Int J Environ Res (2022) 16:10
https://doi.org/10.1007/s41742-021-00391-5

RESEARCH PAPER

Testing the Persistence of Shocks on Ecological Footprint and Sub-accounts: Evidence from the Big Ten Emerging Markets

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Received: 23 September 2021 / Revised: 13 December 2021 / Accepted: 27 December 2021 / Published online: 6 January 2022

Abstract

This study aims to analyze whether the effect of shocks on the ecological footprint and its sub-accounts in the Big Ten emerging economies is transitory or not. To this end, we employ the Fourier augmented Dickey–Fuller unit root test with a fractional frequency (FADF) and the recently developed fractional unit root test with a Fourier function (FUR) on annual data from 1961 to 2017. The results of the FADF unit root test suggest the validity of stationarity for about 30% of the series, while the FUR test indicates evidence of stationarity for almost all footprint series. These results imply that policy shocks to ecological footprints are temporary and policies to reduce environmental pollution in the Big Ten countries do not have the expected impact. Since shocks have temporary effects on ecological footprints, the Big Ten countries should not cause irreversible environmental degradation. The Big Ten governments need to implement permanent structural reforms to counteract the growth of the ecological footprint.

Article Highlights

- **The persistence of the ecological footprint and its six subaccounts in the Big Ten emerging markets is investigated.**
- **Novel Fourier-based and fractional frequency unit root tests are performed.**
- **Almost all series are stationary.**
- **Policy shocks will have temporary effects on the ecological footprint.**

Keywords Ecological footprint · Fourier approximation · Fractional frequency · Stationarity

Introduction

Humanity is significantly affected by environmental conditions, and people exert an ever-increasing influence on the environment through their consumption and production. In particular, the developments associated with the industrial revolution, such as technological progress, rapid population growth and urbanization, have disturbed the balance of nature. This has led to a number of environmental problems and some debates on pollution, global warming, extinction of some species, deforestation, desertification, etc.

Industrialization, rapid urbanization, and the adverse impacts of dirty technologies pose an increasing environmental challenge. Within this framework, scientists conducting solution-oriented research on environmental problems are developing different methods and indicators to evaluate anthropogenic environmental pressure. As one of these indicators, ecological footprint, which is considered as an

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indicator of sustainability and sustainable development, was developed by Wackernagel and Rees (1996). Ecological footprint is a method of measuring the consumption of natural resources and the assimilative capacity needed for the wastes generated in the economy. From a theoretical perspective, Rudolph and Figge (2017) define the ecological footprint as a measure of how much biologically productive soil and water areas are required to produce the resources consumed by society and to eliminate the wastes generated by existing technology and resource use. It is also defined by Wackernagel and Rees (1996) as an indicator that estimates the intensity of natural resource consumption and waste disposal in a given area. Bartelmus (2008) interprets ecological footprint more generally as the demand of nature and the pressure of human activities on the ecological system. In other words, the ecological footprint calculates the land and water areas required to meet human consumption and the resulting waste (Yilanci and Pata 2020a).

The ecological footprint, expressed as global hectares, measures the sufficient biological area required to meet all needs. The biological area can be classified as arable lands, pastures, seas and lakes, carbon-holding areas, etc., and expressed as the capacity to generate resources (Borucke et al. 2013). While the ecological footprint is measured by Van den Bergh and Verbruggen (1999) by multiplying consumption area, production area, and population, according to Rudolph and Figge (2017), it comprises the fields, such as consumption, production, export, and import. In both measurement methods, ecological footprint consists of six different components. The World Wildlife Fund and Kitzes (2007) describe these components as follows: *Grazing land footprint*: It refers to the area required in meat, milk, leather, and wool products. *Fishing grounds footprints:* It is expressed as the freshwater and saltwater areas needed for the survival of consumed seafood. *Cropland footprint* is the measurement of plantation area used to grow oil craps, fiber food products, and animal feeds are planted. *Forest footprint* is the measurement of the area required for pulp, industrial wood, firewood, and timber. *The built-up footprint* is the area of built lands covered with human-made infrastructures, such as transportation, housing, industrial buildings, and hydropower plants. *The Carbon footprint* is a measure of the carbon dioxide (CO_2) emissions that occur at each stage of the life cycle, such as production, transportation, and consumption. CO_2 is emitted not only in domestic production, but also in carbon and fossil fuel based production process of imported products.

Analyzing the stationarity of environmental indicators can provide important information about the feasibility and effectiveness of environmental and energy policies (Pata and Yilanci 2021). Stationary analysis examines whether the effect of a shock on the ecological indicators is persistent or not, and then optimal environmental policies are proposed. If the series is stationary at the level, shocks have only temporary effects. On the other hand, if the series contains a unit root, it can be interpreted as a long-term effect of the shocks (Tiwari et al. 2016). Unit root tests can be used to examine whether the effects of shocks on environmental pollution are temporary or not (Lee and Chang 2008). To test the environmental effects of shocks, researchers have previously studied the stationarity of CO_2 emissions (Heil and Selden 1999; Lanne and Liski 2004; Barassi et al. 2008; Lee and Chang 2009). However, CO_2 emissions are only one type of greenhouse gases, and their excess symbolizes air pollution. The assessment of environmental degradation requires a broader analysis that includes water and soil pollution. In this context, within the above explanations, ecological footprint is a more comprehensive indicator in evaluating environmental problems. Therefore, this study aims to investigate the stationarity of the ecological footprint and all its sub-accounts in the Big Ten countries, namely, Argentina, Brazil, China, India, Indonesia, Mexico, Poland, South Africa, South Korea, and Turkey.

Figure 1 presents the ecological situation in 1961 and 2017 for each Big Ten country. While Argentina, Brazil, China, Indonesia, South Korea, Mexico, South Africa and Turkey had an ecological surplus in 1961, all other countries except Argentina and Brazil had an ecological deficit in 2017. This means that the decline in environmental quality in developing countries has reached gigantic proportions over the last 60 years. Figure 2 shows the change in the overall ecological situation in the Big Ten countries between 1961 and 2017.

A look at Fig. 2 shows that the Big Ten countries had an ecological surplus until 1995. However, since then, the ecological deficit has increased year by year and the ecological footprint per capita was 37% higher than the biocapacity in 2017. This situation implies that environmental degradation in Big Ten countries have increased in the last 20 years and various ecological measures should be taken to avoid environmental problems.

The Big Ten countries describe the leading developing countries according to the classification by Morgen Stanley.

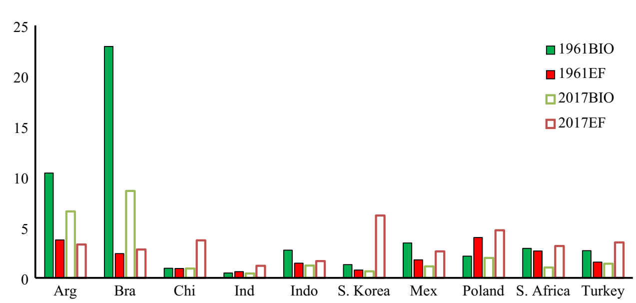

Fig. 1 Country specific ecological situation from the Big Ten (per capita, gha); Source: Global Footprint Network (2021)

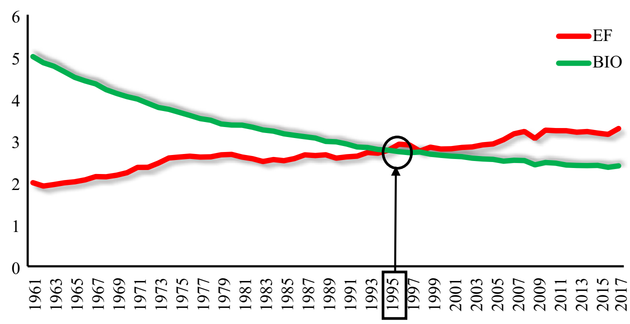

Fig. 2 Average ecological footprint and biocapacity in the Big Ten (per capita, gha); Source: Global Footprint Network (2021)

The main reason why they are considered as the top ten developing countries among the economies of the world is their share in the global GDP. These countries have driven their industrialization process with the help of their economic growth, production structures, foreign trade power and potential to attract foreign capital. As they play a crucial role in global financial stability due to their emerging markets, they are in a position to lead the transition to the free market in the regions of Asia, Central Europe, and Latin America. For this reason, research on the ecological footprint can contribute to environmental and economic policies in these countries. Among the Big Ten Countries, Mexico is the first developing country to join the Organisation for Economic Cooperation and Development (OECD). Brazil, as a developing country, also plays an important role in world trade. Although Argentina and Turkey struggle with high inflation rates, they are also highly open countries in terms of global trade. South Africa has a great population and GDP of the entire continent. Poland is one of the most privatized economies in the post-communist era. South Korea also has a significant GDP share in the East Asia. Indonesia is also a respected emerging economy, not only because of its population strength, but also because of existing American energy investments. Finally, China and India are known to be the major emerging powers not only in Asia but in the whole world.

This study contributes to the literature in three ways. First, this study investigates the stochastic properties of the ecological footprint and its sub-accounts. To our knowledge, only Ulucak and Lin (2017) and Yilanci et al. (2019) investigated all sub-accounts of the ecological footprint. Second, this study uses the newly developed fractional unit root test with a Fourier function. While most of the studies in the literature only investigate whether environmental degradation indicators are stationary or have a unit root, this study considers the intermediary cases and thus; reveals the fractional integration properties of series. In the econometric procedure of the study, the significance of the trigonometric terms sine and cosine is first tested using the F test. If the F-statistic is significant, the Fourier unit root test is used, otherwise conventional unit root tests are used. In the fractional unit root test with Fourier approximation, the stationarity of the series is analyzed using the integration parameter. Conclusions are then drawn about the persistence of the shocks depending on whether the series are stationary or not. Third, this study is the first to analyze the stationarity of the ecological footprint for the Big Ten countries.

The rest of the study is organized as follows: Sect. 2 presents the literature review. Section 3 introduces the methodology used in this study. Section 4 presents the descriptive statistic of data and discusses empirical results. Finally, last section concludes the study.

Literature Review

Recently, environmental economists have focused on empirical testing of three issues, namely, the environmental Kuznets curve (EKC) hypothesis, the pollution haven hypothesis, and the stationarity of ecological indicators. Ecological footprint has been widely used to test the validity of these hypotheses and to analyze stationarity. For example, Destek and Okumus (2019) and Khan et al. (2021) used ecological footprint in testing the PHH hypothesis, and Pata and Kumar (2021) used carbon footprint as the dependent variable. In addition, many researchers have investigated the determinants of ecological and carbon footprints in testing the EKC hypothesis (see, among others, Al-Mulali et al. 2015; Elshimy et al. 2020; Bulut 2021; Lee and Chen 2021; Pata 2021; Sultana et al. 2021, among others).

Empirical studies dealing with the ecological footprint as an ecological indicator have increased in recent years. However, to the best of our knowledge, there are still not enough studies testing the stationarity of this indicator. A recent literature deals with the stationarity properties of the ecological footprint. In this context, Ulucak and Lin (2017) are the first to investigate the stochastic behavior of the ecological footprint for the United States by employing the Fourier unit root test. In doing so, they investigate how the ecological footprint responds to policy shocks. The study suggests that the ecological footprint in the United States contains a unit root; in other words, non-stationary. Solarin and Bello (2018) investigate the ecological footprint in 128 countries over the period 1961–2013. The study employs the unit root tests of Kruse (2011) and Narayan and Popp (2010). The results indicate that the ecological footprint is non-stationary in 96 out of 128 countries. Therefore, they emphasize the permanent impact of environmental policies.

Using the panel KPSS stationary test on annual data from 1961 to 2014, Bilgili and Ulucak (2018) find that the ecological footprint is stationary in G20 countries. The analysis of 20 European Union countries by Ulucak and Apergis (2018) investigates the stationarity of the ecological footprint using the Philips-Sul club convergence test for 1961–2013. The results suggest club convergence in a couple of countries. According to Solarin et al. (2018), the results of the RALS-LM unit root test for 27 OECD countries support convergence in 13 countries but the divergence in 12 countries. Bilgili et al. (2019) employ the KPSS unit root test in selected 60 countries from Asia, Africa, America, and Europe over the period 1961–2014. The study suggests the convergence in Africa, America, and Europe but the divergence in Asian countries. Ozcan et al. (2019) investigate the ecological footprint and its components in four country groups with different income levels, namely, high, middle–high, middle–low-, and low-income countries. The study employs the KPSS panel unit root test over the period 1961–2013. The findings confirm convergence (stationarity) in the countries with high-income levels. Moreover, convergence is also confirmed in half of the countries with low- and middle–high-income levels. Solarin (2019) also conducts a study using residual augmented least-square Lagrenge Multiplier (RALS-LM) unit root test in 27 OECD countries over the period 1961–2013 and finds that the series are stationary in 13 countries and contain unit roots in 12 countries. Solarin et al. (2019) employ a fractional unit root test to investigate the stationarity of ecological footprint in 92 countries for the period 1961–2014. The results show convergence to the average in 25 countries. Yilanci et al. (2019) conduct an analysis for 25 OECD countries by employing the panel Fourier stationarity test over the period 1961–2013. According to the findings, all the components of ecological footprint are stationarity except for fishing grounds. As a policy recommendation, it is suggested that there will be no strong resistance in the movements towards reducing the fishing grounds footprint. Pata and Aydin (2020) perform the Fourier ADF unit root test from 1965 to 2016 and find that ecological footprint has a unit root process for the top-six hydropower energy consuming countries. Solarin (2020) employs Fourier panel stationarity tests for 89 countries from 1961 to 2016 and find that forest products footprint contains a unit root. Yilanci and Pata (2020b) use the two-regime threshold autoregressive panel unit root test from 1961 to 2016 and report that ecological footprint is stationary in Indonesia, Malaysia, the Philippines, Thailand, and Vietnam.

Erdogan and Okumuş (2021) employ the panel Fourier KPSS stationarity test and log-t methods to test the stochastic and club convergence of ecological footprint for the countries with different income groups. They find that in most of the 89 countries, the ecological footprint contains a unit root. Sarkodie (2021) uses econometric and machine learning based estimates for 245 countries and concludes that the ecological footprint has a mean reverting process. According to Solarin et al. (2021a) for built-up land footprint on a sample of 89 countries show that the degree of heterogeneity between countries is relatively higher and some countries display short memory patterns, while others significantly higher orders of integration. Within a different study, Solarin et al. (2021b) also investigate fishing ground footprint in a group of 89 countries. The results indicate that most of the series in upper-middle- and high-income countries exhibit a non-stationary and non-mean-reverting pattern, while the study finds predominantly stationary characteristics in lower middle- and low-income countries. In another recent study, Yilanci et al. (2021) apply the RALS-LM unit root test from 1961 to 2014 and conclude that ecological footprint exhibits mean-reverting behavior in 13 Mediterranean countries.

Recently, some researchers have started to test the stationarity of the ecological balance, which is defined as the difference between ecological footprint and biocapacity. For example, Yilanci and Pata (2020a, b) employ six different unit root tests of the type LM and find that the ecological balance is stationary in nine out of 14 countries over the same period. Ozcan et al. (2021) use the quantile unit root test and found that the ecological balance to be stationary in 13 of the 24 OECD countries from 1961 to 2016. Pata and Yilanci (2021) apply the Fourier quantile unit root test for the same period and emphasize that the ecological balance is stationary in 16 of the 22 countries analyzed.

As can be seen from the literature review above, the absence of analysis of the Big Ten markets underscores the importance of the present study in terms of environmental policy implications. As a comprehensive indicator of environmental policy shocks, the stationarity analyses of the ecological footprint vary across countries and regions. It can be asserted that the socioeconomic aspects, population, industrial structure, and development level could be the reasons for the varied empirical results. Moreover, these differences are probably due to the characteristics of the empirical methods and the countries studied. Due to these differences, there is a need for further studies that test the stationarity of the ecological footprint for different groups of countries using current methods. In contrast to the existing literature, we use the Fourier fractional unit root test of Gil-Alana and Yaya (2020) for the first time to test the stationarity of the ecological footprint. Both using the current method and a different country group, we aim to contribute to the existing literature.

Econometric Methodology

Fourier Unit Root Test with a Fractional Frequency

Since the seminal study of Becker et al. (2006), several new unit root tests have been introduced to the literature that allows multiple structural changes through a Fourier function. The unit root test developed by Enders and Lee (2012) is one of them. Enders and Lee (2012) extended the traditional augmented Dickey–Fuller (ADF) unit root test with a Fourier function, so that the location, form, or number of the breaks do not affect the power of the suggested test. To employ the Fourier ADF unit root test (FADF) of Enders and Lee (2012), we employ the following test equation:

$$\Delta y_t = \alpha_0 + \alpha_1 \sin\left(\frac{2\pi kt}{T}\right) + \alpha_2 \cos\left(\frac{2\pi kt}{T}\right) + \alpha_3 y_{t-1} + \sum_{i=1}^{p} \beta_i \Delta y_{t-i} + e_t, \tag{1}$$

where sin and cos show the trigonometric terms, $\pi = 3.14$, k indicates a particular frequency whose value is determined as endogenously, t, T, and p show the trend term, sample size, and optimal lag length, respectively. We first determine the optimal value for k in the interval [0.1, 0.2, 0.3, …, 5] by yields the minimum sum of squared residuals for Eq. (1). After finding the optimal k value, we determine the optimal lag length p to remedy possible autocorrelation. We use Akaike information criterion to select the p. One can test the null hypothesis of linearity as $\alpha_1 = \alpha_2 = 0$, by performing the usual F test. The necessary critical values are tabulated in Enders and Lee (2012). If the null is rejected, one can test the null hypothesis of a unit root, $\alpha_3 = 0$.

The Fourier unit root test with a fractional frequency is fundamentally superior to other unit root tests in two respects. First, this unit root test deals with smooth structural changes. Breaks in environmental variables may occur in a slow process, and in this case, the use of sharp structural breaks may lead to biased results. Moreover, according to Christopoulos and Leon-Ledesma (2011), the use of a fractional frequency reflects permanent breaks. In this respect, the Fourier unit root test with a fractional frequency provides more accurate information about the stochastic properties of the series by capturing permanent smooth structural shifts.

Fractional Unit Root Test with a Fractional Frequency

As discussed in the literature review section of this study, most empirical studies that investigate whether environmental degradation indicators are stationary or not employ unit root tests in the traditional framework. These traditional unit root tests only consider the cases, where the series has a unit root ($d = 0$) or not ($d = 1$); however, there are two more possible cases when $0 < d < 0.5$ or $0.5 \leq d < 1$. In the former case ($0 < d < 0.5$), the stochastic process of the series is a covariance-stationary process and has a finite variance; in the latter case, the process is not covariance-stationary; that is, it has infinite variance, but it is mean-reverting (Tkacz 2001). To account for these two ignored cases by most studies, in this study we use a fractional unit root test with a Fourier function proposed by Gil-Alana and Yaya (2020). In their study, Gil-Alana and Yaya (2020) extended Robinson's (1994) linear model with a Fourier function to allow for multiple changes. To obtain the test statistic, one can estimate the following model:

$$y_t^* = \delta_0 1_t^* + \lambda_0 t_t^* + \theta_1 \sin_{1,t}^* + \theta_2 \cos_{1,t}^* + v_t, \tag{2}$$

where $y_t^* = (1-L)^{d_0} y_t$, $1_t^* = (1-L)^{d_0} 1_t$, $t_t^* = (1-L)^{d_0} t_t$, $u_t = (1-L)^{d_0} x_t$, $\sin_{1,t}^* = (1-L)^{d_0} \sin\left(\frac{2\pi tk}{T}\right)$, $\cos_{1,t}^* = (1-L)^{d_0} \cos\left(\frac{2\pi tk}{T}\right)$, $x_t^* = (1-L)^{d_0} u_t$.

On the assumption that v_t is stationary, one can estimate Eq. (2) by employing ordinary least squares. The parameters are defined as in the Fourier ADF unit root test. One can follow the same procedure as in the FADF unit root test to find the optimal frequency. To reject linearity, at least one of the trigonometric terms should be statistically significant, as suggested by Yaya et al. (2021).

Data and Empirical Results

This study aims to test the stationarity of ecological footprint (gha per person) and its sub-accounts for the Big Ten countries. The data is collected from Global Footprint Network (2021) and the descriptive statistics of the data is shown in Table 1.

As can be seen in Table 1, China has the highest mean value for built-up footprint, Poland for carbon, cropland, and ecological footprint, Korea for fishing footprint, Brazil for forest and grazing land footprint, while South Africa has the lowest mean for built-up footprint, Turkey for forest products, India for the carbon, cropland, and fishing grounds. Moreover, forest products, grazing land, and ecological footprint. built-up, cropland, and grazing land footprint of Argentina, carbon, ecological, and fishing grounds footprint of Korea, and forest products footprint of Indonesia have the highest standard deviation, which shows that these series have higher volatility than the other series.

After examining the descriptive statistics of the series, we apply a traditional unit root test for the aim of the benchmark. Table 2 presents the results of the Augmented Dickey-Fuller (ADF) unit root test.

The results of the ADF unit root test in Table 2 show that only built-up footprint of Korea, Mexico, South Africa, cropland footprint of Argentina, India, and Turkey, fishing grounds footprint of Turkey, forest products footprint of Argentina, Indonesia, grazing land footprint of China, and ecological footprint of South Africa are stationary. That is 11 out of 70 series are found as stationary according to the results of the ADF unit root test. Only a few series are found to be stationary may be due to the fact that the ADF unit root

Table 1 Descriptive statistics

	Built-up Footprint	Carbon Footprint	Cropland Footprint	Fishing Footprint	Forest Footprint	Grazing Footprint	Ecological Footprint
Argentina							
Mean	0.069	1.086	0.579	0.121	0.220	1.393	3.467
Median	0.064	1.086	0.548	0.117	0.215	1.460	3.388
Maximum	0.108	1.343	1.050	0.255	0.314	2.289	4.607
Minimum	0.035	0.725	0.261	0.020	0.166	0.710	2.866
Std. Dev	0.024	0.170	0.165	0.052	0.035	0.376	0.382
Jarque–Bera	5.220	3.000	4.851	1.896	5.160	1.058	15.638
Probability	0.074	0.223	0.088	0.387	0.076	0.589	0.000
Brazil							
Mean	0.065	0.565	0.535	0.036	0.588	0.957	2.745
Median	0.054	0.596	0.529	0.036	0.589	0.978	2.796
Maximum	0.127	0.949	0.765	0.048	0.678	1.191	3.057
Minimum	0.037	0.258	0.432	0.024	0.430	0.682	2.324
Std. Dev	0.026	0.175	0.073	0.006	0.056	0.161	0.213
Jarque–Bera	7.749	0.762	5.563	0.537	6.047	4.948	4.976
Probability	0.021	0.683	0.062	0.765	0.049	0.084	0.083
China							
Mean	0.077	1.000	0.390	0.048	0.178	0.128	1.821
Median	0.076	0.700	0.384	0.038	0.181	0.128	1.481
Maximum	0.112	2.617	0.581	0.082	0.214	0.140	3.714
Minimum	0.035	0.207	0.259	0.024	0.150	0.117	0.881
Std. Dev	0.022	0.770	0.084	0.024	0.015	0.005	0.893
Jarque–Bera	2.397	9.967	3.316	7.978	2.169	4.568	9.306
Probability	0.302	0.007	0.191	0.019	0.338	0.102	0.010
India							
Mean	0.030	0.277	0.313	0.014	0.144	0.010	0.788
Median	0.031	0.228	0.317	0.015	0.147	0.009	0.761
Maximum	0.049	0.653	0.342	0.019	0.155	0.014	1.195
Minimum	0.016	0.100	0.277	0.010	0.125	0.007	0.602
Std. Dev	0.010	0.163	0.014	0.002	0.008	0.002	0.168
Jarque–Bera	3.753	8.459	2.931	2.425	6.127	10.751	8.109

Built-up Footprint	Carbon Footprint	Cropland Footprint	Fishing Footprint	Forest Footprint	Grazing Foot-print	Ecological Footprint
South Korea						
Mean	0.058	2.321	0.487	0.345	0.207	0.080
Median	0.058	1.885	0.515	0.367	0.200	0.088
Maximum	0.072	4.648	0.677	0.548	0.336	0.169
Minimum	0.045	0.247	0.273	0.078	0.089	0.001
Std. Dev	0.006	1.494	0.115	0.136	0.069	0.050
Jarque–Bera	0.499	6.016	3.655	5.095	1.942	3.068
Probability	0.779	0.049	0.161	0.078	0.379	0.216
Mexico						
Mean	0.038	1.219	0.486	0.057	0.268	0.374
Median	0.039	1.232	0.479	0.068	0.261	0.349
Maximum	0.051	2.519	0.629	0.092	0.324	0.638
Minimum	0.021	0.436	0.340	0.017	0.230	0.210
Std. Dev	0.006	0.445	0.074	0.023	0.023	0.111
Jarque–Bera	7.972	0.214	1.811	5.844	4.101	3.975
Probability	0.019	0.898	0.404	0.054	0.129	0.137
Poland						
Mean	0.064	3.152	0.938	0.111	0.501	0.085
Median	0.065	2.955	0.971	0.073	0.430	0.093
Maximum	0.082	4.298	1.148	0.270	0.904	0.155
Minimum	0.045	2.309	0.572	0.041	0.269	0.024
Std. Dev	0.009	0.552	0.139	0.063	0.169	0.040
Jarque–Bera	1.792	5.591	4.724	6.513	9.574	5.544
Probability	0.408	0.061	0.094	0.039	0.008	0.063
South Africa						
Mean	0.025	2.352	0.344	0.137	0.340	0.169
Median	0.026	2.274	0.339	0.143	0.359	0.178
Maximum	0.036	2.969	0.515	0.237	0.432	0.282
Minimum	0.014	1.778	0.254	0.067	0.202	0.000
Std. Dev	0.005	0.291	0.049	0.047	0.059	0.058
Jarque–Bera	2.038	1.793	15.527	4.625	4.529	4.145

Table 1 (continued)

	Built-up Footprint	Carbon Footprint	Cropland Footprint	Fishing Footprint	Forest Footprint	Grazing Footprint	Ecological Footprint
Probability	0.302	0.007	0.191	0.019	0.338	0.102	0.010
Indonesia							
Mean	0.042	0.313	0.337	0.112	0.455	0.018	1.278
Median	0.047	0.231	0.348	0.090	0.410	0.016	1.267
Maximum	0.061	0.698	0.463	0.233	1.077	0.036	1.662
Minimum	0.019	0.041	0.215	0.042	0.174	0.010	1.030
Std. Dev	0.013	0.207	0.070	0.063	0.251	0.007	0.166
Jarque–Bera	5.732	4.972	3.769	5.787	6.609	11.470	3.688
Probability	0.057	0.083	0.152	0.055	0.037	0.003	0.158

Built-up Footprint	Carbon Footprint	Cropland Footprint	Fishing Footprint	Forest Footprint	Grazing Foot-print	Ecological Footprint
Probability	0.361	0.408	0.000	0.099	0.104	0.126
Turkey						
Mean	0.026	1.087	0.852	0.046	0.243	0.163
Median	0.029	1.009	0.840	0.044	0.243	0.161
Maximum	0.036	2.233	1.009	0.083	0.334	0.259
Minimum	0.014	0.266	0.632	0.012	0.149	0.100
Std. Dev	0.007	0.538	0.066	0.017	0.048	0.042
Jarque–Bera	5.625	3.255	2.967	1.013	1.105	2.530
Probability	0.060	0.196	0.227	0.603	0.576	0.282

test does not allow for structural breaks. Therefore, to consider multiple structural changes, we next apply the FADF unit root test and present the results in Table 3.

Prior to assessing the FADF test statistics, we test the significance of the trigonometric terms via the *F* test. The results of the *F* test indicate that there are nonlinearities in the data generation process for almost half (32) of the series. Therefore, we can test the stationarity of these series using the FADF unit root test. The frequencies of all these series are found as fractional that is evidence of the existence of permanent structural changes (see Christopoulos and Leon-Ledesma 2011). The test results show that built-up footprint of Argentina, India, and Turkey, carbon footprint of Mexico and South Africa, cropland footprint of Brazil, India, Indonesia, Korea, Poland, and Turkey, fishing grounds footprint of Indonesia and South Africa, forest products footprint of Brazil, Indonesia, and South Africa, grazing land footprint of Argentina, Indonesia, Korea, Poland, and South Africa, and ecological footprint of Turkey found as stationary. Overall, 22 out of seventy series is found as stationary.

The FADF test considers only the stationarity and unit root cases. To account for the possibility of fractional integration cases, we next apply the fractional unit root test with a Fourier function (FURF) and tabulate the results in Tables 4 and 5.

The results in Tables 4 and 5 indicate that none of the trigonometric terms are significant for built-up footprint of Poland, carbon footprint of Brazil, cropland footprint of South Africa, and grazing land footprint of Korea. We also find that the integration parameter (*d*) is not significant for the series of the built-up footprint of Poland and Turkey, cropland footprint of Argentina, Brazil, India, Mexico and South Africa, forest products footprint of Argentina, grazing land footprint of Mexico and Poland, and ecological footprint of Turkey. For all the remaining series, at least one of the trigonometric terms found and also integration parameter found as significant that shows that we can use the FURF test to assess the stationarity of these variables (see Yaya et al. 2021).

The results of the FURF test indicate that all these series are stationary with long memory, since the integration parameter ranges from 0 to 0.5. These results suggest that the effects of policies are transitory and decay rather slowly. Since the effect of implementation of policies to decrease environmental degradation to disappear slowly, more permanent effects on environmental degradation require more permanent policies.

In terms of total ecological footprint, our findings are in line with Ozcan et al. (2019), Solarin et al. (2019), Yilanci et al. (2019), Yilanci and Pata (2020b), and Yilanci et al. (2021). In contrast, our results do not coincide with those of Ulucak and Lin (2017), Solarin and Bello (2018), and Pata and Aydin (2020), who report that the ecological footprint

Table 2 Results of ADF unit root test

Countries	Built-up footprint	Carbon footprint	Cropland footprint	Fishing grounds footprint	Forest products footprint	Grazing land footprint	Ecological footprint
Argentina	0.012 (0.955) [2]	−2.087 (0.251) [0]	−3.328 (0.018) [1]**	−2.351 (0.16) [0]	−3.542 (0.01) [0]**	−1.362 (0.595) [0]	−2.593 (0.101) [0]
Brazil	2.044 (1) [1]	−1.663 (0.444) [1]	1.475 (0.999) [6]	−2.244 (0.194) [0]	−0.674 (0.845) [0]	−0.816 (0.806) [3]	−2.086 (0.251) [0]
China	−1.228 (0.655) [7]	1.864 (1) [3]	0.916 (0.995) [2]	−0.343 (0.911) [0]	−0.94 (0.768) [1]	−2.753 (0.072) [1]***	3.274 (1) [10]
India	0.621 (0.989) [2]	4.022 (1) [8]	−4.935 (0) [0]*	−1.893 (0.333) [0]	0.62 (0.989) [0]	−2.054 (0.264) [0]	3.052 (1) [1]
Indonesia	−1.482 (0.535) [0]	1.157 (0.998) [1]	0.306 (0.977) [2]	2.531 (1) [3]	−7.365 (0) [0]*	0.83 (0.994) [2]	0.458 (0.984) [0]
Korea	−3.528 (0.011) [0]**	−0.233 (0.928) [0]	−1.244 (0.649) [1]	−2.395 (0.148) [4]	−2.252 (0.191) [0]	−0.845 (0.798) [2]	−0.554 (0.872) [0]
Mexico	−3.132 (0.03) [1]**	−1.813 (0.371) [1]	−2.236 (0.196) [1]	−1.518 (0.517) [4]	−2.37 (0.155) [0]	−1.988 (0.291) [0]	−1.954 (0.306) [1]
Poland	−1.964 (0.301) [1]	−1.885 (0.337) [1]	−0.752 (0.825) [1]	−1.952 (0.307) [8]	0.46 (0.984) [3]	−0.456 (0.891) [8]	−1.663 (0.445) [0]
South Africa	−4.524 (0.001) [0]*	−2.273 (0.184) [0]	−0.743 (0.826) [8]	−1.213 (0.663) [0]	−1.645 (0.453) [0]	−2.258 (0.19) [9]	−2.772 (0.069) [0]***
Turkey	−1.341 (0.604) [4]	0.704 (0.991) [2]	−5.754 (0) [0]*	−3.348 (0.017) [0]**	−2.03 (0.274) [0]	−1.809 (0.372) [6]	0.097 (0.963) [2]

Notes: *, **, and *** show the significance at the 1%, 5%, and 10% levels. Numbers in parentheses and brackets show the *p* values, and optimal lag-lengths determines using Akaike information criteria, respectively

contains a unit root. Similar to the total ecological footprint, we conclude that all six sub-accounts of ecological footprint are stationary. Yilanci et al. (2019) and Solarin et al. (2021b) find that the fishing ground footprint includes a unit root in 25 OECD countries and 89 countries, respectively, and therefore, pollution by fisheries can be prevented with environmental policies. Our findings show that this is not the case for Big Ten countries, and that policy interventions in the fishing ground footprint will have only temporary effects.

Conclusion

Testing the stationarity of environmental degradation indicators has been one of the most interesting topics in the environmental economics literature over the last two decades. The reason is that the insightful stochastic properties of ecological indicators provide policymakers with important insights into environmental protection. If the indicators are classified as stationary, shocks are temporary. Otherwise, in the unit root process, shocks to environmental degradation have long lasting effects.

In this study, we tested the stationarity of ecological footprint and its six sub-accounts for the Big Ten emerging markets using recently introduced two-unit root tests. We first applied the Fourier ADF unit root test with fractional frequency and found that about 30% of the series are stationary, while the rest are non-stationary. This unit root test only allows us to discriminate between stationary and non-stationary cases, that is $I(0)$, and $I(1)$ cases, respectively. However, the integration level of the variables can also be higher than 0 and lower than 1; that is the series can be fractionally integrated. Therefore, we also employed the fractional unit root with a Fourier function. This is the first time in the literature, that we have simultaneously considered fractionally integrated case and smooth structural shifts in testing the stationarity of ecological footprint and its sub-accounts. Our results show that almost all series are stationary that is policies to reduce environmental pollution do not provide the expected impacts in selected countries.

The results of our analysis show that all ecological footprint series are stationary. For this reason, the governments of the Big Ten countries should not intervene unnecessarily with various environmental measures, such as carbon tax and energy saving policies to reduce their ecological footprint. The effects of these measures will be temporary, because the ecological footprint series are stationary. All the Big Ten countries except Brazil and Argentina have an ecological deficit. In other words, in these countries, the ecological footprint is larger than the biocapacity. To compensate for this environmentally unsustainable situation, the Big Ten countries need to rethink their current production and consumption activities. In this context, both economic growth and environmental development can be

Table 3 Results of Fourier ADF unit root test

Countries	Built-up footprint		Carbon footprint		Cropland footprint		Fishing grounds footprint		Forest products footprint		Grazing land footprint		Ecological footprint	
	FADF test	*F* test	FADF test	*F* test	FADF test	*F* test	FADF test	*F* test	FADF test	*F* test	FADF test	*F* test	FADF test	*F* test
Argentina	−5.588 (0.6) [10] *	15.595*	−2.459 (2.9) [2]	2.908	−2.876 (0.1) [4]	4.809	−3.846 (0.9) [1]	4.792	−3.247 (0.1) [5]	7.974**	−4.094 (0.8) [9]**	11.278*	−3.282 (1.2) [1]	3.774
Brazil	−3.487 (0.2) [1]	7.758**	−2.027 (3.1) [1]	6.273	−4.825 (0.1) [1]*	12.282*	−0.648 (4.5) [1]	7.130***	−4.062 (0.1) [1]**	9.66**	−2.97 (1) [1]	9.157**	−2.653 (3.2) [2]	5.993
China	−2.699 (0.2) [1]	3.105	2.792 (3.3) [3]	3.27	−3.253 (0.1) [1]	5.849	−2.795 (0.8) [1]	8.454**	−2.826 (1.4) [2]	4.953	−3.327 (3.3) [1]	3.459	2.526 (3.4) [10]	0.716
India	−4.168 (0.2) [1]**	9.167**	−2.297 (0.1) 10]	3.648	−5.724 (2.4) [3]*	9.504**	−2.887 (0.1) [1]	2.570	−3.221 (0.4) [1]	7.774**	−2.995 (0.1) [1]	2.596	−1.971 (0.1) [1]	3.309
Indonesia	−2.823 (0.1) [1]	4.478	−2.696 (0.4) [1]	4.593	−4.417 (0.3) [1]**	10.945*	−4.249 (0.4) [1]**	11.102*	−4.662 (1.9) [10]*	11.641*	−4.646 (0.2) [1]*	12.83*	−3.335 (0.4) [1]	15.909*
Korea	−3.981 (1) [1]	2.612	−2.95 (0.5) [1]	5.114	−3.834 (0.2) [1]***	6.711***	−2.5 (0.3) [4]	2.880	−3.96 (0.8) [1]	4.959	−4.218 (0.1) [1]**	7.924**	−3.192 (0.5) [1]	5.415
Mexico	−3.858 (1.9) [1]	3.146	−4.393 (0.4) [4]**	7.899**	−3.316 (0.8) [1]	3.642	−3.645 (0.4) [1]	5.374	−3.956 (1.5) [1]	4.574	−2.467 (0.1) [3]	3.117	−3.251 (0.6) [1]	3.762
Poland	−2.826 (0.1) [1]	2.278	−3.170 (1.1) [1]	5.600	−4.226 (0.5) [3]**	10.030**	−2.722 (1) [3]	11.044*	−2.347 (0.4) [3]	4.201	−6.069 (0.6) [1]*	17.569*	−3.558 (1.2) [2]	5.993
South Africa	−5.085 (0.1) [1]	5.864	−3.431 (1.7) [1]**	8.579**	−1.884 (0.1) [0]	2.319	−3.866 (0.7) [7]***	6.742***	−4.472 (0.1) [10]**	14.047*	−4.25 (0.8) [10]**	9.661**	−3.115 (1.8) [1]	4.354
Turkey	−3.96 (0.5) [2]**	7.882**	−3.413 (0.1) [1]	6.47***	−5.424 (1.2) [2]*	10.556*	−2.540 (4.4) [1]	2.906	−3.153 (1.2) [1]	6.048	−0.777 (1.9) [4]	7.629**	−4.375 (0.1) [1]**	9.667**

Notes: *, **, and *** indicate the significant at the 1%, 5%, and 10% levels. Numbers in parentheses and brackets show the optimal frequencies and optimal lag lengths

Table 4 Results of FURF unit root test for total ecological footprint

Countries	Ecological footprint		
	FURF test statistics	θ_1	θ_2
Argentina	0.465 (2.9) [0.062] *	−0.239 [0.076] *	0.465 [0.079]
Brazil	0.487 (3) [0.08] *	−0.118 [0.04] *	0.487 [0.028] **
China	0.491 (0.1) [0.036] *	−1.175 [1.573]	0.491 [3.206] *
India	0.478 (0.1) [0.079] *	−0.254 [0.297]	0.478 [0.616] *
Indonesia	0.479 (0.6) [0.071] *	−0.32 [0.03] *	0.479 [0.023] *
Korea	0.232 (0.6) [0.124] **	0.163 [0.173]	0.232 [0.165] *
Mexico	0.479 (1.2) [0.05] *	0.443 [0.115] *	0.479 [0.166] *
Poland	0.462 (1.8) [0.108] *	−0.021 [0.068]	0.462 [0.055] *
South Africa	0.43 (0.5) [0.108] *	0.196 [0.362]	0.43 [0.245] *
Turkey	0.041 (0.1) [0.136]	1.853 [0.551] *	0.041 [1.627] **

achieved with environmental policies and permanent structural reforms that can promote green growth, rather than through temporary interventions. To this end, it is important for the Big Ten countries to adopt green energy and production technologies.

Based on the above results, some policy recommendations can be made to the Big Ten governments to improve environmental quality. Direct measures to reduce pollution are ineffective, because the ecological footprint and its components are stationary. Instead, Big Ten governments should take action to offset positive shocks that increase the ecological footprint. For example, if the ecological footprint increases due to a positive shock caused by people's excessive demand for natural resources, Big Ten governments can guide the public to clean resources through green education programs that raise environmental awareness. In addition, the increase in fossil fuel consumption in industry can also lead to a positive shock to the ecological footprint. To offset this, policy makers can support the development of green technologies and the use of renewable energy. Consequently, the stationarity of the ecological footprint underlines the need for indirect rather than direct action against environmental degradation.

This study has some limitations. The methods used in the study are based on the mean of the series. However, some series do not have a normal distribution, and in this case, it may be more appropriate to perform an analysis based on quantiles. In addition, the study focuses only on the ecological footprint and six subcomponents. This limits the analysis of the stochastic properties of emissions, such as nitrogen dioxide, methane, particular matter.

As a final note, our study opens new research possibilities. The number of studies testing the stability of the six sub-accounts of the ecological footprint is quite limited. In this context, more precise information on whether the effects of policy shocks on the ecological footprint are temporary or permanent can be obtained by comparing the results of further studies with those of previous ones.

Author Contributions All authors were involved in the conception and design of the study. VY performed the empirical analysis. UKP reviewed and edited the manuscript. IC written and finalized the

Table 5 Results of FURF unit root test for subaccounts

Countries	Built-up footprint			Carbon footprint			Cropland footprint		
	FURF test statistics	θ_1	θ_2	FURF test statistics	θ_1	θ_2	FURF test statistics	θ_1	θ_2
Argentina	0.343 (0.6) [0.134] **	−0.014 [0.005] **	0.343 [0.004] *	0.482 (2.9) [0.063] *	−0.119 [0.034] *	0.482 [0.028] *	0.04 (0.1) [0.124]	−1.563 [0.464] *	0.04 [1.381] *
Brazil	0.336 (0.1) [0.12] *	−0.062 [0.022] *	0.336 [0.06] *	0.487 (0.1) [0.046] *	1.011 [1.094]	0.487 [2.085]	0.051 (0.1) [0.123]	0.046 [0.134]	0.051 [0.382] **
China	0.47 (0.1) [0.082] *	0.141 [0.025] *	0.47 [0.062]	0.491 (0.1) [0.027] *	−1.232 [1.446]	0.491 [2.946] *	0.445 (0.1) [0.119] *	0.159 [0.101]	0.445 [0.295] *
India	0.268 (0.2) [0.145] ***	0.014 [0.004] *	0.268 [0.004] *	0.488 (0.1) [0.057] *	−0.232 [0.195]	0.488 [0.46] *	−0.022 (2.2) [0.138]	0.008 [0.002] *	−0.022 [0.002]
Indonesia	0.47 (0.4) [0.063] *	0.017 [0.004] *	0.47 [0.002] *	0.416 (0.4) [0.069] *	−0.001 [0.037]	0.416 [0.022] *	0.285 (0.4) [0.093] *	0.027 [0.014] **	0.285 [0.008] *
Korea	0.449 (0.1) [0.094] *	0.081 [0.023] *	0.449 [0.062] **	0.202 (0.4) [0.109] ***	0.693 [0.422]	0.202 [0.146] *	0.28 (0.7) [0.105] **	0.024 [0.018]	0.28 [0.021] *
Mexico	0.344 (0.1) [0.096] *	0.057 [0.04]	0.344 [0.116]	0.481 (1.1) [0.09] *	0.478 [0.119] *	0.481 [0.101] *	0.016 (0.4) [0.148]	0.204 [0.043] *	0.016 [0.022] *
Poland	0.047 (0.1) [0.146]	0.032 [0.019] ***	0.047 [0.053]	0.446 (1.7) [0.107] *	0.05 [0.048]	0.446 [0.041] *	−0.416 (0.1) [0.127] *	−0.035 [0.06]	−0.416 [0.187]
South Africa	0.294 (0.1) [0.091] *	0.076 [0.029] **	0.294 [0.094] **	0.444 (0.5) [0.076] *	−0.116 [0.264]	0.444 [0.164] *	0.202 (0.3) [0.13]	0.182 [0.036] *	0.202 [0.027] *
Turkey	0.132 (0.5) [0.097]	0.004 [0.001] *	0.132 [0] *	0.333 (0.1) [0.176] ***	1.625 [0.763] **	0.333 [1.927] **	−0.367 (1.2) [0.129] *	−0.049 [0.005] *	−0.367 [0.005] **
	Fishing Grounds Footprint			Forest Products Footprint			Grazing Land Footprint		
Countries	FURF Test Statistics	θ_1	θ_2	FURF Test Statistics	θ_1	θ_2	FURF Test Statistics	θ_1	θ_2
Argentina	0.45 (0.7) [0.082] *	0.043 [0.021] **	0.45 [0.022] *	0.132 (0.1) [0.098]	−0.559 [0.075] *	0.132 [0.254] *	0.395 (0.6) [0.093] *	0.419 [0.139] *	0.395 [0.121] **
Brazil	0.48 (4.1) [0.056] *	−0.003 [0.001] *	0.48 [0.001]	0.471 (0.1) [0.089] *	0.539 [0.226] **	0.471 [0.586] *	0.489 (0.8) [0.064] *	0.196 [0.025] *	0.489 [0.026] **
China	0.485 (0.7) [0.062] *	−0.02 [0.002] *	0.485 [0.003] *	0.487 (1) [0.036] *	0.014 [0.005] **	0.487 [0.003] *	0.477 (3.2) [0.078] *	0.002 [0.001] **	0.477 [0.001] *
India	0.482 (2.8) [0.063] *	−0.001 [0.001] *	0.482 [0.001]	0.472 (0.4) [0.053] *	0.018 [0.006] *	0.472 [0.003] *	0.432 (0.1) [0.113] *	−0.025 [0.005] *	0.432 [0.016] *
Indonesia	0.331 (0.3) [0.099] *	−0.017 [0.014]	0.331 [0.008] *	0.49 (0.1) [0.054] *	−2.88 [0.123] *	0.49 [0.362] *	0.295 (0.2) [0.09] *	−0.025 [0.009] *	0.295 [0.009] *
Korea	0.41 (0.4) [0.109] *	0.04 [0.018] **	0.41 [0.008] **	0.446 (1.4) [0.094] *	0.017 [0.007] **	0.446 [0.006] **	0.466 (0.1) [0.071] *	−1.034 [0.189] *	0.466 [0.579] **
Mexico	0.47 (1) [0.074] *	0.084 [0.015] *	0.47 [0.01]	0.489 (0.1) [0.067] *	−0.647 [0.578]	0.489 [1.394] *	0.055 (0.6) [0.1]	0.022 [0.007] *	0.055 [0.004] *
Poland	0.429 (0.7) [0.101] *	0.039 [0.012] *	0.429 [0.009] *	0.474 (0.1) [0.09] *	0.936 [0.337] *	0.474 [0.961] *	−0.175 (0.8) [0.129]	0.032 [0.008] *	-0.175 [0.005] *
South Africa	0.446 (0.4) [0.081] *	0.253 [0.087] *	0.446 [0.03] *	0.452 (0.7) [0.108] *	0.029 [0.03]	0.452 [0.038] **	0.38 (0.1) [0.111] *	0.33 [0.223]	0.38 [0.531]
Turkey	0.422 (4.6) [0.09] *	−0.008 [0.003] *	0.422 [0.004] ***	0.479 (1.5) [0.083] *	0.043 [0.012] *	0.479 [0.011] *	0.486 (1.8) [0.069] *	0.012 [0.006] *	0.486 [0.008] *

Notes: See the notes for Table 4

first draft of the manuscript. All authors read and approved the final manuscript.

Funding None, no fund received.

Data Availability Data is taken from the following website: http://data.footprintnetwork.org/#/.

Code Availability Codes are available upon reasonable request.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

Ethical Approval This article does not contain any studies with human participants performed by any of the authors.

Consent for Publication Not applicable.

Consent to Publish Not applicable.

References

Al-Mulali U, Weng-Wai C, Sheau-Ting L, Mohammed AH (2015) Investigating the environmental Kuznets curve (EKC) hypothesis by utilizing the ecological footprint as an indicator of environmental degradation. Ecol Ind 48:315–323
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
Bartelmus P (2008) Quantitative eco-nomics: How sustainable are our economies? Springer, Netherlands
Becker R, Enders W, Lee J (2006) A stationarity test in the presence of an unknown number of smooth breaks. J Time Ser Anal 27(3):381–409
Bilgili F, Ulucak R (2018) Is there deterministic, stochastic, and/or club convergence in ecological footprint indicator among G20 countries? Environ Sci Pollut Res 25(35):35404–35419
Bilgili F, Ulucak R, Koçak E (2019) Implications of environmental convergence: continental evidence based on ecological footprint. In energy and environmental strategies in the era of globalization. Springer, Berlin
Borucke M, Moore D, Cranston G, Gracey K, Iha K, Larson JE (2013) Accounting for demand and supply of the biosphere's regenerative capacity: the national footprint accounts' underlying methodology and framework. Ecol Ind 24:518–533
Bulut U (2021) Environmental sustainability in Turkey: an environmental Kuznets curve estimation for ecological footprint. Int J Sust Dev World 28(3):227–237
Christopoulos DK, Leon-Ledesma MA (2011) International output convergence, breaks, and asymmetric adjustment. Stud Nonlinear Dyn Econometrics 15(3):1–31
Destek MA, Okumus I (2019) Does pollution haven hypothesis hold in newly industrialized countries? Evidence from ecological footprint. Environ Sci Pollut Res 26(23):23689–23695
Elshimy M, El-Aasar KM (2020) Carbon footprint, renewable energy, non-renewable energy, and livestock: testing the environmental Kuznets curve hypothesis for the Arab world. Environ Dev Sustain 22:6975–7012
Enders W, Lee J (2012) The flexible Fourier form and Dickey-Fuller type unit root tests. Economics Lett 117(1):196–199
Erdogan S, Okumus I (2021) Stochastic and club convergence of ecological footprint: an empirical analysis for different income group of countries. Ecol Indicators 121(2001):107123
Gil-Alana LA, Yaya OS (2020) Testing fractional unit roots with non-linear smooth break approximations using Fourier functions. J Appl Stat. https://doi.org/10.1080/02664763.2020.1757047
Global Footprint Network (2021), http://data.footprintnetwork.org/#/, (accessed on 10.06.2021)
Heil MT, Selden TM (1999) Panel stationarity with structural breaks: carbon emissions and GDP. Appl Econ Lett 6(4):223–225
Khan A, Chenggang Y, Xue Yi W, Hussain J, Sicen L, Bano S (2021) Examining the pollution haven, and environmental kuznets hypothesis for ecological footprints: an econometric analysis of China, India, and Pakistan. J Asia Pacific Econ 26:462–482
Kitzes J, Audrey P, Goldfinger S, Wackernagel M (2007) Current methods for calculating national ecological footprint accounts. Sci Environ Sustain Soc 4(1):1–9
Kruse R (2011) A new unit root test against ESTAR based on a class of modified statistics. Stat Pap 52(1):71–85
Lanne M, Liski M (2004) Trends and breaks in per-capita carbon dioxide emissions, 1870–2028. Energy J 25(4):41–65
Lee CC, Chang CP (2008) New evidence on the convergence of per capita carbon dioxide emissions from panel seemingly unrelated regressions augmented Dickey-Fuller tests. Energy 33(9):1468–1475
Lee CC, Chang CP (2009) Stochastic convergence of per capita carbon dioxide emissions and multiple structural breaks in OECD countries. Econ Model 26(6):1375–1381
Lee CC, Chen MP (2021) Ecological footprint, tourism development, and country risk: international evidence. J Clean Prod 279:123671
Narayan PK, Popp S (2010) A new unit root test with two structural breaks in level and slope at unknown time. J Appl Stat 37(9):1425–1438
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
Ozcan B, Danish, Bozoklu S (2021) Dynamics of ecological balance in OECD countries: sustainable or unsustainable? Sustain Prod Consum 26:638–647
Pata UK (2021) Renewable and non-renewable energy consumption, economic complexity, CO_2 emissions, and ecological footprint in the USA: testing the EKC hypothesis with a structural break. Environ Sci Pollut Res 28(1):846–861
Pata UK, Aydin M (2020) Testing the EKC hypothesis for the top six hydropower energy-consuming countries: evidence from Fourier Bootstrap ARDL procedure. J Clean Prod 264:121699
Pata UK, Kumar A (2021) the influence of hydropower and coal consumption on greenhouse gas emissions: a comparison between China and India. Water 13(10):1387
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
Robinson PM (1994) Efficient tests of nonstationary hypotheses. J Am Stat Assoc 89:1420–1437
Rudolph A, Figge L (2017) Determinants of ecological footprints: What is the role of globalization? Ecol Ind 81:348–361
Sarkodie SA (2021) Environmental performance, biocapacity, carbon and ecological footprint of nations: drivers, trends and mitigation options. Sci Total Environ 751:141912
Solarin SA (2019) Convergence in CO_2 emissions, carbon footprint and ecological footprint: evidence from OECD countries. Environ Sci Pollut Res 26(6):6167–6181

Solarin SA (2020) Towards sustainable development: a multi-country persistence analysis of forest products footprint using a stationarity test with smooth shifts. Sustain Dev 28(5):1465–1476
Solarin SA, Bello MO (2018) Persistence of policy shocks to an environmental degradation index: the case of ecological footprint in 128 developed and developing countries. Ecol Ind 89:35–44
Solarin SA, Gil-Alana LA, Al-Mulali U (2018) Stochastic convergence of renewable energy consumption in OECD countries: a fractional integration approach. Environ Sci Pollut Res 25(18):17289–17299
Solarin SA, Tiwari AK, Bello MO (2019) A multi-country convergence analysis of ecological footprint and its components. Sustain Cit Soc 46:101422
Solarin SA, Gil-Alana LA, Lafuente C (2021a) Persistence and non-stationarity in the built-up land footprint across 89 countries. Ecol Indicators 123:107372
Solarin SA, Gil-Alana LA, Lafuente C (2021b) Persistence and sustainability of fishing grounds footprint: Evidence from 89 countries. Sci Total Environ 751:141594
Sultana N, Rahman MM, Khanam R (2021) Environmental kuznets curve and causal links between environmental degradation and selected socioeconomic indicators in Bangladesh. Environ Dev Sustain. https://doi.org/10.1007/s10668-021-01665-w
Tiwari AK, Kyophilavong P, Albulescu CT (2016) Testing the stationarity of CO_2 emissions series in Sub-Saharan African countries by incorporating nonlinearity and smooth breaks. Res Int Bus Financ 37:527–540
Tkacz G (2001) Estimating the fractional order of integration of interest rates using a wavelet OLS estimator. Stud Nonlinear Dyn Econom 5(1):19–32
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
Ulucak R, Lin D (2017) Persistence of policy shocks to ecological footprint of the USA. Ecol Ind 80:337–343
Van den Bergh JC, Verbruggen H (1999) Spatial sustainability, trade and indicators: an evaluation of the "ecological footprint." Ecol Econ 29(1):61–72
Wackernagel M, Rees W (1996) Our ecological footprint: reducing human impact on the earth. New Society Publishers, Gabriola Island
Wackernagel M, Yount JD (2000) Footprints for sustainability: the next steps. Environ Dev Sustain 2:21–42
Yaya OS, Ogbonna AE, Mudida R, Abu N (2021) Market efficiency and volatility persistence of cryptocurrency during pre-and post-crash periods of Bitcoin: evidence based on fractional integration. Int J Financ Econ 26(1):1318–1335. https://doi.org/10.1002/ijfe.1851
Yilanci V, Pata UK (2020a) Are shocks to ecological balance permanent or temporary? Evidence from LM unit root tests. J Clean Prod 276:124294
Yilanci V, Pata UK (2020b) Convergence of per capita ecological footprint among the ASEAN-5 countries: evidence from a non-linear panel unit root test. Ecol Indicators 113:106178
Yilanci V, Gorus MS, Aydin M (2019) Are shocks to ecological footprint in OECD countries permanent or temporary? J Clean Prod 212:270–301
Yilanci V, Ulucak R, Ozgur O (2021) Insights for a sustainable environment: analysing the persistence of policy shocks to ecological footprints of Mediterranean countries. Spat Econ Anal. https://doi.org/10.1080/17421772.2021.1919313