	−11.698	−11.625	−8.101	−15.945	1.583	−0.037	2.984	0.014	0.993
Netherlands	−4.816	−4.956	−2.260	−6.087	0.877	1.040	3.733	11.764*	0.003
Portugal	−2.260	−2.408	−1.019	−3.522	0.849	−0.015	1.361	6.492**	0.039
Spain	−2.769	−2.597	−1.089	−4.458	0.830	−0.184	2.560	0.795	0.672
Sweden	4.303	4.470	5.643	2.069	0.773	−0.579	2.741	3.406	0.182
UK	−4.635	−4.579	−3.152	−5.993	0.730	0.057	2.378	0.968	0.616

*, **, and *** indicate statistical significance at the 1%, 5%, and 10% levels, respectively

values show that we cannot observe any positive EB except for Finland, Ireland, and Sweden. Therefore, for the remaining countries, we observe an ecological deficit for all years in the analysis period. The probability values of the Jarque–Bera chi-square test statistics show that most of the series are normally distributed.

Methodology

Fourier augmented Dickey–Fuller unit root test

To consider structural breaks in the data generation process, we employ the FADF unit root test introduced by Enders and Lee (2012). Enders and Lee (2012) suggested augmenting the test equation of the ADF unit root test with a Fourier function to allow multiple breaks. We estimate the following equation to apply the FADF unit root test:

$$\Delta EB_t = \alpha_0 + \alpha_1 EB_{t-1} + \alpha_2 \sin\left(\frac{2\pi kt}{T}\right) + \alpha_3 \cos\left(\frac{2\pi kt}{T}\right) + \sum_{j=1}^{p} \theta_i \Delta EB_{t-j} + u_t \quad (1)$$

where EB_t represents the ecological balance. sin and cos are the trigonometric terms that comprise the Fourier function and employed for allowing smooth changes. t and T show a trend term and number of observations, respectively. p is the optimal lag length. We use the t-*sig* approach to determine the p. We determine the value of k, which indicates a particular frequency, by estimating the Eq. (1) for all values of $k \in [0.1,\ 0.2, 0.3,\ \ldots, 4.9,\ 5]$ and choosing the k that produces the minimum sum of the squared residuals.

After estimating Eq. (1) with the optimal p and k, we test the null hypothesis of non-significance of the trigonometric terms, $H_0 : \alpha_2 = \alpha_3 = 0$, with the traditional F test statistic, which is distributed as non-standard. If we reject the null, we can test the null of a unit root, $H_0 : \alpha_1 = 0$, by employing the FADF test; otherwise we should use the ADF unit root test. The critical values for the F test and FADF test can be obtained from Enders and Lee (2012).

Wavelet decomposition

One can test whether the effect of policy shocks on ecological balance is transitory or permanent in the considered period by testing the stationarity of the EB series. However, shocks can only be effective in the short- or long-run. To distinguish the effects of shocks over different time scales, we employ the discrete wavelet transform (DWT) method to decompose the EB series into different frequencies. The orthogonal approximation of DWT is expressed as follows:

$$EB(t) = \sum_k s_{j,k}\phi_{j,k}(t) + \sum_k d_{j,k}\psi_{j,k}(t) + \sum_k d_{j-1,k}\psi_{j-1,k}(t) + \ldots + \sum_k d_{1,k}\psi_{1,k}(t) \quad (2)$$

where $\phi_{j,k}$ and $\Psi_{j,k}$ represent the scaling and wavelet functions, respectively. While the former captures long-run behavior, the latter captures short-run behavior. The smoothing and detail coefficients, represented by $s_{j,k}$ and $d_{j,k}$, respectively, provide information about the trend and short-term components.

In this study, we employ the maximal overlap discrete wavelet transform (MODWT) since DWT restricts the use of statistical analysis when the number of wavelets and

Table 2 Unit root test results for original series

Country	F test	Optimal frequency	FADF	ADF
Austria	3.517	0.4	–	−1.494 (0) [0.53]
Belgium	5.941	2.1	–	−3.418 (10) [0.015]**
Denmark	3.731	0.8	–	−1.369 (8) [0.590]
Finland	4.158	0.1	–	−1.339 (4) [0.605]
France	3.609	2	–	−2.059 (6) [0.262]
Germany	3.645	0.9	–	−1.647 (6) [0.452]
Greece	4.088	3.7	–	−2.02 (3) [0.278]
Ireland	2.627	0.2	–	−2.433 (1) [0.138]
Italy	2.874	3.5	–	−2.674 (3) [0.085]***
Luxembourg	8.030**	1.3	−3.726 (2)**	
Netherlands	2.609	3.5	–	−3.336 (7) [0.018]**
Portugal	3.584	4	–	−1.083 (0) [0.717]
Spain	3.663	3.8	–	−2.464 (3) [0.130]
Sweden	6.954***	0.4	−3.401 (4)	
UK	3.984	1.8	–	−0.379 (0) [0.905]

The critical values for the F test at the 5% and 10% levels are 7.58 and 6.35, respectively. The numbers in parentheses show the optimal lag lengths, whereas the numbers in brackets represent the *p*-values

** and *** indicate significance at 5% and 10% levels, respectively

scaling coefficients decreases. We can present the wavelet ($w_{j,t}$) and scaling ($v_{j,t}$) coefficients of the MODWT as follows:

$$w_{j,t} = \sum_{l=0}^{L-1} \frac{\psi_{j,l}}{2^{j/2}} EB_{t-l \bmod N} \tag{3}$$

$$v_{j,t} = \sum_{l=0}^{L-1} \frac{\phi_{j,l}}{2^{j/2}} EB_{t-l \bmod N} \tag{4}$$

Following the suggestion of Gençay et al. (2001), we use Daubechies Least Asymmetric wavelet filter with a wavelet length of eight (LA8). To determine the largest scale, the following formula was used:

$$J = \log_2(T) \tag{5}$$

where T shows the number of observations. Consequently, in this study, we apply the FADF and ADF unit root tests to both the original and decomposed series to reveal the effects of policy shocks at different frequencies.

Empirical Findings

To test the persistency of the shocks on the EB, we first consider the original series. Table 2 presents the results of FADF and ADF unit root tests applied to the original series.

The findings in Table 2 demonstrate that the Fourier function is significant only for Luxembourg and Sweden. We find optimal frequencies as fractional for these countries, showing that structural breaks are permanent in the EB series for these countries. The FADF unit root test results show that we can reject the null hypothesis of a unit root for the EB series of Luxembourg. Besides, the results of the ADF unit root tests show that the EB series are stationary in Belgium, Italy, and the Netherlands. The remaining series are not stationary, which provides evidence that the effect of shocks is permanent for the remaining countries during the analysis period. However, these results do not provide any information about the periods in which the shocks are permanent. To reveal the effect of shock at different frequencies, we first use Eq. (5) and find the maximum scale as six, then decompose the series into different scales. We obtain six components from the original series: d1, d2, d3, d4, d5, and s5. While d1 shows the lowest time scale, d5 shows the highest time scale, and s5 indicates the trend of the original series. In this study, we follow the suggestions of Andersson (2016) and Ha et al. (2018) and combine the components to obtain three scales: short-run (d1 + d2), medium-run (d3), and long-run(d4 + d5). While the short-run indicates a time period that is less than eight years, the medium-run captures the dynamics in 8 to 16 years, and the long-run expresses a time period that is over 16 years. We test the persistence of the shock on the EB in the short-run and present the test results in Table 3.

The F statistics in Table 3 indicate that the Fourier functions are not statistically significant. Therefore, we should apply the ADF unit root test instead of the FADF unit root test. The results of the ADF unit root test reveal that all series are stationary in the short-run, which proves that the shocks will not be permanent in the short-run. In other words, policies on the EB would not be effective in the short-run. Next, we test the stationarity of the EB series in the medium-run. The findings are tabulated in Table 4.

Table 3 Unit root test results for short-run components

Country	F test	Optimal frequency	FADF	ADF
Austria	1.432	5	–	−6.715 (9) [0.000]*
Belgium	0.911	4.9	–	−5.142 (10) [0.000]*
Denmark	0.121	0.1	–	−5.489 (10) [0.000]*
Finland	0.425	5	–	−4.977 (10) [0.000]*
France	1.023	4.1	–	−5.579 (10) [0.000]*
Germany	0.024	4.9	–	−7.694 (8) [0.000]*
Greece	0.609	5	–	−5.408 (9) [0.000]*
Ireland	0.052	5	–	−5.771 (10) [0.000]*
Italy	0.350	3.9	–	−5.502 (10) [0.000]*
Luxembourg	2.397	5	–	−5.202 (10) [0.000]*
Netherlands	0.103	3.9	–	−7.671 (10) [0.000]*
Portugal	1.689	4.1	–	−5.353 (10) [0.000]*
Spain	5.695	4.2	–	−5.742 (10) [0.000]*
Sweden	0.305	5	–	−5.659 (10) [0.000]*
UK	0.547	4.2	–	−7.349 (7) [0.000]*

The critical value for the F-test at the 10% level is 6.35. The numbers in parentheses show the optimal lag lengths, whereas the numbers in brackets represent the *p*-values

*Shows the significance at 1% level

Table 4 Unit root test results for medium-run components

Country	F test	Optimal frequency	FADF	ADF
Austria	3.514	5	–	−3.253 (10) [0.023]**
Belgium	5.973	5	–	−3.286 (8) [0.021]**
Denmark	8.313**	4.6	−1.805 (10)	–
Finland	2.201	4.1	–	−7.755 (7) [0.000]*
France	2.417	4	–	−3.275 (8) [0.022]**
Germany	6.500***	3.4	−5.408 (9)*	–
Greece	5.148	3.9	–	−1.683 (10) [0.433]
Ireland	4.295	3.8	–	−1.626 (10) [0.462]
Italy	11.701*	3.6	−1.356 (10)	–
Luxembourg	16.581*	5	−1.860 (10)	–
Netherlands	21.626*	3.3	−2.850 (10)***	–
Portugal	14.112*	4.1	−3.772 (9)*	–
Spain	22.245*	4.3	−0.56 (10)	–
Sweden	4.215	4.4	–	−5.566 (7) [0.000]*
UK	10.167**	3.9	−7.049 (7)*	–

The critical values for the F test at the 10%, 5%, and 1% levels are 6.35, 7.58, and 10.35, respectively. The numbers in parentheses show the optimal lag lengths, whereas the numbers in brackets represent the *p*-values

*, **, and *** show the significance at the 1%, 5%, and 10% levels, respectively

The findings in Table 4 show that the Fourier function is significant for the EB series of Denmark, Germany, Italy, Luxembourg, the Netherlands, Portugal, Spain, and the UK. The high values of the optimal frequencies show that the EB series of the EU countries are under the influence of numerous structural changes. Most of the frequencies are found to be fractional, which shows that the changes are permanent for these EB series; besides, we found the optimal frequency as an integer for Luxembourg's EB series, which shows that the structural changes are temporary. The results of the FADF unit root test show that the EB series of Germany, the Netherlands, Portugal, and the UK are stationary, while the findings of the ADF unit root test indicate that the EB series of Austria, Belgium, Finland, France, and Sweden are stationary. In other words, the policies implemented for the EB series of these countries will not be effective in the medium run. The EB series of the remaining countries are found to have a unit root, which proves that the implemented

Table 5 Unit root test results for long-run components

Country	F test	Optimal frequency	FADF	ADF
Austria	7.052***	1.8	−4.136 (10)*	
Belgium	15.681*	2	2.579 (10)	
Denmark	14.112*	2.1	−0.958 (10)	
Finland	2.286	1.9		−2.564 (10) [0.108]
France	22.256*	2	−5.135 (10)*	
Germany	12.289*	0.8	−5.036 (10)*	
Greece	1.964	2		−5.084 (10) [0.000] *
Ireland	9.443**	2.1	−0.292 (10)	
Italy	21.761*	1.9	−7.185 (10)*	
Luxembourg	15.048*	1.8	−4.575 (10)*	
Netherlands	12.631*	1.9	−3.566 (10)**	
Portugal	12.319*	1.8	−4.557 (10)*	
Spain	15.998*	2	−6.604 (10)*	
Sweden	18.503*	1.2	0.109 (9)	
UK	15.141*	1.7	−7.596 (10)*	

The critical values for the F test at the 10%, 5%, and 1% levels are 6.35, 7.58, and 10.35, respectively. The numbers in parentheses show the optimal lag lengths, whereas the numbers in brackets represent the *p*-values

*, **, and *** show the significance at the 1%, 5%, and 10%, levels, respectively

Table 6 Summary of the results

Country	Original series	Short-run components	Medium-run components	Long-run components
Austria	$N-S$	S	S	S
Belgium	S	S	S	$N-S$
Denmark	$N-S$	S	$N-S$	$N-S$
Finland	$N-S$	S	S	$N-S$
France	$N-S$	S	S	S
Germany	$N-S$	S	S	S
Greece	$N-S$	S	$N-S$	S
Ireland	$N-S$	S	$N-S$	$N-S$
Italy	S	S	$N-S$	S
Luxembourg	S	S	$N-S$	S
Netherlands	S	S	S	S
Portugal	$N-S$	S	S	S
Spain	$N-S$	S	$N-S$	S
Sweden	$N-S$	S	S	$N-S$
UK	$N-S$	S	S	S

S Stationary, $N-S$ Non-stationary

policies will be effective in these countries. Next, we provide the results of unit root tests for the long-run in Table 5.

The results in Table 5 reveal that we cannot reject the null hypothesis of non-significance of the Fourier function only for the EB series of Finland and Greece. The results of the FADF and ADF unit root tests show that we cannot reject the null of a unit root for Belgium, Denmark, Finland, Ireland, and Sweden. Thus, we can conclude that environmental policies are effective in the long term in these countries.

Overall, the findings present that Fourier functions are found to be significant for more EB series as the period length increases; that is, structural changes are effective, especially in the medium and long-run. We found 4 of 14 series as stationary when we consider the original series; however, the components of the series show that all the series are stationary in the short-run, nine of them are stationary in the medium-run, and ten of them are stationary in the long-run. In other words, when the implemented policies are not effective in the short-run, are effective only in five countries in the long-run. These findings show the importance of considering different frequencies when testing the efficiency of the implemented policies. A summary of these findings is presented in Table 6.

Discussion

We applied the FADF and the ADF unit root test by considering the original and decomposed series. Regarding the original series, the test results prove that all the EBs of the considered countries, except Belgium, Italy, Luxembourg, and the Netherlands, are stationary. In other words, the environmental policies are permanently effective in eleven of 15 countries. The governments of Belgium, Italy, Luxembourg, and the Netherlands cannot implement effective environmental policies because the ecological balance of these countries will return to its long-term trend; in contrast, these countries can forecast the future values of the ecological balance. The empirical findings concerning the difference in stochastic behavior ecological balance of the considered total sample are supported by Yilanci and Pata (2020b), Pata and Yilanci (2021), and Ozcan et al. (2021). For example, Ozcan et al. (2021) note that three of 27 OECD countries have a sustainable ecological balance, whereas the remaining countries have an unsustainable ecological balance. Moreover, Pata and Yilanci (2021) underline the different evidence about the stochastic behavior of the ecological balance of G10 and N11 countries; the ecological balance contains a unit root for five out of 21 countries. Yilanci and Pata (2020b) also support the evidence regarding the different stochastic behavior ecological balance of G7 and E7 countries. Along with these studies, this study confirms that environmental policies should be specialized and implemented in terms of the stochastic patterns of the environmental indicators. As for the decomposed series, the results of each country's series vary in the short-term, medium-term, and long-term. The EB is found to be stationary for all countries in the short-term, implying that the pro-environmental policies will not have continuous power over the EB. Regarding the medium-term, six countries of the remaining whole countries will implement pro-environmental policies because their series contain a unit root. Finally, five countries of the EB are not stationary in the long-term. The various implications of viewing different frequencies highlight the importance of the time interval when determining the efficiency of the implemented environmental policies. Thus, as a result of the findings, considering different frequencies in investigating the stochastic properties of the environmental degradation indicators is recommended.

Conclusion and Policy Recommendations

The world has encountered various threats, including floods, droughts, melting glaciers, and deforestation. The list of environmental degradation can be sorted by length, but global warming and climate change are the primary drivers of global environmental degradation. Global environmental challenges have pushed scientists to inquire into the drivers of climate change and promote policies to tackle and prevent environmental degradation. The investigation of the stochastic properties of environmental indicators appears to be one of the most received attention in the literature for several reasons. For example, if an environmental degradation indicator contains a unit root, that is, it is not stationary, pro-environmental policies will promote a persistent impact on the environmental degradation indicator. With the help of this knowledge, the government can determine targets and objectives in terms of sustainability.

Furthermore, environmental indicators are vital for policymakers to determine and implement effective and accurate ecological policies. CO_2 emissions have been the most commonly employed environmental indicators in the literature, while it represents only air pollution. Therefore, EF has begun to be applied in environmental studies because it is a more comprehensive environmental indicator that considers air, soil, and water pollution. However, the use of EF in this study only provides information about the pressure caused by human activities in the environment. EB is a prominent environmental indicator because it is obtained from the difference between EF and BIO, which provides knowledge regarding the limits and sustainability of the environment. Within this objective, this study analyses the stochastic properties of the ecological balance of EU-15 countries over the period 1961–2018. For this purpose, we perform the FADF and ADF unit root tests on both the original and the decomposed series to reveal the effect of shocks at different frequencies. The results of the analysis present that the shocks of the environmental management policies induce a permanent effect on 10 of 15 considered countries. Additionally, if the ecological balance is decomposed into short-, medium, and long-term time scales, the implication of the analysis varies at different frequencies. The result of the test performed in the short-run components displays that all series do not contain a unit root, and all policy shocks have no effect in the short-run. However, the shocks of pro-environmental policies have a persistent effect on the six series in the medium and the five series in the long-run. These results imply that the government's environmental management will not generate the solution in the short-run, but the effects of these policies will become effective as time progresses. For example, improving production techniques with energy efficiency, decreasing fossil fuel dependence, increasing the share of renewable energy sources in total energy, and promoting advanced agriculture, live stood, and fishing techniques which are policies to provide outcomes in the long-term, are some prominent policies.

As for five of the 15 considered countries whose EB is stationary, it is recommended that unnecessary targets and policies should not be implemented to regulate the EB because the interventions aiming to improve the environmental quality do not provide persistent solutions. The direct measure can not deviate the EB to a long-term path; hence internal dynamics and indirect targets should be considered. Technological improvements and transforming the recent energy source to renewable energy sources are recommended policies for five of the 15 countries considered. Increasing renewable energy sources such as solar, wind, and biomass will be vital in improving environmental quality. The government should subsidize the private sector operating and investing in renewable energy within this scope. Moreover, the tax-exempt these firms' profit may be other significant recommended policies. Improving technological structure also provides an essential outcome because of reducing fossil fuels. As for the ten out of 15 countries whose EB is nonstationary, it is recommended that specific targets and measures can be implemented because the shocks from these policies will shift the EB from its long-term trend path. For example, some recommended policies for considered countries are imposing carbon taxes and encouraging the usage of low-carbon vehicles, promoting recycling goods, and promoting environmentally friendly agriculture and fishing techniques.

With reference to the specific policy recommendation for each country, the EB series of Denmark and Ireland persistently deviates from its long-run trend path in the original and all different frequencies except the short-run. As a result of the finding, the environmental quality of Denmark and Ireland can be enhanced with the help of various pro-environmental policies. Shrinking fossil fuels, diminishing energy intensity encouraging renewable energy, and designing green and environmentally friendly technologies have been recommended for Ireland and Denmark to improve their EB. On the other hand, the stochastic properties of the EB of Austria, France, Germany, Netherlands, Portugal, and the UK are stationary at original and different frequencies. In another explanation, the EB temporarily varies from the mean value in six countries. The policies implemented by the six countries will not permanently influence the path of the EB. Still, the government can forecast the future movement of the EB by observing past behavior. Moreover, future studies may investigate the sustainability of EB for other EU countries. Especially considering the pre- and post-EU periods, the effect of the EU process on environmental progress can be examined.

Data Availability

Global Footprint Network GFN (2022) https://data.footprintnetwork.org/#/.

Author Contributions VY: Methodology, Writing – original draft, Writing – review & editing. ZA: Writing – original draft, Writing – review & editing. OÇ: Writing – original draft, Writing – review & editing. BB: Writing – original draft, Writing – review & editing. All authors reviewed the manuscript.

Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

References

Ahmad M, Khattak SI, Khan A, Rahman ZU (2020) Innovation, foreign direct investment (FDI), and the energy–pollution–growth nexus in OECD region: a simultaneous equation modeling approach. Environ Ecol Stat 27(2):203–232. https://doi.org/10.1007/s10651-020-00442-8

Ahmed M, Khan AM, Bibi S, Zakaria M (2017) Convergence of per capita CO2 emissions across the globe: insights via wavelet analysis. Renew Sustain Energy Rev 75:86–97. https://doi.org/10.1016/j.rser.2016.10.053

Aldy JE (2007) Divergence in state-level per capita carbon dioxide emissions. Land Econ 83(3):353–369. https://doi.org/10.3368/le.83.3.353

Andersson FN (2016) Identifying and modelling cycles and long waves in economic time series. In Ljungberg J (ed), Structural analysis and the process of economic development (pp. 54–75). Routledge, London

Apergis N, Payne JE (2017) Per capita carbon dioxide emissions across US states by sector and fossil fuel source: evidence from club convergence tests. Energy Econ 63:365–372. https://doi.org/10.1016/j.eneco.2016.11.027

Aydin C, Esen O, Aydin R (2022) Analyzing the economic development-driven ecological deficit in the EU-15 countries: new evidence from PSTR approach. Environ Sci Pollut Res 29(10):15188–15204. https://doi.org/10.1007/s11356-021-16773-3

Barassi MR, Cole MA, Elliott RJ (2008) Stochastic divergence or convergence of per capita carbon dioxide emissions: re-examining the evidence. Environ Resour Econ 40(1):121–137. https://doi.org/10.1007/s10640-007-9144-1

Barassi MR, Cole MA, Elliott RJ (2011) The stochastic convergence of CO2 emissions: a long memory approach. Environ Resour Econ 49(3):367–385. https://doi.org/10.1007/s10640-010-9437-7

Bartelmus P (2008) Quantitative eco-nomics: how sustainable are our economies? Dordrecht: Springer Netherlands

Bastianoni S, Niccolucci V, Pulselli RM, Marchettini N (2012) Indicator and indicandum: "Sustainable way" vs "prevailing conditions" in the ecological footprint. Ecol Indic 16:47–50. https://doi.org/10.1016/j.ecolind.2011.10.001

Bilgili F, Ulucak R (2018a) The nexus between biomass–footprint and sustainable development. Ref Modul Mater Sci Mater Eng 699:10600–10609. https://doi.org/10.1016/B978-0-12-803581-8.10600-9

Bilgili F, Ulucak R (2018b) Is there deterministic, stochastic, and/or club convergence in ecological footprint indicator among G20 countries. Environ Sci Pollut Res 25(35):35404–35419. https://doi.org/10.1007/s11356-018-3457-1

Bilgili F, Ulucak R, Koçak E (2019) Implications of environmental convergence: continental evidence based on ecological footprint. In Shahbaz M, Balsalobre D (eds), Energy and environmental strategies in the era of globalization (pp. 133−165). Springer, Cham

Borucke M, Moore D, Cranston G, Gracey K, Iha K, Larson J, Lazarus E, Morales JC, Wackernagel M, Galli A (2013) Accounting for demand and supply of the biosphere's regenerative capacity: the national footprint accounts' underlying methodology and framework. Ecol Indic 24:518–533. https://doi.org/10.1016/j.ecolind.2012.08.005

Brock WA, Taylor MS (2010) The green Solow model. J Econ Growth 15(2):127–153. https://doi.org/10.1007/s10887-010-9051-0

Burnett JW (2016) Club convergence and clustering of US energy-related CO2 emissions. Resour Energy Econ 46:62–84. https://doi.org/10.1016/j.reseneeco.2016.09.001

Çelik O, Adali Z, Bari B (2022) Does ecological footprint in ECCAS and ECOWAS converge? Empirical evidence from a panel unit root test with sharp and smooth breaks. Environ Sci Pollut Res 1−13. https://doi.org/10.1007/s11356-022-23178-3

Charfeddine L, Mrabet Z (2017) The impact of economic development and social-political factors on ecological footprint: a panel data analysis for 15 MENA countries. Renew Sustain Energy Rev 76:138–154. https://doi.org/10.1016/j.rser.2017.03.031

Christidou M, Panagiotidis T, Sharma A (2013) On the stationarity of per capita carbon dioxide emissions over a century. Econ Model 33:918–925. https://doi.org/10.1016/j.econmod.2013.05.024

Deters H (2019) European environmental policy at 50: five decades of escaping decision traps. Environ Policy Gov 29(5):315–325. https://doi.org/10.1002/eet.1855

Enders W, Lee J (2012) The flexible Fourier form and Dickey–Fuller type unit root tests. Econ Lett 117(1):196–199. https://doi.org/10.1016/j.econlet.2012.04.081

Erdogan S, Okumus I (2021) Stochastic and club convergence of ecological footprint: an empirical analysis for different income group of countries. Ecol Indic 121:107123. https://doi.org/10.1016/j.ecolind.2020.107123

Esen O, Yildirim DC, Yildirim S (2021) Pollute less or tax more? Asymmetries in the EU environmental taxes–Ecological balance nexus. Environ Impact Assess Rev 91:106662. https://doi.org/10.1016/j.eiar.2021.106662

Europe Sustainable Development Report (2021) https://eu-dashboards.sdgindex.org/

Figge L, Oebels K, Offermans A (2017) The effects of globalization on ecological footprints: an empirical analysis. Environ Dev Sustain 19(3):863–876. https://doi.org/10.1007/s10668-016-9769-8

Galli A, Kitzes J, Niccolucci V, Wackernagel M, Wada Y, Marchettini N (2012) Assessing the global environmental consequences of economic growth through the ecological footprint: a focus on China and India. Ecol Indic 17:99–107. https://doi.org/10.1016/j.ecolind.2011.04.022

Gencay R, Selcuk F, Whitcher B (2001) Differentiating intraday seasonalities through wavelet multi-scaling. Phys A 289(3-4):543–556. https://doi.org/10.1016/S0378-4371(00)00463-5

Geng Y, Zhang L, Chen X, Xue B, Fujita T, Dong H (2014) Urban ecological footprint analysis: a comparative study between Shenyang in China and Kawasaki in Japan. J Clean Prod 75:130–142. https://doi.org/10.1016/j.jclepro.2014.03.082

Gil-Alana LA, Solarin SA (2018) Have US environmental policies been effective in the reduction of US emissions? A new approach using fractional integration. Atmos Pollut Res 9(1):53–60. https://doi.org/10.1016/j.apr.2017.06.008

Global Footprint Network (GFN) (2010). https://www.footprintnetwork.org/content/images/uploads/Ecological_Footprint_Atlas_2010.pdf

Global Footprint Network (GFN) (2022). https://data.footprintnetwork.org/?_ga=2.220268888.1349911081.1661096811-738472127.1647851111#/countryTrends?cn=5001&type=BCtot,EFCtot

Ha J, Tan PP, Goh KL (2018) Linear and nonlinear causal relationship between energy consumption and economic growth in China: new evidence based on wavelet analysis. PloS One 13(5):1–21. https://doi.org/10.1371/journal.pone.0197785

Haider S, Akram V (2019) Club convergence analysis of ecological and carbon footprint: evidence from a cross-country analysis. Carbon Manag 10(5):451–463. https://doi.org/10.1080/17583004.2019.1640135

He J, Wan Y, Feng L, Ai J, Wang Y (2016) An integrated data envelopment analysis and emergy-based ecological footprint methodology in evaluating sustainable development, a case study of Jiangsu Province, China. Ecol Indic 70:23–34. https://doi.org/10.1016/j.ecolind.2016.05.042

Herrerias MJ (2013) The environmental convergence hypothesis: carbon dioxide emissions according to the source of energy. Energy Policy 61:1140–1150. https://doi.org/10.1016/j.enpol.2013.06.120

Hopton ME, White D (2012) A simplified ecological footprint at a regional scale. J Environ Manag 111:279–286. https://doi.org/10.1016/j.jenvman.2011.07.005

Intergovernmental Panel on Climate Change (IPCC) (2018). Global warming of 1.5°C. https://www.ipcc.ch/site/assets/uploads/sites/2/2022/06/SR15_Full_Report_HR.pdf

Isik C, Ahmad M, Ongan S, Ozdemir D, Irfan M, Alvarad R (2021) Convergence analysis of the ecological footprint: theory and empirical evidence from the USMCA countries. Environ Sci Pollut Res 28(25):32648–32659. https://doi.org/10.1007/s11356-021-12993-9

Kounetas KE (2018) Energy consumption and CO2 emissions convergence in European Union member countries. A tonneau des Danaides? Energy Econ 69:111–127. https://doi.org/10.1016/j.eneco.2017.11.015

Lenschow A, Sprungk C (2010) The myth of a green Europe. JCMS J Common Mark Stud 48(1):133–154. https://doi.org/10.1111/j.1468-5965.2009.02045.x

Li XL, Tang DP, Chang T (2014) CO2 emissions converge in the 50 US states-sequential panel selection method. Econ Model 40:320–333. https://doi.org/10.1016/j.econmod.2014.04.003

Li X, Lin B (2013) Global convergence in per capita CO2 emissions. Renew Sustain Energy Rev 24:357–363. https://doi.org/10.1016/j.rser.2013.03.048

Lin J, Inglesi-Lotz R, Chang T (2018) Revisiting CO2 emissions convergence in G18 countries. Energy Sources Part B 13(5):269–280. https://doi.org/10.1080/15567249.2018.1460422

Mancini MS, Galli A, Coscieme L, Niccolucci V, Lin D, Pulselli FM, Bastianoni S, Marchettini N (2018) Exploring ecosystem services assessment through ecological footprint accounting. Ecosyst Serv 30:228–235. https://doi.org/10.1016/j.ecoser.2018.01.010

McDonald GW, Patterson MG (2004) Ecological footprints and interdependencies of New Zealand regions. Ecol Econ 50(1-2):49–67. https://doi.org/10.1016/j.ecolecon.2004.02.008

McKitrick R (2007) Why did US air pollution decline after 1970? Empir Economic 33(3):491–513. https://doi.org/10.1007/s00181-006-0111-4

McLellan R, Iyengar L, Jeffries B, Oerlemans N (2014) Living planet report 2014: species and spaces, people and places. Switzerland: WWF International

Miao CL, Sun LY, Yang L (2016) The studies of ecological environmental quality assessment in Anhui Province based on ecological footprint. Ecol Indic 60:879–883. https://doi.org/10.1016/j.ecolind.2015.08.040

Monfreda C, Wackernagel M, Deumling D (2004) Establishing national natural capital accounts based on detailed ecological footprint and biological capacity assessments. Land Use Policy 21(3):231–246. https://doi.org/10.1016/j.landusepol.2003.10.009

Niccolucci V, Pulselli FM, Tiezzi E (2007) Strengthening the threshold hypothesis: economic and biophysical limits to growth. Ecol Econ 60(4):667–672. https://doi.org/10.1016/j.ecolecon.2006.10.008

Nourry M (2009) Re-examining the empirical evidence for stochastic convergence of two air pollutants with a pair-wise approach. Environ Resour Econ 44(4):555–570. https://doi.org/10.1007/s10640-009-9301-9

Ozcan B, Danish, Bozoklu S (2021) Dynamics of ecological balance in OECD countries: sustainable or unsustainable. Sustain Prod Consum 26:638–647. https://doi.org/10.1016/j.spc.2020.12.014

Ozcan B, Ulucak R, Dogan E (2019) Analyzing long lasting effects of environmental policies: evidence from low, middle and high income economies. Sustain Cities Soc 44:130–143. https://doi.org/10.1016/j.scs.2018.09.025

Panayotou T (1993) Empirical tests and policy analysis of environmental degradation at different stages of economic development. Working Paper. International Labour Office, Geneva

Pata UK, Yilanci V (2021) Investigating the persistence of shocks on the ecological balance: Evidence from G10 and N11 countries. Sustain Prod Consum 28:624–636. https://doi.org/10.1016/j.spc.2021.06.027

Rees WE (1992) Ecological footprints and appropriated carrying capacity: what urban economics leaves out. Environ Urbanization 4(2):121–130. https://doi.org/10.1177/095624789200400212

Rudolph A, Figge L (2017) Determinants of ecological footprints: what is the role of globalization. Ecol Indic 81:348–361. https://doi.org/10.1016/j.ecolind.2017.04.060

Rugani B, Roviani D, Hild P, Schmitt B, Benetto E (2014) Ecological deficit and use of natural capital in Luxembourg from 1995 to 2009. Sci Total Environ 468:292–301. https://doi.org/10.1016/j.scitotenv.2013.07.122
Solarin SA, Bell MO (2018) Persistence of policy shocks to an environmental degradation index: the case of ecological footprint in 128 developed and developing countries. Ecol Indic 89:35–44. https://doi.org/10.1016/j.ecolind.2018.01.064
Solarin SA, Gil-Alana LA, Lafuente C (2021) Persistence and sustainability of fishing grounds footprint: evidence from 89 countries. Sci Total Environ 751:141594. https://doi.org/10.1016/j.scitotenv.2020.141594
Solarin SA, Tiwari AK, Bello MO (2019) A multi-country convergence analysis of ecological footprint and its components. Sustain Cities Soc 46:101422. https://doi.org/10.1016/j.scs.2019.101422
Sun J, Su CW, Shao GL (2016) Is carbon dioxide emission convergence in the ten largest economies. Int J Green Energy 13(5):454–461. https://doi.org/10.1080/15435075.2014.966373
Tillaguango B, Alvarado R, Dagar V, Murshed M, Pinzón Y, Méndez P (2021) Convergence of the ecological footprint in Latin America: the role of the productive structure. Environ Sci Pollut Res 28(42):59771–59783. https://doi.org/10.1007/s11356-021-14745-1
Tiwari AK, Kyophilavong P, Albulescu CT (2016) Testing the stationarity of CO2 emissions series in Sub-Saharan African countries by incorporating nonlinearity and smooth breaks. Res Int Bus Financ 37:527–540. https://doi.org/10.1016/j.ribaf.2016.01.005
Torras M (2003) An ecological footprint approach to external debt relief. World Dev 31(12):2161–2171. https://doi.org/10.1016/j.worlddev.2003.09.001
Toth G, Szigeti C (2016) The historical ecological footprint: from over-population to over-consumption. Ecol Indic 60:283–291. https://doi.org/10.1016/j.ecolind.2015.06.040
Tunkrova L (2008) The Nordic countries 'exceptionalism' in eu environmental policy. Contemporary European. Studies 2:21–46
Ulucak R, Apergis N (2018) Does convergence really matter for the environment? An application based on club convergence and on the ecological footprint concept for the EU countries. Environ Sci Policy 80:21–27. https://doi.org/10.1016/j.envsci.2017.11.002
Ulucak R, Lin D (2017) Persistence of policy shocks to ecological footprint of the USA. Ecol Indic 80:337–343. https://doi.org/10.1016/j.ecolind.2017.05.020
United Nations Development Program (UNDP) (2022). https://www.undp.org/sustainabledevelopmentgoals#:~:text=The%20Sustainable%20Development%20Goals%20(SDGs)%2C%20also%20known%20as%20the,people%20enjoy%20peace%20and%20prosperity
Wackernagel M (1994) Ecological footprint and appropriated carrying capacity: a tool for planning toward sustainability. Doctoral dissertation, University of British Columbia
Wackernagel M (2014) Comment on "ecological footprint policy? Land use as an environmental indicator". J Ind Ecol 18(1):20–23. https://doi.org/10.1111/jiec.12094
Wackernagel M, Rees WE (1998) Our ecological footprint: reducing human impact on the earth. New society publishers, Gabriola Island, BC
Yilanci V, Pata UK (2020a) Convergence of per capita ecological footprint among the ASEAN-5 countries: evidence from a non-linear panel unit root test. Ecol Indic 113:106178. https://doi.org/10.1016/j.ecolind.2020.106178
Yilanci V, Pata UK (2020b) Are shocks to ecological balance permanent or temporary? Evidence from LM unit root tests. J Clean Prod 276:124294. https://doi.org/10.1016/j.jclepro.2020.124294
Yilanci V, Gorus MS, Aydin M (2019) Are shocks to ecological footprint in OECD countries permanent or temporary. J Clean Prod 212:270–301. https://doi.org/10.1016/j.jclepro.2018.11.299
Yilanci V, Gorus MS, Solarin SA (2022a) Convergence in per capita carbon footprint and ecological footprint for G7 countries: evidence from panel Fourier threshold unit root test. Energy Environ 33(3):527–545. https://doi.org/10.1177/0958305X211011461
Yilanci V, Pata UK, Cutcu I (2022b) Testing the persistence of shocks on ecological footprint and sub-accounts: evidence from the big ten emerging markets. Int J Environ Res 16(1):1–13. https://doi.org/10.1007/s41742-021-00391-5
Yilanci V, Ulucak R, Ozgur O (2022c) Insights for a sustainable environment: analyzing the persistence of policy shocks to ecological footprints of Mediterranean countries. Spat Econ Anal 17(1):47–66. https://doi.org/10.1080/17421772.2021.1919313

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.