Environmental Science and Pollution Research (2018) 25:35404–35419
https://doi.org/10.1007/s11356-018-3457-1

RESEARCH ARTICLE

Is there deterministic, stochastic, and/or club convergence in ecological footprint indicator among G20 countries?

Faik Bilgili[1] · Recep Ulucak[1]

Received: 11 May 2018 / Accepted: 12 October 2018 / Published online: 22 October 2018

Abstract

Ecological footprint has been widely accepted as an indicator of environmental performance in recent years since it considers carbon dioxide emissions, the collapse of fisheries, the change in land use, and deforestation. This paper investigates, if exists, the convergence in per capita ecological footprint among G20 countries by employing the annual data for the period 1961 to 2014. A bootstrap-based panel KPSS test with structural breaks and club convergence test are carried out. Eventually, this paper is expected to contribute to the literature of natural resources and ecology/environment by (1) monitoring the panel variable of ecological footprint, (2) launching stochastic and deterministic convergence analyses, and (3) estimating the club convergence parameters. In conclusion, the confirmative results in favor of environmental convergence are obtained by exhibiting the stochastic and deterministic convergences and deriving the output of merging clubs.

Keywords Environmental convergence · Ecological footprint · Global environmental policies · Deterministic convergence · Stochastic convergence · Club convergence

Introduction

Environmental threats have become a major concern to be collectively dealt with by all countries (Charfeddine et al. 2018). Especially, global warming and thus climate change have been a serious threat and collective actions of countries have become even more important since climate change is a global common problem and requires common resource management and governance (Cooper, 2018). Therefore, countries should have common environmental quality understanding against the developments threatening the nature. To this end, observing current and future (forecast) environmental conditions of countries through a comprehensive environmental indicator, in order to track their efforts in struggling with environmental threats, might be useful for policy implications (Isman et al., 2017; Solarin & Bello, 2018; Ulucak & Apergis, 2018). For example, it is expected that the countries, which convergence in environmental quality understanding, will be able to implement their common environmental policies more effectively in the context of a common environmental quality framework against threats to nature. So, environmental convergence becomes crucial for policy implications (Aldy, 2006; Apergis, Payne, & Topcu, 2017; Burnett, 2016; Herrerias, 2013).

There exists really a notable concern about the environmental threats (such as global warming, climate change, ozone depletion, and air or water pollution) because of the destructive effects of the threats on human welfare. Thereby, this concern leads researchers to provide administrators and/or societies regarding policy recommendations based on their empirical analyses in order to prevent the societies from relevant threats. Determining convergence of countries in environmental indicators such as pollution, carbon emission, or ecological footprint might help researchers/administrators to observe the speed and/or efficiency and/or success of environmental policies. One might assert that such policies will be more successful in case of convergence than the policies in case of divergence of countries in pollution or carbon emission or ecological footprint. Therefore, the issue whether or not countries converge takes great attention in the literature (e.g., Acar & Lindmark, 2017; Acar, Söderholm, & Brännlund, 2017;

Responsible editor: Philippe Garrigues

✉ Recep Ulucak
r.ulucak@erciyes.edu.tr

Faik Bilgili
fbilgili@erciyes.edu.tr

[1] Faculty of Economics and Administrative Sciences, Erciyes University, Kayseri, Turkey

Acaravcı & Erdogan, 2016; Ahmed, Khan, Bibi, & Zakaria, 2016; Apergis & Payne, 2017; Burnett, 2016).

Empirical evidence in favor of convergence indicates that countries have same transition path and per capita values of the environmental variables are becoming equal over time (Herrerias, 2013). In other words, countries will eventually have the same quality or degradation level in terms of environmental values. Thusly, a common environmental policy within these countries could be implemented and it is quite likely to be successful (Acaravcı & Erdogan, 2016; Presno et al. 2015; Romero-Ávila, 2008; Westerlund & Basher, 2008). Kyoto and Paris agreements underline important implications with respect to environmental convergence and environmental common policies (Burnett, 2016).

Target variables are also important as a proxy to represent degradation in environment. Although CO_2 emissions are widely analyzed to constitute policy rules, other pollution types (degradations in soil, forest, water, etc.) are also noteworthy in struggling with ecological threats since they have interactive roles within ecosystem. In this respect, ecological footprint indicator developed by Wachernagel & Rees (1996) has attracted great attention recently.

Ecological footprint observes the environmental statistical fact regarding the natural resources which are demanded by human activities (Kitzes & Wackernagel 2009; Wackernagel 2002). Conceptually, it is considered as a burden of consumption and production activities of people on the nature (Bartelmus (2008). It consists of six components (Cropland, Grazing Land, Fishing Grounds, Forest Land, Built-Up Land and Carbon Footprint) and it includes the CO_2 emissions within the carbon footprint. Thus, the ecological footprint has been considered as a prominent and meaningful indicator to measure the environmental degradation or sustainability within the environmental literature (Neumayer 2004; Nijkamp et al. 2004; Dietz et al. 2007; Bartelmus 2008; Cordero et al. 2008; Caviglia-Harris et al. 2009; Kitzes & Wackernagel 2009; Wiedmann & Barrett 2010; Bastianoni et al. 2012; Galli et al. 2012; Borucke et al. 2013).

The current literature employs CO_2 emissions to investigate the environmental convergence as shown in Strazicich & List (2003), Aldy (2006, 2007), Brock & Taylor (2010), Li & Lin (2013), Wang et al. (2014), Presno et al. 2015), Tiwari et al. (2016), Apergis & Payne (2017). However, employing only CO_2 emissions in environmental analyses has been criticized (see Arrow et al., 1995 and Stern, 2003) due to the fact that environmental pollution consists of not only CO_2, but also other parts of pollution types (water pollution, deforestation, wastes, etc.). Additionally, carbon emissions might be decreased through technological innovations or deterrent laws while the level of other pollution types increases (Stern, 2014). Though all pollutants cannot be properly measured in relevant models, a model with more inclusive environmental variable might yield more reliable and valid results. Ecological footprint may be more appropriate variable than CO_2 emissions to measure the environmental degradation since it provides a basis for setting goals, identifying options for actions, and tracking progress toward stated goals (Borucke et al., 2013; Mancini et al., 2017; Ulucak & Lin, 2017). Actually, it has been widely used as an indicator of environmental degradation variable by several research articles in recent times (e.g., Ulucak & Bilgili, 2018; Pablo-Romero & Sánchez-Braza, 2017; Charfeddine & Mrabet, 2017; Charfeddine, 2017; Aşıcı & Acar, 2016; Ozturk et al. 2016; Al-Mulali et al. 2015; Hervieux & Darné, 2015).

This manuscript aims at investigating the environmental convergence hypothesis by using the ecological footprint for G20 countries. Some empirical methodologies introduced in the "Data and methodology" section have been employed to be able to detect probabilities of stochastic, deterministic, and club convergence through annual data from 1961 to 2014. The annual data is the last updated data from The Global Footprint Network (2017). To do best of our knowledge, this is the first paper to investigate the convergence in environmental quality by using the ecological footprint indicator for G20 countries. G20 group is a mix of the world's largest developed and developing economies, representing about two thirds of the world's population, 85% of global gross domestic product, and over 75% of global trade. G20 declares to prioritize green growth policies by promoting low-carbon development strategies in order to achieve sustainable green growth goals. If declarations are pertinaciously practiced by its members, the G20 may be a perfect forum to deal with environmental issues as stated by Oliveira & Silveira (2014). So, implications of this study provide the inspiration for policy makers and contribute to the literature throughout empirical investigations on time series and cross sections developments of ecological footprint.

The rest of the manuscript is organized as follows: the next section briefly summarizes the environmental convergence literature, then, the third section introduces the data and empirical methodologies. Later, the fourth section evaluates the estimation output of this research and the fifth section reveals the conclusions, discussion points, and relevant policy implications.

Literature review

The existence of environmental convergence might yield important implications. It enables policy makers to determine appropriate strategies in order to reduce adverse effects of pollution and other threats on the environment (Aldy, 2006; Burnett, 2016; Herrerias, 2013). For instance, the common environmental policies could be implemented by convergent countries successfully (Ahmed et al., 2016) and convergent countries can struggle collectively with environmental threats.

It makes easier to protect the global climate system by agreeing the common emission abatement obligations as indicated in Kyoto or Paris Climate agreements (Westerlund & Basher 2008). The convergence can also imply that countries are converging toward a common understanding of global threats. The empirical basis of common environmental policies might be strengthened by paying more attention to the economic, social, or institutional sources of environmental degradation (Pettersson et al. 2014).

The convergence analyses in the literature have been conducted with several different concepts. Following the implications of neoclassical growth model developed by Solow (1956), the negative correlation between initial and subsequent values of a variable that is originally investigated by per capita income is known as β-convergence (Barro & Sala-i-Martin, 1992). It is also called absolute or unconditional convergence under the assumption of same growth dynamics for all countries (Islam, 2003). Contrary to unconditional convergence, the steady state characteristics of individual countries imply "conditional convergence," and each economy has particular steady state equilibrium, and each country approaches to its own equilibrium in this concept. Similarly, if economies are grouped by common characteristics as given in Durlauf & Johnson (1995) and Galor (1996), each group has the same steady state equilibrium, and each group reaches its own equilibrium. This is known as "club convergence." For conditional convergence analyses, the proper countries should be selected among all other countries. By the same token, for club convergence analysis, the appropriate sub-groups are needed to be chosen from the available sample. On the other hand, two types of conditional β-convergence need to be mentioned based on specification in which the possible linear trend and slope shifts are included. These shifts are stochastic convergence and deterministic convergence (Carlino & Mills, 1993; Li & Papell, 1999). The another one is σ-convergence suggested by Quah (1993), and it analyzes whether the distribution of income across countries becomes equal or not (Young, Higgins, & Levy, 2008).

One might observe throughout the relevant literature review that the seminal works focusing on CO_2 emissions to investigate the environmental convergence reveal similar and/or different outputs. Table 1 explores the relevant seminal works, period, country, the methodology, variable, and empirical output. Different potential output of the works might stem from the papers' own different methodologies, data set, and regions. Considering CO_2 emissions, some papers in the literature have examined the convergence across regions (e.g., Aldy, 2007; Apergis & Payne, 2017; Baldwin & Wing, 2013; Burnett, 2016; Huang & Meng, 2013; Wang et al., 2014; Wu et al. 2016; Yang et al. 2016), as some papers have investigated the same issue across sectors by using industry-specific data (e.g., Apergis & Payne, 2017; Brännlund et al. 2015; Mishra & Smyth, 2017; Moutinho et al. 2014; Wang & Zhang, 2014). The considerable part of the literature has explored the convergence across the countries.

The seminal papers which analyze the environmental convergence hypothesis by using CO_2 emissions can also be grouped by their methodologies. Lanne & Liski (2004), Strazicich and List (2003), Aldy (2007), Lee & Chang (2008), Lee, Chang, & Chen (2008), Westerlund & Basher (2008), Nourry (2009), Li et al. (2014), Presno et al. 2015), Tiwari et al. (2016), Acaravcı & Erdogan (2016), and Ahmed et al. (2016) conduct unit root approach to investigate stochastic convergence while Panopoulou & Pantelidis (2009), Herrerias (2013), Yan et al. (2017), Burnett (2016), Apergis & Payne (2017), and Ulucak & Apergis (2018) follow club convergence procedures proposed by (Phillips & Sul, 2007). On the other hand, Yang et al. (2016), de Oliveira and Bourscheidt (2017), Aldy (2006), and Li & Lin (2013) conduct the test for convergence by using regression approach in dynamic specification. Ordás Criado & Grether (2011), Li et al. (2017), and Huang & Meng (2013) consider spatial properties of the countries, Brock and Taylor (2010) foreground cross section dimensions, Pennino et al. (2017) use Gaussian kernel density functions and transition probability matrix, Acar et al. (2017) perform meta-analysis and Kounetas (2018) applies distribution dynamics analysis in order to investigate convergence. Following current literature, one might claim that unit root and club convergence approaches are widely preferred for determining convergence.

Current literature can be classified by their sample selection and results. In this manner, convergence is verified for Chinese regions by Boussemart et al. (2015), Yang et al. (2016), Huang & Meng (2013), and Long et al. (2017). No convergence and mixed results are produced for the United States in general by Aldy (2007), Li et al. (2014), Burnett (2016), and Apergis & Payne (2017). Evidence for convergence is revealed for OECD countries by Lee, Chang, & Chen (2008), Presno et al. 2015), and Acar & Lindmark (2017) while Nourry (2009) disconfirms convergence for OECD countries. Analyzing EU countries, Jobert, Karanfil & Tykhonenko (2010) confirm convergence while Kounetas (2018) disconfirms it. Other studies in the literature tabulated in Table 1 find different results for various samples. However, to the best of our knowledge, any study investigating environmental convergence for G20 countries is not available in the literature.

Data and methodology

This manuscript follows annual data of ecological footprint per capita provided by Global Footprint Network for the period 1961–2014. The data is the most recent updated data (The Global Footprint Network, 2017). G20 countries have been selected among other countries because of some identical

Table 1 Summary literature review

Researchers	Sample	Methodology	Indicator	Results
Lanne and Liski (2004)	16 countries	Panel unit root	Carbon dioxide emissions	No convergence
Boussemart et al. (2015)	30 Chinese regions	Non-parametric approach	Carbon dioxide emissions	Convergence
Yang et al. (2016)	Chinese provinces	Panel GMM, fixed, random effect	Carbon dioxide emissions	Convergence
de Oliveira and Bourscheidt (2017)	40 countries	Panel GMM, fixed, random effect	Carbon emissions and methane	Convergence
Strazicich and List (2003)	21 countries	Panel unit root	Carbon dioxide emissions	Stochastic conditional convergence
Nguyen Van (2005)	100 countries	Non-parametric approach	Carbon dioxide emissions	Mixed for different samples
Aldy (2006)	88 countries	DF-GLS, Markov chain	Carbon dioxide emissions	Mixed for different samples
Aldy (2007)	US states	Panel stationarity, Markov chain	Carbon dioxide emissions	No convergence
Lee and Chang (2008)	21 OECD countries	Panel unit root	Carbon dioxide emissions	Mixed results for different samples
Lee, Chang, & Chen (2008)	21 OECD countries	Stationarity analysis	Carbon dioxide emissions	Convergence
Westerlund and Basher (2008)	16 developed, 12 developing countries	Panel unit root	Carbon dioxide emissions	Convergence
Nourry (2009)	127 countries and OECD	Pair-wise approach, stationarity	Carbon and sulfur dioxide	Mixed results
Panopoulou and Pantelidis (2009)	128 countries	Panel club convergence	Carbon dioxide emissions	Club convergence
Jobert, Karanfil & Tykhonenko (2010)	EU countries	Bayesian estimation	Carbon dioxide emissions	Convergence
Brock and Taylor (2010)	173 countries	Cross-sectional approach	Carbon dioxide emissions	Convergence
Ordás Criado & Grether (2011)	Different regions	Spatial distribution analysis	Carbon dioxide emissions	Convergence
Herrerias (2013)	162 countries	Panel club convergence and Pair-wise stationarity	Carbon dioxide emissions	Mixed results for different samples
Yan et al. (2017)	72 countries	Panel club convergence	Low-carbon technology level	Club convergence
Li et al. (2017)	Yangtze River Delta	Spatial panel data	Carbon dioxide emissions	Convergence
Li and Lin (2013)	110 countries	Panel GMM	Carbon dioxide emissions	Convergence
Huang and Meng (2013)	Provinces of China	Spatial panel data	Carbon dioxide emissions	Convergence
Li et al. (2014)	50 US states	SPSM	Carbon dioxide emissions	Mixed results for different samples
Presno et al. 2015)	28 OECD countries	Stationarity	Carbon dioxide emissions	Convergence
Burnett (2016)	US states	Panel club convergence	Carbon dioxide emissions	Mixed results for different samples
Tiwari et al. (2016)	35 Sub-Saharan countries	Stationarity	Carbon dioxide emissions	Convergence
Ahmed et al. (2016)	162 countries	Wavelet stationarity	Carbon dioxide emissions	Mixed results for different samples
Acaravcı and Erdogan (2016)	7 regions of the World	Panel unit root	Carbon dioxide emissions	Convergence
Acar and Lindmark (2016)	86 Countries	Regression analysis	Carbon dioxide emissions	Mixed results
Apergis and Payne (2017)	US states	Panel club convergence test	Carbon dioxide emissions	Mixed results for different samples
Acar and Lindmark (2017)	OECD	Regression analysis	Carbon dioxide emissions	Convergence
Long et al. (2017)	China's cement manufacturers	Stationarity, Panel Fixed and Random effect	Eco-efficiency	Convergence
Pennino et al. (2017)	Mediterranean countries	Gaussian kernel density functions and transition probability matrix	Three different ecological indicators	Convergence
Ulucak & Apergis (2018)	EU countries	Panel club convergence test	Ecological footprint	Convergent clubs
Acar et al. (2017)	Industrialized countries	Meta-analysis	Carbon dioxide emissions	Convergence
Kounetas (2018)	EU countries	Distribution dynamics analysis	Carbon dioxide, energy consumption	No convergence

structures. For instance, G20 are probably near their steady states (Bernard & Durlauf, 1996; Romero-Ávila, 2008). The countries are Argentina, Australia, Brazil, China, Canada, France, Germany, India, Indonesia, Italy, Japan, South Korea, Mexico, South Africa, Turkey, UK and the USA. Russia and Saudi Arabia have been excluded from the sample because of some unavailable data points.

The main purpose of ecological footprint calculations is to annually observe how much biologically productive capacity of the world is needed for consumption and production activities of people (Kitzes & Wackernagel, 2009). Biologically productive sea and land areas for fishing grounds, crops, grazing, forest, and built-up are considered in ecological footprint calculations to measure required areas, natural resources consumption, and wastes by transforming plenty of environmental data into one indicator. A wide range of related databases of international organizations, such as International Energy Agency (IEA), International Panel on Climate Change (IPCC) database, United Nations (UN) commodity trade statistics database, Food and Agricultural Organization (FAO) production database, FAO trade database, FAO technical conversion factors, FAO fisheries statistical database, FAO ForeSTAT statistical database, Global Forest Resources Assessment, Global Agro-Ecological Zones (GAEZ), FAO ResourceSTAT statistical database, and Global land use database, provide data for footprint calculations. Having considered the differences in land types of countries by using balancing factors that standardize land use types, cropland footprint, grazing land footprint, fishing grounds footprint, forest land footprint, built-up land footprint, and carbon footprint are separately calculated and the sum of these calculations yields the size of ecological footprint.

Ecological footprint represents the area in global hectares required to meet consumption of people and the area needed to absorb the carbon dioxide emissions in a country or region (Lin et al. 2016). The need of productive areas increases as ecological footprint becomes larger. Thereby, the rise of ecological footprint is undesired because it causes degradation in environment. Hence, efficient policies have vital importance to healthfully sustain life. Global Footprint Network institutionally calculates and shares ecological footprint data for over 180 countries and calculation procedures are introduced by Lin et al. (2016) and Lazarus et al. (2014) in detail.

CO_2 emissions emitted by people or firms during a year or to the tones of carbon emitted in the production sectors are also considered by carbon footprint calculations and carbon footprint has the largest share in total calculation (see https://www.footprintnetwork.org). Therefore, ecological footprint might be a useful indicator to follow environmental targets against global warming or climate change (Cordero et al., 2008; Isman et al., 2017). The European Environment Agency (EEA 2010, 2015), the European Parliament, the European Commission (Best et al., 2008), and the United Nations Development Program monitor the ecological footprint as a useful tool in evaluating environmental performance of countries (UNDP, 2014). Wiedmann & Barrett (2010) make a review of more than 150 articles and survey on people who are interested in ecological indicators to determine the usefulness of ecological footprint. They report that it is most useful as a part of basket indicators and it is seen as a strong communication tool. Zhang, Dzakpasu, Chen, & Wang (2017) explore validity and utility of ecological footprint and they state that ecological footprint is advantageous over other methodologies in analyzing sustainability. Due to its growing popularity, ecological footprint has been widely used as an indicator in the literature (e.g., Acar & Aşıcı, 2017; Al-mulali, Solarin, Sheau-Ting, & Ozturk, 2016; Bello, Solarin, & Yen, 2018; Rashid et al., 2018; Solarin & Al-Mulali, 2018; Solarin & Bello, 2018; Ulucak & Erdem, 2017).

The group of 20 largest and richest economies declared to prioritize green growth policies at Mexico Summit in 2012 and to sustain this matter to be the agenda topic at subsequent summits.[1] The green growth debates have already been the agenda topic of meetings in the context of sustainability under the guidance of the United Nations since 1970s. Another consideration to be mentioned is that G20 members have come to terms for promoting low-carbon development strategies in order to achieve sustainable green growth goals. Additionally, forthcoming policies to encourage innovations and deployment of clean and efficient energy technologies have been decided to put into practice by leaders (see G20, 2011) since such technologies on renewable energy sources are crucial for better environmental condition and low-carbon footprint (Kahia et al. 2017a, b). So, convergence in environmental conditions might occur among G20 countries. On the other hand, the G20 group is a mix of the world's largest developed and developing economies, representing about two thirds of the world's population, 85% of global gross domestic product, and over 75% of global trade. Therefore, if the countries have common policies against environmental threats, the fight against global warming might be successful. G20 would look like the perfect forum to deal with environmental issues (Oliveira & Silveira, 2014).

Figure 1 depicts per capita footprint series for each country for the period 1961–2014. USA, Canada, and Australia have largest ecological footprint per capita although they have started to decrease their footprints and seem to reach average value of full samples. India and Indonesia have the smallest per capita values with nearly horizontal appearance. The other countries have almost followed similar trends approaching same frontier line in the figure in recent years. Common movements toward same frontier in general might be a little evidence for convergence since convergence is interpreted

[1] G20 Leaders Declaration, Las Cabos, Mexico. http://www.consilium.europa.eu/uedocs/cms_Data/docs/pressdata/en/ec/131069.pdf

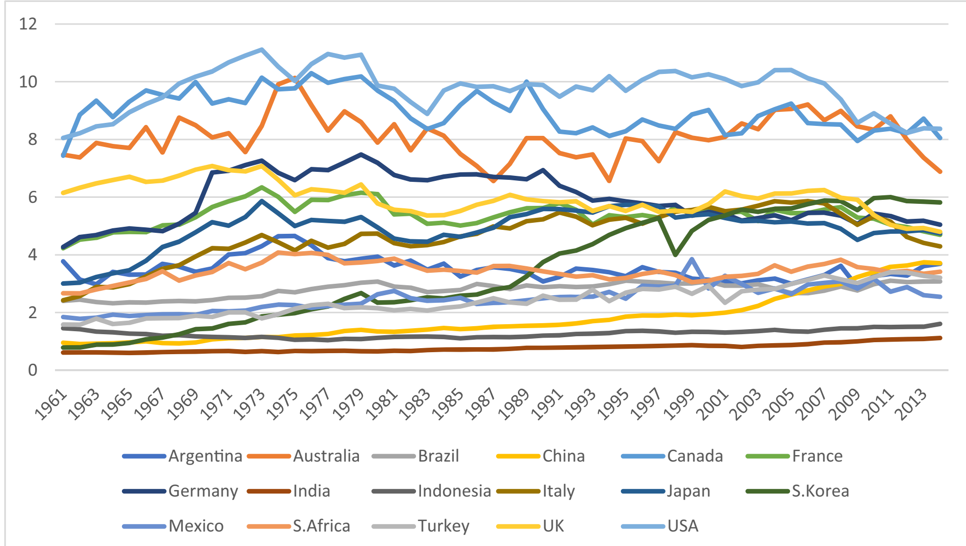

Fig. 1 Ecological footprint series for G20 countries (1961–2014)

that countries have the same transition path and per capita values of the environmental variables are becoming equal over time (Herrerias, 2013). However, more explicit empirical evidence about convergence might be revealed through stationarity analyses in the "Empirical results" section.

Panel unit root tests are commonly used in the relevant literature to analyze convergence across countries or regions. The result is conditional β-convergence if relevant test statistics cannot reject stationarity. (Islam, 2003). A researcher might also need to pay attention that individual effects, which may vary across countries, should be included into the analysis of testing the conditional β-convergence (Charles, Darne, & Hoarau, 2012). Thereby, panel unit root tests considering individual effects are convenient for conditional beta convergence since they are based on negative correlation between initial and subsequent values of a variable. While stochastic convergence is confirmed in case of stationarity (Carlino & Mills, 1993), the deterministic convergence requires (1) elimination of the deterministic trend (Herrerias, 2013; Romero-Ávila, 2008) and/or (2) structural breaks in the trend to eliminate the deterministic trend (Li & Papell, 1999).

Panel data literature comprises alternative unit root tests that are relatively more powerful under some circumstances. Some papers assume that cross sections are dependent and do not consider cross section dependence problem (Choi, 2001; Harris & Tzavalis 1999; Hadri 2000; Im et al. 2003; Levin, et al. 2002; Maddala & Wu, 1999) while some other papers take into account of the dependence issue (Hadri & Kurozumi, 2012; Carrion-i-Silvestre et al. 2005; Moon & Perron, 2004; Pesaran, 2007; Smith et al. 2004). These relevant works follow "first generation" and "second generation" panel unit root tests, respectively.

Under cross-sectional dependence, described as the interaction between cross-sectional units, a second generation panel unit root analyses are expected to exhibit more efficient and consistent estimations, because cross-sectional dependence leads to efficiency loss for least squares and invalidates conventional t tests and F tests (Baltagi, Feng, & Kao, 2012). Hence, the first step in our analysis is to determine whether the data is cross-sectionally dependent. Pesaran et al. (2008) propose a bias-adjusted type of Breusch & Pagan (1980). Following Breusch & Pagan (1980), LM (Lagrange multiplier) statistic is given below:

$$LM = T \sum_{1=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij}^2 \quad (1)$$

where $\hat{\rho}_{ij}$ denotes sample estimate pair-wise correlation of the residuals. The term, (ϑ_{it}) then is the estimate of residuals from OLS (u_{it}) and $\hat{\rho}_{ij}$ are calculated through Eq. 2.

$$\hat{\rho}_{ij} = \frac{\sum_{t=1}^{T} \vartheta_{it}\vartheta_{jt}}{\left(\sum_{t=1}^{T} \vartheta_{it}^2\right)^{1/2}\left(\sum_{t=1}^{T} \vartheta_{jt}^2\right)^{1/2}} \quad (2)$$

Pesaran et al. (2008) reformulated the LM statistics by following additional assumptions and introducing an idempotent matrix (see Pesaran et al. 2008, 108).

$$LM_{adj} = \sqrt{\frac{2}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{(T-k)\hat{\rho}_{ij}^2 - \mu_{Tij}}{v_{Tij}} \quad (3)$$

where μ and v are the exact mean and variance of $(T-k)\hat{\rho}_{ij}^2$, respectively. The null hypothesis of the test states "no cross-sectional dependence" as depicted by H_0: Cov $(u_{it}, u_{jt}) = 0$, for all t, $i \neq j$. In case of weak dependence and heterogenous slopes in large panels with standard normal distribution, Pesaran (2015) proposes a new CD test approach based on the relative expansion rates of N and T:

$$CD = \sqrt{\frac{2}{N(N-1)}}\left(\sum_{i=1}^{T}\sum_{j=i+1}^{N}\sqrt{T}\hat{\rho}_{ij}\right) \tag{4}$$

The second step of our analysis is to apply unit root test to monitor the possibility of convergence or divergence. Unit root tests tend to accept the null hypothesis if the series have structural breaks (Perron, 1989) and they may lead biased and spurious results due to breaks in the time series data (Charfeddine & Ben Khediri 2016).

Structural breaks, that may stem from policy changes or from possible various shocks which are connected with the relevant variable, are more likely to occur over a longer time span. Ignoring structural breaks may lead to inconsistent estimation and invalid inference (Baltagi, Feng, & Kao, 2016).

Given the importance of structural breaks in the behavior of series, we have preferred to employ panel KPSS test that allows multiple structural breaks, proposed by Carrion-i-Silvestre et al. (2005). The model under the multiple breaks is constructed as follows:

$$x_{it} = \zeta_{it} + \beta_i t + \epsilon_{it} \tag{5}$$

$$\zeta_{it} = \sum_{k=1}^{m_i}\psi_{i,k} D\left(T^i_{b,k}\right)_t + \sum_{k=1}^{m_t}\delta_{i,k} DU_{i,k,t} + \zeta_{i,t-1} + v_{i,t} \tag{6}$$

where $v_{i,t} \sim i.i.d.\left(0,\sigma^2_v\right)$ and $k(k-1,\ldots m_i,\ m_i \geq 1)$ represents the number of breaks. The breaks are denoted by dummy variables within the model given in Eq. 6. The dummy variables are defined as (1) $D\left(T^i_{b,k}\right)_t = 1$ for $t = \left(T^i_{b,k}\right)_t + 1$ and 0 elsewhere, and (2) $DU_{i,\ k,\ t} = 1$ for $t > T^i_{b,k}$ and 0 elsewhere. For example, for the ith cross section, $T^i_{b,k}$ denotes kth date of break as $k = 1,\ldots, m_i$, $m_i \geq 1$. Then, the following model is established in order to test the null hypothesis implying stationarity $\left(H_0 : \sigma^2_{v,i} > 0\ for\ i = \forall 1,\ldots N\right)$.

$$x_{it} = \zeta_i + \sum_{k=1}^{mi}\psi_{i,k} DU_{i,k,t} + \beta_i t + \sum_{k=1}^{mi}\delta_{i,k} DT_{i,k,t} + v_{i,t} \tag{7}$$

The model given by Eq. 7 allows (1) structural breaks that might be located at different dates for each cross section and (2) different number of breaks for each cross section in the panel. There might exist different impacts of structural breaks on each individual time series. These impacts are observed by $\psi_{i,\ k}$ and $\delta_{i,\ k}$. Therefore, each one may have different effects on the sections. Following the panel unit root procedures proposed by Hadri (2000) who adapted a test statistics based on the average of the univariate stationarity test given in Kwiatkowski, Phillips, Schmidt, & Shin (1992), panel KPSS test is defined as

$$LM(\lambda) = \frac{1}{N}\sum_{i-1}^{N}\left(\hat{\omega}_i^{-2} T^{-2}\sum_{t-1}^{T}\hat{S}^2_{i,t}\right) \tag{8}$$

where $\hat{S}_{i,t} = \sum_{j=1}^{t}\hat{\varepsilon}_{i,j}$ signifies the partial sum process obtained from OLS residuals for Eq. 7 and $\hat{\omega}^2_i$ denotes its long run variance that allows the disturbances to be heteroscedastic. λ in Eq. 8 indicates that the LM test depends on the break dates. The breaks are determined by following Bai & Perron (1998) procedure. Having determined the optimal number of breaks, the panel KPSS test is normalized by Eq. 9.

$$Z\left(\hat{\lambda}\right) = \frac{\sqrt{N}\left(LM\left(\hat{\lambda}\right) - \overline{\xi}\right.}{\overline{\varsigma}} \tag{9}$$

where $\overline{\xi}$ and $\overline{\varsigma}$ are individual mean and variance of $\left(\hat{\lambda}_i\right)$,

Table 2 Panel KPSS test results (stochastic convergence)

		Bootstrap critical values			m	$Tb1$	$Tb2$
		10%	5%	1%			
Individual results							
Argentina	0.233	0.191	0.235	0.345	2	1970	1980
Australia	0.080	0.167	0.207	0.303	1	1972	–
Brazil	0.071	0.133	0.160	0.237	1	1973	–
China	0.075	0.161	0.201	0.314	2	1986	2003
Canada	0.087	0.151	0.180	0.264	2	1967	1990
France	0.075	0.188	0.230	0.338	2	1969	1980
Germany	0.163	0.143	0.171	0.241	2	1969	1991
India	0.178	0.170	0.219	0.331	2	1988	2006
Indonesia	0.090	0.156	0.189	0.277	2	1967	1993
Italy	0.041	0.154	0.192	0.276	2	1968	1986
Japan	0.079	0.159	0.192	0.273	1	1967	–
South Korea	0.172	0.139	0.171	0.255	2	1973	1990
Mexico	0.092	0.139	0.169	0.238	2	1972	1995
South Africa	0.051	0.147	0.181	0.256	2	1969	1989
Turkey	0.260	0.154	0.191	0.305	2	1985	2004
UK	0.018	0.190	0.240	0.337	1	1974	–
USA	0.050	0.247	0.305	0.442	2	1967	2006
Panel results							
Panel test[a]	0.612	2.872	3.742	5.346			
Panel test[b]	2.118	2.714	3.223	4.198			

m is the number of structural breaks, T_{b1} and T_{b2} depict the structural break dates of break 1 and break 2, respectively. [a] is under assumption of homogeneity of long run variance, [b] is under assumption of heterogeneity of long run variance

Table 3 Panel KPSS test results (deterministic convergence)

		Bootstrap critical values			m	T_{b1}	T_{b2}
		10%	5%	1%			
Panel A: individual results							
Argentina	0.076	0.098	0.133	0.195	1	1976	–
Australia	0.071	0.099	0.127	0.199	0	–	–
Brazil	0.027	0.100	0.133	0.204	2	1973	2004
China	0.032	0.115	0.146	0.212	2	1992	2002
Canada	0.059	0.103	0.135	0.201	1	1979	–
France	0.032	0.089	0.120	0.203	1	1971	–
Germany	0.037	0.091	0.126	0.193	2	1969	1991
India	0.024	0.108	0.142	0.208	2	1988	2001
Indonesia	0.035	0.104	0.135	0.204	1	1975	–
Italy	0.113	0.099	0.124	0.188	2	1973	2005
Japan	0.036	0.097	0.129	0.195	2	1973	1987
South Korea	0.049	0.082	0.110	0.164	1	1985	–
Mexico	0.108	0.123	0.162	0.243	0	–	–
South Africa	0.019	0.100	0.128	0.198	2	1973	2003
Turkey	0.139	0.099	0.132	0.203	1	1980	–
UK	0.026	0.093	0.125	0.192	2	1979	2006
USA	0.028	0.102	0.133	0.211	2	1979	2003
Panel B							
Panel test[a]	2.874	3.516	4.314	5.894			
Panel test[b]	3.005	5.811	6.635	8.249			

m is the number of structural breaks, T_{b1} *and* T_{b2} depict the structural break dates of break 1 and break 2, respectively. [a] is under assumption of homogeneity of long run variance, [b] is under assumption of heterogeneity of long run variance

respectively. Therefore, the test statistic has the asymptotic standard normal distribution. However, bootstrap critical values are calculated by following Maddala & Wu (1999) in order to take into account of cross section dependence.

Another approach in convergence literature is club convergence. Phillips and Sul (2007) propose a club convergence test (PS). The PS test, which considers heterogeneities, is based on a non-linear time-varying factor model. Thus, results are efficient, consistent, and unbiased under the existence of heterogeneity and stationarity (Burnett, 2016). In this procedure, convergence is determined by convergent factor loadings r_{it}. By using individual average of the series, the transition path h_{it} is computed $\overline{log_t}$ by $h_{it} = logy_{it}/\overline{log_t}$. Finally, cross-sectional variation ratio (H_1/H_t) is constructed as given in Eq. (10):

$$H_t = \frac{1}{N}\sum_{i=1}^{N}(h_{it}-1)^2 \quad (10)$$

Having determined the distance of the panel from the common limit is calculated through Eq. (9), the null hypothesis of convergence for each individual is established as $H_0: r_i = r_t and\ \alpha \geq 0$, $H_A: r_i \neq r_t and\ \alpha < 0$. The null hypothesis then is tested by *Log t* regression in Eq. (11).

$$\log(H_1/H_t) - 2logL(t) = c + b\ logt + u_t \quad (11)$$

The null hypothesis that states relative/conditional convergence is rejected at 95% confidence interval if the one-sided t test < -1.65. Later, clustering procedure starts to determine convergent units. To this end, units are arrayed by their last observation and the *log t test* is run to determine convergence for the first k highest units in order to form the sub-group(s). This procedure is repeated for the remaining units to filter each unit for club membership and to form the first convergence club.

Empirical results

Before applying panel unit root test, the cross section dependence is firstly checked by performing Breusch & Pagan (1980)

Table 4 Panel unit test results

	Constant		Constant and trend	
	Statistic	p value	Statistic	p value
Hadri & Kurozumi (2012)				
Z_A^{SPC}	−0.6556	0.7440	−1.3859	0.8526
Z_A^{LA}	0.5045	0.3070	−2.3451	0.8937
Moon & Perron (2004)				
t_α^*	−3.529	0.008	−1.451	0.101
t_b^*	−3.216	0.004	−1.302	0.103
Smith et al. (2004)				
*Max**	−1.954	0.057	−2.185	0.036
*Min**	3.829	0.065	4.577	0.030
*WS**	−3.137	0.028	−3.814	0.018

Table 5 Club convergence test results

		Coefficient	t statistic
First convergence club	India, Italy, Japan, Mexico, Turkey, Argentina, China, and South Korea	0.380	4.821
Second convergence club	Australia, Brazil, Canada, France, Germany, Indonesia, South Africa, the UK, and the USA)	0.816	7.096
Club merging statistic (club 1 + club 2)	India, Italy, Japan, Mexico, Turkey, Argentina, China, South Korea, Australia, Brazil, Canada, France, Germany, Indonesia, South Africa, the UK, and the USA)	0.257	2.036

LM test, Pesaran et al. (2008) LM_{adj} test, and Pesaran (2015) CD test. The statistics for LM, LM_{adj}, and CD tests are 291.685 (with a p value = 0.000), 336.214 (with a p value = 0.000), and 104.476 (with a p value = 0.000) respectively. These results reveal that the null hypothesis of no cross-sectional dependence is strongly rejected, and, that bootstrap critical values should be used for panel KPSS test to consider the dependence problem. Then, panel KPSS test is carried out for the cases of stochastic and deterministic convergence. The results are presented in Table 2 for stochastic convergence. Column 3 in Table 2 shows individual test statistics for each country. The test statistics for Turkey and South Korea exceed the critical values of 10% and 5%. The statistics for Argentina, Germany, and India exceed critical value of 10%. However, for all other countries, the test statistics fall within the region of acceptance. Thusly, null hypothesis of stationarity cannot be rejected. Panel results given at the bottom of tables yield as well that the null hypothesis of panel stationarity cannot be rejected.

Deterministic convergence results are tabulated in Table 3. In this case, the test statistics for Turkey and Italy exceed critical values of 10%. However, all other countries test statistics fall within the region of acceptance. So, null hypothesis of stationarity cannot be rejected. Also, panel results indicate that the null hypothesis of panel stationarity cannot be rejected.

Having applied panel KPSS test with structural breaks, some alternative panel unit root tests that consider cross-sectional dependence are carried out to verify convergence among G20 countries. These tests are developed by Hadri & Kurozumi (2012), Moon & Perron, (2004), and Smith et al. (2004). Two statistics proposed by Hadri & Kurozumi conduct the test for stationarity while the others launch the test for non-stationarity under their null hypotheses.

Table 4 displays alternative unit root tests results and they almost verify the outputs obtained by panel KPSS test with structural breaks in Tables 2 and 3 except t_a^* and t_b^* statistics for the case of constant and trend. On the other hand, Max^* and Min^* statistics yield the output that non-stationarity cannot be rejected at 5% but can be rejected at 10%.

Another approach to test the convergence is the club convergence approach. Table 5, throughout the PS test results, explores that relevant countries of a club move from their disequilibrium positions to their club-specific steady state positions. The PS procedure firstly produces two convergent clubs: (1) India, Italy, Japan, Mexico, Turkey, Argentina, China, South Korea, (2) Australia, Brazil, Canada, France, Germany, Indonesia, South Africa, the UK, and the USA for the second one. Considering the coefficient b in Eq. 10, if the one-sided t_b statistic is lower than $t_b < -1.65$, the null hypothesis of convergence is

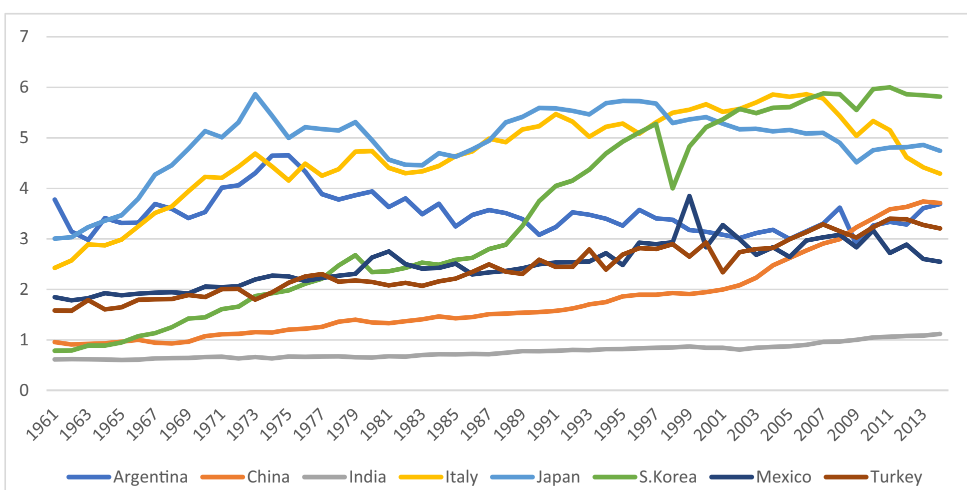

Fig. 2 Ecological footprint series for the first club members (1961–2014)

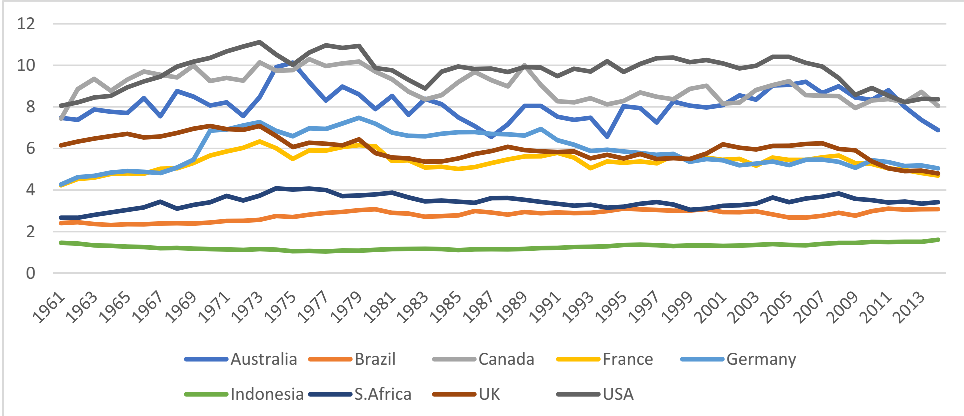

Fig. 3 Ecological footprint series for second club members (1961–2014)

rejected at 5% significance level. If the coefficient b on log t is equal to zero or greater than zero ($b \geq 0$), then, one fails to reject the null hypothesis of convergence. Since t-statistics presented in Table 4 for *log t* are positive, the null hypothesis cannot be rejected (see Phillips & Sul, 2007, 1811).

Phillips & Sul (2009) propose to rerun the *log t* test across the sub-clubs to observe the possibility of merging clubs into larger clubs. Having determined two convergent clubs, the club merging statistic yields, as well, that these clubs converge to each other. First club mainly consists of Asian countries except Italy and Mexico. Japan and Italy follow very similar paths as displayed in Fig. 2. However, historical movements for ecological footprints of first club members seem to be able to be classified into the same group when comparing trend paths of club 1 and club 2 through Figs. 2 and 3. Considering Fig. 2, special attention may be paid why India is in this club since it has different path from the others. One might claim that it performs similar progress with Indonesia in the second club for footprint series. Looking at Figs. 2 and 3, we only differentiate them by last observations because India has followed upward trend since then 2004 while Indonesia has saved its horizontal furtherance. Within this context, last observations may be important since club convergence procedure of Phillips & Sul (2007) arrays units by their last observations and the *log t test* is run to determine club members (see Phillips & Sul, 2007). This may be one of the probable causes why India is in the first club.

Historical movements of footprints for second club members seem to be more coherent from Fig. 3 since each one almost tends to median frontier in general. The country which prominently separates from the others is Indonesia in this club. One of the possible reasons for this clustering may stem from the procedures of club convergence. Also, South Africa and Brazil as developing countries take attention among the other developed countries in the second club. Their footprints fluctuate within similar frontiers nearly although Brazil has higher values for ecological footprint than South Africa's values.

Some incoherencies in clustering process of club convergence approach for the first and second clubs may be required more detailed analyses to be able to be clearly understood. We explored potential sources of these results by comparing descriptive statistics of each series for club members and could not find an explicit sign in order to support clustering. Additionally, one or two factors such as economic growth, income level, country size, or continent in which the relevant country is located seem to be insufficient to explain why Italy, Japan, or India are in the first club and South Africa, Indonesia, or Brazil are in the second club. Therefore, differences in natural endowments of countries, the country/regional level available technology, country/regional level socio-economic determinants (i.e., preferences, cultural habits, population growth rate, GDP growth rate, expenditures on health, education, and infrastructure) as indicated in Qi et al., (2018) and Baabou et al. (2017) should be analyzed in a broader concept that goes beyond the aims of this manuscript and will be considered in forthcoming studies.

Conclusions, discussion points, and policy implications

The literature on environment, natural resources, energy, and energy policies has focused specifically on factors that threaten nature, natural quality, and, hence human health for the last three decades. The United Nations Conference on Sustainable Development (2012) indicates that, in order for countries/regions to be able to reach sustainable development, policy makers need to follow global actions to reach economic and social progress through the goals of growth, employment, and, strengthening environmental protection. The importance of relevant targets discussed, i.e., at the conferences held in Rio in 1992, in Kyoto in 1997 and 2005, and in Paris in 2015, might be subject to change from country to country (Bilgili et al. 2017).

Countries need to follow common environmental quality policies against the natural degradation. It is expected that the countries, which convergence in environmental quality understanding, might be able to conduct their common environmental policies more efficiently to combat the potential threats to natural assets (i.e., threats to land, forests, fishery, water sources, and atmosphere).

The ecological footprint indicator shows how much natural resources are consumed and how much of this consumption can be reproduced by nature. Therefore, this indicator seems to be a more important indicator than others (such as air pollution, carbon emissions, global warming). This paper explores the existence of environmental convergence by employing the ecological footprint data of G20 countries, through panel KPSS, a bootstrap-based panel unit root test with structural breaks, and club convergence test proposed by Phillips & Sul, (2009). The paper, then, observes whether their footprints become equal over time by employing annual data for the period 1961–2014. This work eventually reaches stochastic and deterministic convergence. Later, this paper conducts club convergence tests, and, produces two convergent clubs. Club merging statistics reveal also the result of the convergence of the two clubs. Considering all results, we may state that environmental convergence appears across G20 countries.

Apart from the statistical output from convergence analyses of this work, one might need, as well, to seek for the possible potential source(s) of the convergence. The change in composition of energy production between renewables and non-renewables, hence the change in composition of energy consumption, and relevant recent trends in energy policies might underpin the empirical output of this manuscript. The energy policies implemented by governments to stop global warming have gained great importance especially within last two–three decades. One might also consider the following possible determinants of convergence output of this manuscript: (1) the convergence of relative prices of renewables and non-renewables (Bilgili, 2014); (2) the convergence in taxes implemented on energy products (Bilgili, 2010), integrated tax-subsidy policy for carbon emission (Galinato & Yoder, 2010); (3) the recent developments of biofuels consumption (Zhou & Thomson, 2009), the convergence in solid biomass consumption (Bilgili, 2012); (4) the impact of renewables consumption on GDP growth and CO_2 emissions (Bilgili, 2015; Bilgili et al. 2016; Chiu & Chang, 2009; Torregrosa et al. 2013); and (5) the demand side management energy policies and energy goals to reach energy efficiency and/or lower CO_2 emissions (Ardakani & Ardehali, 2014; Bergaentzlé et al., 2014; EIA, 2014), respectively.

Throughout literature evidence and the empirical evidence of this research, we might reach several implications for the current and future climate or environmental actions.

Firstly, the existence of environmental convergence can help policymakers determine common policies in reducing adverse effects on the environment. Hence, a common environmental policy might be conducted in convergent countries efficiently. The existence of convergence might help convergent countries reach three major social targets of societies of convergent economies: (1) the consumption (utility) maximization of societies, (2) sustainable higher levels of welfare, and (3) clean environment.

The common environmental polices considering footprint indicator might follow an optimal international trade policy to reduce the negative externalities of the trade that result in pollution and environmental degradation. Tian et al. (2017) state that, although, for instance, China and her trade partners EU countries are close to each other in terms of environmental footprint (China (4.73 Gt) and EU countries (4.53 Gt)) in terms of 2008. Europe's footprint emissions are 8.21 times higher than China's footprint emissions. Therefore, Tian et al. (2017) suggest that each country need to follow the policies to promote the resource efficiency and to reduce the pollution. To this end, trading countries should follow international resource database of energy, emissions, and resource footprints.

(i) The DSM policies should monitor (1) households' demand for final goods and services (e.g., food, textile, furniture products, housing, heating, cooling, transportation, and communication), (2) the demand for raw materials, intermediate/manufactured goods, and equipment pool by private sector to produce the final goods, and, finally (3) governments' demand for goods, commodities, and services. The demand for final goods and services might be considered the basic drivers of ecological footprint.

(ii) Elimination of deviations among other countries' ecological footprint values. This paper results in convergence in ecological footprint among G20 countries. This result implies that G20 convergent countries, as a region, have stationary ecological footprint measurement. The theoretical and practical implication of stationarity of ecological footprint in G20 may reveal that the policy makers can foresee the ecological footprint in short, medium, and the long-term without surprise, unforeseen permanent change. This in turn brings about another implication that policy makers may implement long-term steady sate energy policies to manage the international and national trade and demand policies.

On the other hand, the potential possible deviations in ecological footprint levels in other countries rather than G20 might appear due to differences in (1) country/regional level natural endowments, (2) the country/regional level available technology (such as, capabilities of vertical or horizontal gas extracting and capabilities of oil drilling in land and/or ocean), and (3) country/regional level socio-economic determinants (i.e., preferences, cultural habits, population growth rate, GDP growth rate, expenditures on health, education, infrastructure) as indicated in Qi et al., (2018) and Baabou et al. (2017). Therefore, the ecological footprint determinants might be followed by administrators to be able to design and reach both country level and regional/World level environmental policies to achieve sustainable growth and environmental quality.

Secondly, the empirical basis of common environmental policies might be strengthened by paying more attention to the all economic, social, or institutional sources of environmental degradation. Another implication follows from the fact that convergence is generally regarded as a key for global climate projections. For instance, Climate Projections prepared by IPCC are based on the assumption of convergence. Understanding future level and distribution of environmental problems can serve to determine appropriate magnitude of abatement efforts and to allocate abatement obligations.

A hopeful conclusion from the convergence is that initial levels of relevant variables are associated with slower growth (Stern, 2015). Hence, it is resembled by the EKC hypothesis and proposed as an alternative to the EKC (Brock & Taylor, 2003, 2010; Stern, 2015). From this viewpoint, the ecological footprint has a decreasingly growing process and it decreases over time (in the long run). However, we might not have a long run by the time global environmental threats become irreversible. According to IPCC *Climate Change 2014 Synthesis Report*, the Earth's atmosphere has already warmed by 1.5 °C since 1900 and 2.0 would be irreversible. Therefore, environmental policies should be vital and privileged for all countries. Based on the panel KPSS unit root test, the ecological footprint is found stationary. This finding is a very important consideration for policy implications and discussions since the stationarity gives information about policy efficiency or inefficiency (Belbute & Pereira, 2017; Ulucak & Lin, 2017 Smyth & Narayan 2015). For a stationary series, an innovation that generally refers to policy changes has no persistent effect on the relevant variable. In such a situation, a more permanent policy stance is required to be able to get success. Hence, policy makers should be strong-willed to protect the environment on both local and global scale.

To do best of our knowledge, this is the first work to investigate the convergence in ecological footprint for G20 countries. Thereby, this study contributes to the literature of natural resources and environment by (1) monitoring the panel variable of ecological footprint, (2) launching deterministic convergence analyses, (3) conducting stochastic convergence tests, and (4) running the club convergence tests. This paper, then, focuses on the environmental convergence with regard to conditional stochastic, deterministic, and club convergence. New possible potential researches in the future might need to employ (1) alternative methodologies through, i.e., non-linear asymmetric approaches, and/or (2) new convergence concepts through, i.e., regime switching divergence/convergence analyses in order to check the generality of the empirical findings of this paper and the validity of available works of the relevant literature of natural resources and environmental quality.

Executive summary

This paper reaches eventually the highlights presented below. The paper:

a) underlines the importance of relatively new ecological indicator: ecological footprint,
b) examines the environmental convergence hypothesis by observing panel of ecological indicator data,
c) performs panel unit root tests with structural breaks and club convergence tests,
d) reveals stochastic and deterministic convergence in ecological footprint,
e) reaches, as well, the merging clubs in ecological footprint,
f) suggests that the countries need to follow common environmental policies based on ecological footprint indicator, and
g) provides policy makers with several environmental policies.

Appendix

Table 6

Table 6 Descriptive statistics for ecological footprint series

	Mean	Median	Maximum	Minimum	Standard deviation	Skewness	Kurtosis
Argentina	3.511932	3.443311	4.651935	2.885670	0.392291	1.046291	4.056058
Australia	8.111579	8.064451	10.13019	6.559617	0.739436	0.291325	3.297699
Brazil	2.795351	2.883131	3.106045	2.319935	0.243544	−0.645582	2.120205
China	1.777134	1.514521	3.740306	0.911248	0.817024	1.122308	3.202053
Canada	8.977496	8.926791	10.29804	7.438794	0.681558	0.137328	2.162995
France	5.370415	5.407772	6.338119	4.229499	0.443010	−0.143593	2.862915
Germany	5.932819	5.760628	7.475371	4.272328	0.855997	0.080729	1.682338
India	0.773162	0.732784	1.120083	0.601512	0.142210	0.825759	2.753546
Indonesia	1.267223	1.262796	1.608080	1.041957	0.139194	0.377591	2.235598
Italy	4.662639	4.728441	5.862601	2.425363	0.871560	−0.824629	3.109459
Japan	4.903279	5.090672	5.863017	3.006034	0.681461	−1.302365	4.308520
South Korea	3.443711	2.841532	5.999868	0.785119	1.808657	0.069995	1.484471
Mexico	2.491379	2.498674	3.847254	1.783703	0.429920	0.465570	3.304923
South Africa	3.434782	3.427024	4.082211	2.664184	0.317488	−0.188614	3.200950
Turkey	2.419266	2.342906	3.399018	1.576783	0.522233	0.231565	1.977773
UK	5.993968	5.966729	7.080254	4.799216	0.555500	0.018544	2.554559
USA	9.737091	9.877392	11.11268	8.053772	0.789855	−0.499259	2.451168

References

Acar S, Lindmark M (2016) Periods of converging carbon dioxide emissions from oil combustion in a pre-Kyoto context. Environ Dev 19: 1–9. https://doi.org/10.1016/j.envdev.2016.06.005

Acar S, Lindmark M (2017) Convergence of CO_2 emissions and economic growth in the OECD countries: did the type of fuel matter? Energy Sources Part B 12:1–10. https://doi.org/10.1080/15567249.2016.1249807

Acar S, Söderholm P, Brännlund R (2017) Convergence of per capita carbon dioxide emissions: implications and meta-analysis. Clim Pol 18:1–14. https://doi.org/10.1080/14693062.2017.1314244

Acar S, Aşıcı AA (2017) Nature and economic growth in Turkey: what does ecological footprint imply? Middle East Dev J 9(1):101–115

Acaravcı A, Erdogan S (2016) The convergence behavior of CO_2 emissions in seven regions under multiple structural breaks. Int J Energy Econ Policy 6(3):575–580

Ahmed M, Khan AM, Bibi S, Zakaria M (2016) Convergence of per capita CO_2 emissions across the globe: insights via wavelet analysis. Renew Sust Energ Rev 75:86–97. https://doi.org/10.1016/j.rser.2016.10.053

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 Indic 48:315–323

Al-mulali U, Solarin SA, Sheau-Ting L, Ozturk I (2016) Does moving towards renewable energy cause water and land inefficiency? An empirical investigation. Energy Policy 93:303–314

Aldy JE (2006) Per capita carbon dioxide emissions: convergence or divergence? Environ Resour Econ 33:533–555. https://doi.org/10.1007/s10640-005-6160-x

Aldy JE (2007) Divergence in state-level per capita carbon dioxide emissions. Land Econ 83(3):353–369

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

Apergis N, Payne JE, Topcu M (2017) Some empirics on the convergence of carbon dioxide emissions intensity across US states. Energy Sources Part B 12(9):831–837

Ardakani FJ, Ardehali MM (2014) Novel effects of demand side management data on accuracy of electrical energy consumption modeling and long-term forecasting. Energy Convers Manag 78:745–752

Arrow K, Bolin B, Costanza R, Dasgupta P, Folke C, Holling CS, Pimentel D (1995) Economic growth, carrying capacity and the environment. Science 268:520–521

Aşıcı AA, Acar S (2016) Does income growth relocate ecological footprint? Ecol Indic 61:707–714. https://doi.org/10.1016/j.ecolind.2015.10.022

Baabou W, Grunewald N, Ouellet-Plamondon C, Gressot M, Galli A (2017) The ecological footprint of Mediterranean cities: awareness creation and policy implications. Environ Sci Pol 69:94–104. https://doi.org/10.1016/j.envsci.2016.12.013

Bai J, Perron P (1998) Estimating and testing linear models with multiple structural changes. Econometrica 66(1):47. https://doi.org/10.2307/2998540

Baldwin JG, Wing IS (2013) The spatiotemporal evolution of U.S. carbon dioxide emissions: stylized facts and implications for climate policy. J Reg Sci 53(4):672–689

Baltagi B, Feng Q and Kao C (2012) A Lagrange multiplier test for cross-sectional dependence in a fixed effects panel data model (No. 137). Retrieved from http://surface.syr.edu/cpr

Baltagi BH, Feng Q, Kao C (2016) Estimation of heterogeneous panels with structural breaks. J Econ 191(1):176–195

Barro RJ, Sala-i-Martin X (1992) Convergence. J Polit Econ 100(2):223–251

Bartelmus P (2008) Quantitative economics: how sustainable are our economies? Springer, Amsterdam, 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

Belbute JM, Pereira AM (2017) Do global CO_2 emissions from fossil-fuel consumption exhibit long memory? A fractional-integration analysis. Appl Econ 49:1–16. https://doi.org/10.1080/00036846.2016.1273508

Bello MO, Solarin SA, Yen YY (2018) The impact of electricity consumption on CO_2 emission, carbon footprint, water footprint and ecological footprint: the role of hydropower in an emerging economy. J Environ Manag 219:218–230

Bergaentzlé C, Clastres C, Khalfallah H (2014) Demand-side management and European environmental and energy goals: an optimal complementary approach. Energy Policy 67:858–869

Bernard AB, Durlauf SN (1996) Interpreting tests of the convergence hypothesis. J Econ 71(1–2):161–173

Best A, Blobel D, Cavalieri S, Giljum S, Hammer M, Lutter S et al (2008) Potential of the ecological footprint for monitoring environmental impacts from natural resource use. Sustain Dev

Bilgili F (2010) Energy tax harmonization in EU: time series and panel data evidence. University Library of Munich, Germany. Retrieved from http://econpapers.repec.org/paper/pramprapa/24013.htm

Bilgili F (2012) Linear and nonlinear TAR panel unit root analyses for solid biomass energy supply of European countries. Renew Sust Energ Rev 16(9):6775–6781

Bilgili F (2014) Convergence analysis of oil and diesel prices for industries and households in the European region. Energy Sources Part B 9(2):140–148

Bilgili F (2015) Business cycle co-movements between renewables consumption and industrial production: a continuous wavelet coherence approach. Renew Sust Energ Rev 52:325–332

Bilgili F, Koçak E, Bulut Ü (2016) The dynamic impact of renewable energy consumption on CO_2 emissions: a revisited environmental Kuznets curve approach. Renew Sust Energ Rev 54:838–845

Bilgili F, Koçak E, Bulut Ü, Kuşkaya S, (2017) Can biomass energy be an efficient policy tool for sustainable development?. Renewable and Sustainable Energy Reviews 71:830-845

Boussemart JP, Leleu H, Shen Z (2015) Environmental growth convergence among Chinese regions. China Econ Rev 34:1–18

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

Brännlund R, Lundgren T, Söderholm P (2015) Convergence of carbon dioxide performance across Swedish industrial sectors: an environmental index approach. Energy Econ 51:227–235

Breusch TS, Pagan AR (1980) The Lagrange multiplier test and its applications to model specification in econometrics. Rev Econ Stud 47(1):239. https://doi.org/10.2307/2297111

Brock, WA, & Taylor, MS (2003). The kindergarten rule of sustainable growth. NBER No. Working Paper 9597 Massachusetts

Brock WA, Taylor MS (2010) The Green Solow model. J Econ Growth 15(2):127–153

Burnett JW (2016) Club convergence and clustering of U.S. energy-related CO_2 emissions. Resour Energy Econ 46:62–84

Carrion-i-Silvestre J, del Barrio-Castro T, Lopez-Bazo E (2005) Breaking the panels: an application to the GDP per capita. Econ J 8(2):159–175

Carlino GA, Mills LO (1993) Are U.S. regional incomes converging? J Monet Econ 32(2):335–346

Caviglia-Harris JL, Chambers D, Kahn JR (2009) Taking the "U" out of Kuznets. A comprehensive analysis of the EKC and environmental degradation. Ecol Econ 68(4):1149–1159

Charfeddine L, Ben Khediri K (2016) Financial development and environmental quality in UAE: cointegration with structural breaks. Renew Sust Energ Rev 55:1322–1335

Charfeddine L (2017) The impact of energy consumption and economic development on ecological footprint and CO_2 emissions: evidence from a Markov switching equilibrium correction model. Energy Econ 65:355–374

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 Sust Energ Rev 76:138–154

Charfeddine L, Yousef Al-Malk A, Al Korbi K (2018) Is it possible to improve environmental quality without reducing economic growth: evidence from the Qatar economy. Renew Sust Energ Rev 82:25–39

Charles A, Darne O, Hoarau JF (2012) Convergence of real per capita GDP within COMESA countries: a panel unit root evidence. Ann Reg Sci 49(1):53–71

Chiu CL, Chang TH (2009) What proportion of renewable energy supplies is needed to initially mitigate CO_2 emissions in OECD member countries? Renew Sust Energ Rev 13(6):1669–1674

Choi I (2001) Unit root tests for panel data. J Int Money Financ 20(2): 249–272

Cooper M (2018) Governing the global climate commons: the political economy of state and local action, after the U.S. flip-flop on the Paris agreement. Energy Policy 118:440–454

Cordero EC, Marie Todd A, Abellera D (2008) Climate change education and the ecological footprint. Bull Am Meteorol Soc 89(6):865–872

Dietz T, Rosa EA, York R (2007) Driving the human ecological footprint. Front Ecol Environ 5(1):13–18

Durlauf SN, Johnson PA (1995) Multiple regimes and cross-country growth behaviour. J Appl Econ 10(4):365–384

EEA (2010) The European environment state and outlook 2010: synthesis. Copenhagen. Retrieved from http://www.ab.gov.tr/files/ardb/evt/1_avrupa_birligi/1_6_raporlar/1_3_diger/environment/eea__2010_the_european_environment_synthesis.pdf

EEA (2015). The European environment — state and outlook 2015, Synthesis Report. Copenhagen. Retrieved from https://www.eea.europa.eu/soer#tab-synthesis-report

EIA (2014) Electric utility demand side management 2014. Retrieved from http://www.eia.gov/electricity/data/eia861/dsm/index.html

G20 (2011) 2011 G20 Cannes summit final compliance report. http://www.g20.utoronto.ca/compliance/2011cannes-final/index.html

Galinato GI, Yoder JK (2010) An integrated tax-subsidy policy for carbon emission reduction. Resour Energy Econ 32(3):310–326

Galli A, Wiedmann T, Ercin E, Knoblauch D, Ewing B, Giljum S (2012) Integrating ecological, carbon and water footprint into a "footprint family" of indicators: definition and role in tracking human pressure on the planet. Ecol Indic 16:100–112

Galor O (1996) Convergence? Inferences from theoretical models. Econ J 106(437):1056. https://doi.org/10.2307/2235378

Global Footprint Network (2017) Ecological footprint. Retrieved from https://www.footprintnetwork.org/our-work/ecological-footprint/

Hadri K (2000) Testing for stationarity in heterogeneous panel data. Econ J 3(2):148–161

Hadri K, Kurozumi E (2012) A simple panel stationarity test in the presence of serial correlation and a common factor. Econ Lett 115. Retrieved from http://www.sciencedirect.com/science/article/pii/S0165176511005015:31–34

Harris RD, Tzavalis E (1999) Inference for unit roots in dynamic panels where the time dimension is fixed. J Econ 91(2):201–226

Herrerias MJ (2013) The environmental convergence hypothesis: carbon dioxide emissions according to the source of energy. Energy Policy 61:1140–1150

Hervieux MS, Darné O (2015) Environmental Kuznets curve and ecological footprint: a time series analysis. Econ Bull 35(1):814–826

Huang B, Meng L (2013) Convergence of per capita carbon dioxide emissions in urban China: a spatio-temporal perspective. Appl Geogr 40:21–29

Im KS, Pesaran MH, Shin Y (2003) Testing for unit roots in heterogeneous panels. J Econ 115(1):53–74

Islam N (2003) What have we learnt from the convergence debate? J Econ Surv 17(3):309–362

Isman M, Archambault M, Charles NK, Lin D, Iha K, Ouellet-Plamondon C (2017) Ecological footprint assessment for targeting climate change mitigation in cities: a case study of 15 Canadian cities according to census metropolitan areas (CMA). J Clean Prod 174:1032–1043. https://doi.org/10.1016/J.JCLEPRO.2017.10.189

Jobert T, Karanfil F, Tykhonenko A (2010) Convergence of per capita carbon dioxide emissions in the EU: legend or reality? Energy Econ 32(6):1364–1373

Kahia M, Kadria M, Ben Aissa MS, Lanouar C (2017a) Modelling the treatment effect of renewable energy policies on economic growth: evaluation from MENA countries. J Clean Prod 149:845–855

Kahia M, Aïssa MSB, Lanouar C (2017b) Renewable and non-renewable energy use - economic growth nexus: the case of MENA net oil importing countries. Renew Sust Energ Rev 71:127–140

Kitzes J, Wackernagel M (2009) Answers to common questions in ecological footprint accounting. Ecol Indic 9(4):812–817

Kounetas KE (2018) Energy consumption and CO_2 emissions convergence in European Union member countries. A tonneau des Danaides? Energy Econ 69:111–127

Kwiatkowski D, Phillips PCB, Schmidt P, Shin Y (1992) Testing the null hypothesis of stationarity against the alternative of a unit root. How sure are we that economic time series have a unit root? J Econ 54(1–3):159–178

Lanne M, Liski M (2004) Trends and breaks in per-capita carbon dioxide emissions, 1870–2028. Energy J 25(4). https://doi.org/10.5547/ISSN0195-6574-EJ-Vol25-No4-3

Lazarus, E., Zokai, G., Borucke, M., Panda, D., Iha, K., Morales, J. C., … Naina, G. (2014). Working guidebook to the national footprint accounts 2014. Retrieved from http://www.footprintnetwork.org/content/images/article_uploads/NFA2014Guidebook 7–14-14.pdf

Lee CC, Chang CP, Chen PF (2008) Do CO_2 emission levels converge among 21 OECD countries? New evidence from unit root structural break tests. Appl Econ Lett 15(7):551–556

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

Levin A, Lin CF, Chu J (2002) Unit root tests in panel data: asymptotic and finite-sample properties. J Econ 108(1):1–24

Li J, Huang X, Yang H, Chuai X, Wu C (2017) Convergence of carbon intensity in the Yangtze River Delta, China. Habitat Int 60:58–68

Li Q, Papell D (1999) Convergence of international output time series evidence for 16 OECD countries. Int Rev Econ Financ 8(3):267–280

Li XL, Tang DP, Chang T (2014) CO_2 emissions converge in the 50 U.S. states — sequential panel selection method. Econ Model 40:320–333

Li X, Lin B (2013) Global convergence in per capita CO_2 emissions. Renew Sust Energ Rev 24:357–363

Lin, D., Hanscom, L., Martindill, J., Borucke, M., Cohen, L., Galli, A., … Wackernagel, M. (2016). Working guidebook to the national footprint accounts. Oakland. Retrieved from http://www.footprintnetwork.org/content/documents/National_Footprint_Accounts_2016_Guidebook.pdf

Long X, Sun M, Cheng F, Zhang J (2017) Convergence analysis of eco-efficiency of China's cement manufacturers through unit root test of panel data. Energy 134:709–717

Maddala GS, Wu S (1999) A comparative study of unit root tests with panel data and a new simple test. Oxf Bull Econ Stat 61(1):631–652

Mancini MS, Galli A, Niccolucci V, Lin D, Hanscom L, Wackernagel M, Bastianoni S, Marchettini N (2017) Stocks and flows of natural capital: implications for ecological footprint. Ecol Indic 77. Retrieved from http://www.sciencedirect.com/science/article/pii/S1470160X17300390,:123–128

Mishra V, Smyth R, (2017) Conditional convergence in Australia's energy consumption at the sector level. Energy Economics 62:396-403

Moon HR, Perron B (2004) Testing for a unit root in panels with dynamic factors. J Econ 122(1):81–126

Moutinho V, Robaina-Alves M, Mota J (2014) Carbon dioxide emissions intensity of Portuguese industry and energy sectors: a convergence analysis and econometric approach. Renew Sust Energ Rev 40:438–449

Neumayer E (2004) Indicators of sustainability. In: Tietenberg TH, Folmer H (eds) The international yearbook of environmental and resource economics 2004/2005. Edward Elgar, Cheltenham, pp 139–189

Nijkamp P, Rossi E, Vindigni G (2004) Ecological footprints in plural: a meta-analytic comparison of empirical results. Reg Stud 38(7):747–765

Nguyen Van P (2005) Distribution dynamics of CO_2 emissions. Environ Resour Econ 32(4):495–508

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

de Oliveira G, Bourscheidt DM (2017) Multi-sectorial convergence in greenhouse gas emissions. J Environ Manag 196:402–410

Oliveira V, Silveira M (2014) The G20 debate on environmental issues: is minilateralism the solution? Monçoes 3(6):254–275

Ordás Criado C, Grether JM (2011) Convergence in per capita CO_2 emissions: a robust distributional approach. Resour Energy Econ 33(3):637–665

Ozturk I, Al-Mulali U, Saboori B (2016) Investigating the environmental Kuznets curve hypothesis: the role of tourism and ecological footprint. Environ Sci Pollut Res 23(2):1916–1928

Pablo-Romero MP, Sánchez-Braza A (2017) The changing of the relationships between carbon footprints and final demand: panel data evidence for 40 major countries. Energy Econ 61:8–20

Panopoulou E, Pantelidis T (2009) Club convergence in carbon dioxide emissions. Environ Resour Econ 44(1):47–70

Pennino MG, Bellido JM, Conesa D, Coll M, Tortosa-Ausina E (2017) The analysis of convergence in ecological indicators: an application to the Mediterranean fisheries. Ecol Indic 78:449–457

Perron P (1989) The great crash, the oil price shock, and the unit root hypothesis. Econometrica 57(6):1361–1401

Pesaran MH (2007) A simple panel unit root test in the presence of cross-section dependence. J Appl Econ 22(2):265–312

Pesaran MH, Ullah A, Yamagata T (2008) A bias-adjusted LM test of error cross-section independence. Econ J 11(1):105–127

Pesaran MH (2015) Testing weak cross-sectional dependence in large panels. Econ Rev 34(6–10):1089–1117

Pettersson F, Maddison D, Acar S, Soderholm P (2014) Convergence of carbon dioxide emissions: a review of the literature. Int Rev Environ Resour Econ 7(2):141–178

Phillips PCB, Sul D (2007) Transition modeling and econometric convergence tests. Econometrica 75(6):1771–1855

Phillips PCB, Sul D (2009) Economic transition and growth. J Appl Econ 24(7):1153–1185

Presno MJ, Landajo M, Fernández GP (2015) Stochastic convergence in per capita CO_2 emissions. An approach from nonlinear stationarity analysis. Energy Econ 70:563–581. https://doi.org/10.1016/j.eneco.2015.10.001

Qi Z, Gao C, Na H, Ye Z (2018) Using forest area for carbon footprint analysis of typical steel enterprises in China. Resour Conserv Recycl 132:352–360. https://doi.org/10.1016/J.RESCONREC.2017.05.016

Quah D (1993) Galton's fallacy and tests of the convergence hypothesis. Scand J Econ 95(4):427. https://doi.org/10.2307/3440905

Rashid A, Irum A, Ali Malik I, Ashraf A, Rongqiong L, Liu G et al (2018) Ecological footprint of Rawalpindi; Pakistan's first footprint analysis from urbanization perspective. J Clean Prod 170:362–368

Romero-Ávila D (2008) Convergence in carbon dioxide emissions among industrialised countries revisited. Energy Econ 30(5):2265–2282

Smith LV, Leybourne S, Kim TH, Newbold P (2004) More powerful panel data unit root tests with an application to mean reversion in real exchange rates. J Appl Econ 19(2):147–170

Smyth R, Narayan PK (2015) Applied econometrics and implications for energy economics research. Energy Econ 50:351–358

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 Indic 89:35–44

Solarin SA, Al-Mulali U (2018) Influence of foreign direct investment on indicators of environmental degradation. Environ Sci Pollut Res 25(25):24845–24859

Solow RM (1956) A contribution to the theory of economic growth. Q J Econ 70(1):65–94

Stern DI (2003) The rise and fall of the environmental Kuznets curve the rise and fall of the environmental Kuznets curve (working papers in economics). New York. Retrieved from http://www.rpi.edu/dept/economics/

Stern DI (2014) The environmental Kuznets curve: a primer (CCEP working paper 1404)

Stern DI (2015) The environmental Kuznets curve after 25 years (CCEP Working Paper No. 1514). Crawford. Retrieved from https://ccep.crawford.anu.edu.au/sites/default/files/publication/ccep_crawford_anu_edu_au/2016-01/ccep1514_0.pdf

Strazicich MC, List JA (2003) Are CO_2 emission levels converging among industrial countries? Environ Resour Econ 24(3):263–271

Tian X, Wu R, Geng Y, Bleischwitz R, Chen Y (2017) Environmental and resources footprints between China and EU countries. J Clean Prod 168:322–330. https://doi.org/10.1016/J.JCLEPRO.2017.09.009

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

Torregrosa AJ, Broatch A, Plá B, Mónico LF (2013) Impact of Fischer–Tropsch and biodiesel fuels on trade-offs between pollutant emissions and combustion noise in diesel engines. Biomass Bioenergy 52:22–33. https://doi.org/10.1016/j.biombioe.2013.03.004

Ulucak R, Bilgili F (2018) A reinvestigation of EKC model by ecological footprint measurement for high, middle and low income countries. J Clean Prod 188:144–157. https://doi.org/10.1016/j.jclepro.2018.03.191

Ulucak R, Lin D (2017) Persistence of policy shocks to ecological footprint of the USA. Ecol Indic 80:337–343

Ulucak R, Erdem E (2017) The environment in economic growth models: an application based on ecological footprint. Hacettepe Univ J Econ Adm Sci 35(4):115–147

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 Pol 80:21–27

United Nations Conference on Sustainable Development (2012), United Nations Conference on Sustainable Development Rio+20, https://sustainabledevelopment.un.org/rio20

UNDP (2014) Human development report 2014: sustaining human progress, reducing vulnerabilities and building resilience. New York

Wackernagel M (2002) What we use and what we have: ecological footprint and ecological capacity (No. 510-444–3041). Oakland.

Retrieved from https://edisciplinas.usp.br/pluginfile.php/49503/mod_resource/content/1/texto17.pdf

Wackernagel M and Rees W (1996) Our ecological footprint: reducing human impact on the earth. The new catalyst bioregional series. New Society Publishers

Wang J, Zhang K (2014) Convergence of carbon dioxide emissions in different sectors in China. Energy 65:605–611

Wang Y, Zhang P, Huang D, Cai C (2014) Convergence behavior of carbon dioxide emissions in China. Econ Model 43:75–80. https://doi.org/10.1016/j.econmod.2014.07.040

Westerlund J, Basher SA (2008) Testing for convergence in carbon dioxide emissions using a century of panel data. Environ Resour Econ 40(1):109–120

Wiedmann T, Barrett J (2010) A review of the ecological footprint indicator—perceptions and methods. Sustainability 2(6):1645–1693

Wu J, Wu Y, Guo X, Cheong TS (2016) Convergence of carbon dioxide emissions in Chinese cities: a continuous dynamic distribution approach. Energy Policy 91:207–219

Yang J, Zhang T, Sheng P, Shackman JD (2016) Carbon dioxide emissions and interregional economic convergence in China. Econ Model 52:672–680

Yan Z et al (2017) Convergence or divergence? Understanding the global development trend of low-carbon technologies. Energy Policy 109:499–509

Young AT, Higgins MJ, Levy D (2008) Sigma convergence versus beta convergence: evidence from U.S. county-level data. J Money Credit Bank 40(5):1083–1093

Zhang L, Dzakpasu M, Chen R, Wang XC (2017) Validity and utility of ecological footprint accounting: a state-of-the-art review. Sustainable Cities and Society 32:411–416

Zhou A, Thomson E (2009) The development of biofuels in Asia. Appl Energy 86:11–20