The shadow economy-environmental quality nexus in OECD countries: empirical evidence from panel quantile regression

Lan Khanh Chu1 · Dung Phuong Hoang2

Received: 5 November 2021 / Accepted: 19 April 2022 / Published online: 29 April 2022 © The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract
This study examines the heterogenous impact of shadow economy on the ecological footprint. We apply the panel quantile regression to a panel dataset of 32 OECD countries from 1990 to 2015. The estimation results indicate that the shadow economy-ecological footprint nexus follows an inverted U-shaped pattern. Initially, the higher size of the informal economy leads to more ecosystem degradation. When the shadow economy increases to certain thresholds, its environmental impact reverts to benefit. Such threshold changes with the evolution of the ecological footprint. Specifically, it first rises then decreases along with the degradation of the ecosystem. Moreover, the heterogeneous panel causality test reports the one-way directional running from the shadow economy to the ecological footprint in OECD countries. Likewise, environmental effects of other control variables, including trade openness, energy intensity, renewable energy, and income, are also not homogeneous across various levels of the ecological footprint. The significant and heterogeneous relationships between ecological footprint and its determining factors provide insightful implications for governments in tailoring environmental regulations upon different ecological conditions.

Keywords Ecological footprint · OECD countries · Quantile regression · Shadow economy

Introduction
The world is facing long-term shifts in temperatures and weather patterns that endanger both economic growth and human existence (UNEP 2019). This phenomenon is caused by not only the natural process but also, and more severely, the loss of natural resources and greenhouse gas emissions, as resulted from human activities. Preventing dangerous human interference with the ecological system, therefore, has become one of the most crucial strategies to pursue sustainable growth. This target has been mentioned and ratified by 197 nations in the 26th global climate summit on the United Nations Framework Convention on Climate Change (also known as COP26). There is a substantial strand of research that examines the socioeconomic impacts of humans on environmental quality, hence aiding policymakers in alleviating environmental costs of humanity (Bowles and Park 2005; Dietz and Rosa 1997; Khan et al. 2021; Khan and Hou 2021; York 2007). However, the findings are inconclusive due to the complexity of the socio-economic environment (Chu and Hoang 2021; Pata 2018; Sun et al. 2018; Tawiah et al. 2021). This calls for further research to shed more light on the mechanisms underlying the sophisticated human–environment relationship.

For decades, OECD countries have taken efforts to mitigate environmental pollution through technological innovation and stringent environmental regulations and standards (OECD 2015, 2020). Nevertheless, their oversized consumption of natural resources and polluting emissions mostly exceed the biocapacity of the area available to them (OECD 2022). In fact, the level of environmental deterioration varies across OECD members. While the USA, Japan, and Germany emit billions of tons of greenhouse gas every year, other nations such as Sweden, Switzerland, New Zealand, Norway, and Luxembourg contribute only less than 100 million tons of emissions annually. The enduring ecological deficit and heterogeneity in environmental quality in these...
well-developed economies pose a question about the validity of the well-known Environmental Kuznets curve (EKC) (Grossman and Krueger 1991; Panayotou 1993). Based on this framework, it is expected that when an economy reaches a certain income level, energy efficiency (as the outcome of the technology progress) and the rising environmental awareness (as resulted from higher demand for well-being) would decrease pollution and ensure sustainable development. Nevertheless, empirical studies report that the pollution may rise again despite the continuous increase in income (Allard et al. 2018; Álvarez-Herránz et al. 2017; Koc and Bulus 2020; Caravaggio 2020; Sinha et al. 2017) or there is even no turning point in such a relationship (Jalil and Mahmud 2009; Ghosh 2010; Massagony and Budiono 2022). One of the reasons for the failure of the EKC hypothesis may be because it ignores the presence of the shadow economy, which encompasses either illegal activities or unreported income from the production of legal goods and services (Alm and Embaye, 2013).

Downsizing the underground sectors has always been an important policy goal in OECD countries. Although the expansion of the shadow economy has ceased in almost OECD countries within recent 10 years, new developments in informal activities such as non-cash payment, the emergence of the sharing and gig economies, and the misuse of technology for creating false data (fictitious invoices and receipt and identity fraud) make it more difficult and costly for administrators to detect and restrain the underground activities (OECD 2017). From a theoretical perspective, the shadow economy could exert both positive and negative impacts on the environment. On the one hand, the shadow economy helps slow down environmental deterioration as it expands due to its small-scale and labor-intensive nature (the scale effect) (Elgin and Öztunali 2014a, 2014b). On the other hand, the informal sector may add to environmental pollution by entailing more energy use for illicit production and consumption activities while enabling firms in the official sector to hide their polluting manufacture (the deregulation effect) (Chaudhuri and Mukhopadhyay 2006; Elgin and Öztunali 2014a, 2014b; Tamazian et al. 2009). It is, therefore, interesting to examine how the declining trend of the shadow economy influence environmental quality across OECD countries and whether further efforts in downsizing the informal sector is rewarded with the improvement of the ecological system.

The literature on the informality-environmental quality nexus has been well-established; however, there is a lack of consensus regarding empirical evidence. While most empirical studies affirm the deregulation effect (Abid 2015; Baloch et al. 2021; Biswas et al. 2012; Chen et al. 2018; Imamoglu 2018; Köksal et al. 2020; Mazhar and Elgin 2013), others support the scale effect (Nkengfack et al. 2021; Shao et al. 2021). On the other hand, Elgin and Öztunali (2014a, 2014b) and Yang et al. (2021) find an inverted U-shaped linkage between the two factors. One of the reasons for inconclusive findings in previous works is the variety of indicators for environmental quality. Most studies use CO₂ emission as a proxy for environmental deterioration (Abid 2015; Elgin and Öztunali 2014a, 2014b; Imamoglu 2018; Nkengfack et al. 2021). Meanwhile, others use a composite indicator based on primary pollutant sources, including CO₂, soot and dust, and capita wastewater (Chen et al. 2018); CO₂ and SO₂ (Biswas et al. 2012), or N₂O, CH₄, and CO₂ (Canh et al. 2019). Compared to air pollution, the ecological footprint, as coined by the Global Footprint Network, has been increasingly used as a more precise and comprehensive indicator for environmental deterioration caused by human activities. This construct indicates how much biologically productive land (croplands, grazing lands for animal products, and forested areas) and marine areas are required to either provide renewable resources, as compensating for the consumption of a population, or absorb pollutant emissions generated from their energy consumption. Correspondingly, the higher level of ecological footprint implies how badly the environment is affected by a group of people. There is a growing body of research that examines the determinants of the ecological footprint. While international trade, financial development, urbanization, and globalization raise the ecological footprint in most countries (Kongbuamai et al. 2020; Rudolph and Figge 2017; Dogan et al. 2019), technological progress, especially green technology, is endorsed as a long-term cure for the ecological system (Chu 2021a; Dogan et al. 2019). Nevertheless, the literature on the relationship between shadow economy and ecological footprint remains limited. To our best knowledge, Köksal et al. (2020) is the only research that affirms that the underground sectors have a long-term positive impact on the ecological footprint. However, the study by Köksal et al. (2020) has three limitations. First, Köksal et al. (2020) only use panel data for Turkey and, hence, could not investigate the heterogeneity in the informality-ecological footprint linkage across countries. Second, despite the two-sided impacts of shadow economy on environmental quality, Köksal et al. (2020) ignore the possibility of a non-linear relationship between the two constructs. Third, the employment of the ecological footprint as a proxy for environmental quality allows separating the environmental costs of production from consumption sources. Specifically, for a given nation, while the ecological footprint of production is calculated based on the consumption of biocapacity originating from the national production activities, the consumption ecological footprint indicates the consumption of biocapacity by the nation’s inhabitants during their consumption of either domestic or imported goods (Ree 1992). Nonetheless, Köksal et al.
(2020) fail to examine the potential difference between the impact of the shadow economy on the ecological footprint of production and that of consumption ecological footprint.

In response to these research gaps, this study focuses on the non-linear relationship between the shadow economy and ecological footprint of either production or consumption as well as its heterogeneity across the distribution of the ecological footprint. Specifically, this study’s objectives are three-fold. First, given both positive and negative forces in environmental impacts of underground activities, this research tests the inverted U-shaped relationship between shadow economy and ecological footprint. Second, by employing the panel quantile regression to a panel data-set of 32 OECD countries from 1990 to 2015, this study explores the heterogeneity in the effect of shadow economy on the ecological system and the underlying patterns. Specifically, we track the existence and changes of the turning points (of the inverted U-shaped pattern) in the informality-environmental quality linkage across quantiles of the ecological footprint to detect any differences and trends. Third, this research further gets insights into this relationship by separately examining the environmental impact of informal sectors on production ecological footprint and that of consumption ecological footprint. Correspondingly, the existence and magnitudes of turning points in those relationships are compared to yield novel findings.

This study has at least three contributions. First, it enriches the current literature about the non-linearity relationship between two key issues, shadow economy and environmental quality, as proxied by ecological footprint. To our best knowledge, no study so far has been implemented in the context of OECD countries to estimate the environmental effect of the shadow economy. Therefore, the analysis about the heterogeneous impact of shadow economy on the ecological footprint in 32 OECD countries itself is an interesting contribution. Second, this paper makes the methodological contribution by employing the panel quantile regression approaches, proposed by Canay (2011) and Powell (2016). This approach deals effectively with the non-normality and heterogeneity of panel data. The econometric benefits of panel quantile regression allow us to provide a more comprehensive picture of the environmental effect of the shadow economy, especially in the context of countries that lie at extreme distribution. Third, this study provides insightful findings of the environmental costs of shadow economy from the consumption and production sources separately. Specifically, there is an inverted U-shaped relationship between shadow economy and ecological footprint of consumption and production. However, the thresholds over which the impact of shadow economy changes from positive to negative across quantile distribution of ecological footprint differ in the two cases.

The remainder of the paper is as follows. “Theoretical framework and literature review” presents the theoretical framework and literature review. “Methodology” describes the data and methodological approach. “Result and discussion” presents the estimation results and discussions. The last section concludes and draws policy implications.

**Theoretical framework and literature review**

**Theoretical framework**

The shadow economy plays a critical role in human interference with the ecological system. The literature documents both positive and negative forces in the shadow economy-environmental quality nexus. Theoretically, this relationship could be explained through three primary sources, including production (the scale effect), the enforcement of environmental regulation (the deregulation effect), and international trade (the trade-related effect).

**The scale effect**

The shadow economy could affect the extent to which production activities release pollutants to the environment through its scale of production, also called “the scale effect” (Elgin and Öztunali 2014a, 2014b). Specifically, since the underground economy encompasses either illegal activities or unreported income from the production of legal goods and services (Alm and Embaye 2013), it deliberately maintains the small-scale operation to make it easier to hide from the government. Moreover, the less secure business environment also discourages informal firms to invest in a larger production scale (Mead and Morrission 1996). Even when the informal firms aspire for expansion, the lack of access to formal finance and necessary public goods and services limits their business growth (Straub 2005). Further, as characterized by a higher labor-intensive yet lower capital-intensive production model, the shadow economy is less prone to environmental degradation, as compared to the formal sector (Antweiler et al. 2001).

**The deregulation effect**

The underground activities may intensify the environmental burdens from production activities through its “deregulation effect” (Elgin and Öztunali 2014a, 2014b). This effect could be observed from three primary perspectives. First, due to intrinsic features, the shadow economy itself is characterized by a lack of environmental regulation. This makes the underground activities, which are mostly unlicensed and low technology-intensive, become a major source of pollution (Wang and Dear 2017). Second, pressures from rigorous
environmental legislation motivate the formal firms to hide their polluting manufacturing into the underground sectors for cost-cutting (Mazhar and Elgin 2013). This may shift the pollution from the formal sectors to the shadow economy (Baksi and Bose 2016). Third, according to the three-sector general equilibrium framework, formal firms may purchase immediate goods from their informal counterparts, which are not subject to environmental taxes and standards (Chaudhuri and Mukhopadhyay 2006). As the underground sector grows, this further widens the gap between the actual and the allowable level of pollution. The deregulation effect of the shadow economy, therefore, reduces the effectiveness of environmental legislation even in the formal sector and, hence, contributes to more environmental degradation.

The trade-related effect

Shadow economy, due to its intrinsic factors, could reduce barriers to international trade and, hence, foster trade flows. On the one hand, the shadow economy helps exporters overcome cost barriers of international expansion (Melitz 2003) and increase their competitiveness by paying lower wages and obtaining cheaper inputs (Zagoršek et al. 2009). On the other hand, the shadow economy increases the demand for imported goods by allowing lower prices through tax invasion. In addition, as an integral part of the shadow economy, trafficking of illegal goods contributes to both imports and exports (OECD 2017). While the exports of domestic products help transfer the ecological footprint to other countries, the imports would intensify the ecological footprint counted for the importing country. Consequently, as the shadow economy grows, the ecological footprint of a nation may either increase or decrease depending on the relative comparison between the ecological footprint of exports and that of imports.

According to the theoretical framework for the trade-environment nexus proposed by Tayebi and Younespour (2012), all else equal, a capital-abundant country (normally rich nations) should produce and exchange capital-intensive goods (with high environmental impacts) for labor-intensive goods (cleaner products). Meanwhile, a labor-abundant country (the poorer nation) tends to exchange labor-intensive goods (with high environmental impacts) for capital-intensive goods, in this study, it is referred to as the “trade-related effect” of informality on the environmental quality.

Literature review and hypothesis development

The non-linear nature of the shadow economy-ecological footprint linkage

There is a growing body of literature that examines the shadow economy and environmental quality linkage. However, this relationship is found heterogeneous among different countries. Based on the MIMIC model approach with autoregressive-distributed lag (ARDL) and other co-integrating estimation techniques, Imamoglu (2018) analyzes the relationship between the size of the shadow economy and CO₂ emissions in Turkey over the 1970–2014 period. The study reveals that the growth of informal economic activities helps slow down the increase of environmental pollution from production. In contrast, the deregulation effect of informality on the environment is found valid in many studies. In line of the Environmental Kuznets Curve hypothesis, Abid (2015) finds that similar to the formal sector, the shadow economy in Tunisia grows at the costs of the environment, as proxied by CO₂ emissions. This monotonically positive relationship is held for the period 1980–2009 based on a co-integrated VECM model specification. Likewise, Chen et al. (2018) examine the effects of environmental legislation and the size of shadow economy on environmental quality within 30 provinces in China between 1998 and 2012. Estimation results from the generalized method of moments (GMM) analysis show that the shadow economy deteriorates the efficacy of environmental controls, and this further increases the environmental costs of production activities (as proxied by the emissions of primary pollutants, including CO₂, soot and dust, and capita wastewater). Similarly, Baloch et al. (2021) utilize the ARDL-bound testing approach and panel data of Pakistan covering the 1966–2008 period to evaluate the environmental risks resulting from the growth of shadow economy. The study affirms that underground economic activities significantly boost the level of CO₂ emissions from all primary sources.

Not only findings among countries are heterogeneous, but empirical evidence resulting from regional and international data is also inconsistent. Nkengfack et al. (2021) employ the ARDL methodology to revisit the informality-environmental quality nexus for 22 sub-Saharan African countries between 1991 and 2005. In line with the scale effect of the shadow economy, a higher share of the shadow economy is found to curve the emissions of CO₂ in both
the short run and the long run, especially among the lower-middle-income countries. To reach a generalized conclusion about the informality-environmental pollution nexus, Biswas et al. (2012) use fixed-effects panel regressions for more than 100 countries over the 1999–2005 period. The estimation results indicate that a higher share of the black economy is associated with a lower level of both CO2 and SO2 emissions, which fits the scale effect of informality. Similarly, based on a data set of 134 nations from 1980 to 2018, Shao et al. (2021) suggest that the shadow economy may act as an instrument to manage environmental risks from production activities. The panel data threshold regressions and co-integration techniques indicate that the shadow economy demonstrates negative linkages with gas emissions in both the short run and the long run. In contrast, Mazhar and Elgin (2013) prove the validity of the deregulation effect at the international level based on a data set of 161 countries between 2007 and 2010. The study reveals the mechanism underlying environmental pollution in the presence of underground economic activities. Specifically, the imposition of stringent environmental regulation in the formal sector will result in the expansion of the shadow economy that, in turn, intensifies CO2 emissions.

A research strand has emerged to seek an explanation for the inconsistent empirical evidence of the relationship between shadow economy and pollution. It is suggested that the direction of the informality-environment linkage depends on the relative strength of either the scale effect or the deregulation effect against the other. Correspondingly, there exists a non-linear relationship between shadow economy and environmental quality so that the position of each country along the relationship curve would determine whether the positive or negative environmental externalities of the informal sector is witnessed. Elgin and Öztunali (2014a) find an inverted U-shaped relationship between shadow economy and carbon emissions in Turkey during 1950–2009. In more detail, a low level of carbon emissions is correlated to a small or large share of the informal sector. Meanwhile, larger levels of CO2 emissions are associated with medium levels of informality. The non-linear nature of the informality-environmental quality linkage is further affirmed in empirical research in China by Yang et al. (2021). Estimation results indicate an inverted U-shaped association between the size of the informal sector and environmental pollution. As the black economy grows, the deregulation effect of informality is found dominated in raising carbon emissions before the scale effect is strong enough to demonstrate positive environmental externalities. The same conclusion is reached for international evidence of 152 countries from 1999 and 2009 (Elgin and Öztunali 2014b). However, there is a lack of literature on the non-linear relationship between shadow economy and environmental quality for country groups, especially among OECD nations.

The literature provides rich evidence about the heterogeneous impacts of shadow economy on environmental quality. Nevertheless, most previous studies employ air pollution as the primary indicator of environmental quality with various measures. While most studies use CO2 emission as a proxy for environmental deterioration (Abid 2015; Elgin and Öztunali 2014a, 2014b; Imamoglu 2018; Nkengfack et al. 2021); others use a composite indicator based on primary pollutant sources, including CO2, soot and dust, and capita wastewater (Chen et al. 2018); CO2 and SO2 (Biswas et al. 2012); or N2O, CH4, and CO2 (Canh et al. 2019). This may be a reason for the inconclusive findings as found in the informality-environment literature. In this research, we employ ecological footprint, a more comprehensive indicator for environmental deterioration, to revisit the non-linear relationship between shadow economy and environmental quality. This construct is used by Köksal et al. (2020) to examine the environmental impacts of shadow economy in Turkey during the 1961–2014 period. However, the study by Köksal et al. (2020) ignores the possibility of the non-linear relationship between informality and environmental quality. Based on the existing literature, we argue that the expansion of the informal sectors would strengthen both the deregulation effect and the scale effect. In the initial phase, the deregulation effect of informality may prevail in raising the ecological footprint. As the shadow economy continues to grow to a sufficiently high level, the reduction of demand for natural resources and polluting emission, as resulted from the scale effect, could be strong enough to offset the deregulation effect and dominate with a negative impact on the ecological footprint. On the other hand, the trade-related effect, which may exert either a negative or a positive impact on ecological footprint, would support the scale effect or deregulation effect respectively but would not change the non-linear nature of the informality-environment nexus.

H1: There is an inverted U-shaped relationship between shadow economy and ecological footprint

The heterogeneous environmental impact of shadow economy across levels of ecological footprint

Beyond the non-linear relationship, the literature suggests that the heterogeneous impacts of shadow economy on the environmental quality could be explained by income levels (Canh et al. 2019; Sohail, 2021; Swain et al., 2019) or the existence of moderators in such a relationship. First, Biswas et al. (2012) highlight the role of corruption control in negating the deregulation effect of the informal sector on environmental pollution. This conclusion is drawn based on international evidence over the 1999–2005 period. Similarly, Dauda et al. (2021) assert that weak institutions in Africa from
The heterogeneous impacts of shadow economy on production and consumption heterogeneous footprint

While previous studies on the relationship between the shadow economy and the environmental quality mostly focus on either the total emissions or the pollution from production activities only, little attention is paid to the impact of the underground sector on the environmental impacts of consumption. In a panel study on Pakistan from 1966 and 2008, Baloch et al. (2021) examine the impact of shadow economy on CO₂ emissions from both production and consumption. Despite that the study attempts to include different sources of emissions, it fails to separate and compare the effects of underground economic activities on emission from production and that from consumption activities. In this research, we argue that production and consumption activities, as two primary sources of energy use and pollution, need to be tackled by different measures. Therefore, it is necessary and interesting to examine and contrast the environmental impacts of underground activities between the two sources.

The employment of the ecological footprint as an indicator for environmental deterioration in this study allows us to separate the estimation of the ecological footprint of production from that of consumption. For a given nation, the ecological footprint of production is calculated based on the consumption of biocapacity originating from the national production activities. In this regard, the impact of shadow economy on the ecological footprint of production is characterized by the scale effect and the deregulation effect. On the other hand, the ecological footprint of consumption indicates the consumption of biocapacity by the nation’s inhabitants during their consumption of either domestic or imported goods (Ree, 1992). Given that the output of the production process is either consumed domestically or exported, the ecological footprint of consumption is the sum of ecological production and net ecological footprint of trade (the difference between the ecological footprint of imports and that of exports). Correspondingly, the relationship between shadow economy and ecological footprint of consumption is characterized by not only the scale effect and the deregulation effect but also trade-related effect which may exert either a positive or negative effect on the ecological footprint. Regardless of the direction and magnitude of the trade-related effect, this would determine different thresholds of shadow economy where positive environmental externalities of underground activities could be witnessed in the case of production ecological footprint from that of consumption ecological footprint (Fig. 1).

H₃: There is an inverted U-shaped relationship between shadow economy and either production ecological footprint or consumption ecological footprint, but their turning points occur at different levels of informality.
Methodology

Model construction

The present study extends the STIRPAT model of Dietz and Rosa (1994) by incorporating the shadow economy variable to examine how this factor influences the ecosystem in OECD countries. The STIRPAT model identifies the impacts of socioeconomic elements, including population, affluence, and technology on the environment. The standard form of STIRPAT is expressed as follows:

$$ENV_{it} = \theta P_{it}^\alpha A_{it}^\beta T_{it}^\gamma \epsilon_{it}$$

(1)

where ENV represents environmental quality, \(P\) denotes population, \(A\) indicates affluence, \(T\) stands for technology, and \(\epsilon\) is the error term. We can transform model (1) into an econometric model where all variables are expressed in their logarithm form as follows:

$$\ln ENV_{it} = \theta \ln P_{it} + \alpha \ln A_{it} + \beta \ln T_{it} + \gamma \ln \epsilon_{it} + \epsilon_{it}$$

(2)

where \(\theta\) is the intercept; \(\alpha, \beta,\) and \(\gamma\) are coefficients, which measure the environmental elasticity of population, affluence, and technology; and \(i\) and \(t\) are countries and times, respectively. Based on the review of existing, this paper selects ecological footprint to proxy for environmental quality and a group of explanatory variables representing its determining factors. The potential influencers of the ecosystem include shadow economy (Elgin and Öztunali 2014a, 2014b), trade openness (Ali et al. 2021; Shahbaz et al. 2017), and gross domestic products (Destek et al. 2018; Nassani et al. 2017) (representing affluence level) as well as energy intensity (Danish et al. 2020) and renewable energy (Chen and Lei 2018; Chu and Le 2021) (reflecting technology level). Because the per capita measurement is applied for both sides of Eq. (2), the following equation does not directly contain the variables that capture the population level (Canh et al. 2021). In addition, to capture the possible inverted U–shaped relationship between shadow economy and ecological footprint, we include both variable shadow economy and its square in the model. The econometric regression model can be re-expressed for hypothesis testing as follows:

$$\ln EF_{it} = \phi_0 + \phi_1 SHA_{it} + \phi_2 SHA_{it}^2 + \phi_3 OPE_{it} + \phi_4 ENE_{it} + \phi_5 REN_{it} + \phi_6 GDP_{it} + \phi_7 GDP_{it}^2 + \epsilon_{it}$$

(3)

where \(EF\) represents the ecological footprint of production or consumption; \(SHA\) represents the shadow economy; \(OPE, ENE, REN,\) and \(GDP\) denote the trade openness, energy intensity, renewable energy, and GDP, respectively. \(\alpha\) denotes the common slope coefficients to be estimated.

Based on hypothesis \(H_1\), it is expected that if an inverted U–shaped relationship between shadow economy and environmental externalities exists, the signs of shadow economy and its square are positive and negative, respectively. Specifically, if \(\phi_1\) and \(\phi_2\) are statistically positive and negative, the inverted U–shaped relationship is established. Initially,
an increase in the informal sector causes the environment to degrade. When the informal sector expands to a certain level, often called a threshold or turning point, further extension of the informal sector reduces damage to the environment. Considering the fact that data have been already transformed into the natural logarithm, the level of shadow economy at the turning point will be computed by taking the exponential of the $-\frac{\phi_1}{2\phi_2}$. The calculation of this threshold across the distribution of ecological footprint will confirm or reject hypotheses $H_2$ while the comparison between those of production and consumption will validate hypothesis $H_3$.

The energy intensity is believed to exert a harmful impact on environmental quality because it is considered a primary force of energy usage (Danish et al. 2020). The expected signs of coefficients of trade openness and renewable energy are either positive or negative based on the strength of their effects on consumption or production ecological footprint. The environmental impact of GDP per capita depends on the current stage of the country’s economic development (Chu 2021b; Álvarez-Herránz et al. 2017). Accordingly, the impact may follow a U-shaped or an inverted U-shaped pattern.

**Econometric method**

With the increasing integration in terms of economic and other social, political, and even environmental issues, it is most likely that cross-section dependence occurs in the panel data. This phenomenon is further highly expected in the case of developed countries like OECD countries. Given this potential characteristic, the assumption of independence between cross-country estimation may lead to misleading information and inconsistent and biased outcomes (Westerclund, 2007). Therefore, this paper firstly tests the cross-sectional dependence variable by the method developed by Pesaran (2015). If the cross-section dependence exists, the use of first-generation unit root tests is not applicable. We there rely on Pesaran (2007) cross-sectionally augmented Dickey Fuller panel unit root test to check the stationarity of variables. To examine whether there exists a long-term relationship between variables of interest, the Westerlund (2007) co-integration test is employed. This approach uses four statistics, two for group mean statistics and two for panel statistics.

Before implementing the panel quantile regression approach, it is essential to examine whether the data is normally distributed or not. This study relies on Shapiro and Wilk (1965) and Bera and Jarque (1981). In terms of graphical illustration, the quantile–quantile normality test is employed to display the distribution of data. If the two tests reject the null hypothesis that the data is normally distributed as well as the graphical illustration shows that the plots of variables do not fall on the normally distributed line, the paper can proceed with the panel quantile regression method.

This paper resorts to the panel quantile regression to verify the heterogeneous effect of shadow economy on ecological footprint. If it is verified that the variables of interest and residuals from regressions do not follow the normality distribution, the traditional mean approaches...
fail to provide consistent estimated results. In contrast, the quantile regression does not rely on the normality assumption. Second, in the case that data of dependent variables contain outliers (or heavy-tailed distribution), such asymmetric feature may result in over- or under-estimation of parameters. However, the quantile regression proves effective in such an issue because its estimation process is based on the median (instead of the mean). Third, the panel quantile regression with fixed effects can mitigate the problem of unobserved individual heterogeneity and aid identification. Fourth, if it is interesting to explore the policy implications based on varying impacts of the independent variable at different points in the conditional distribution of dependent variables, quantile regression is considered as an appropriate approach. Therefore, we put forward the estimation model as follows:

\[
Q_{EF_i}(\tau |a_i) = \varphi_1 + \varphi_{SHA_i} + \varphi_{SHA_i^2} + \varphi_{PPE_i} + \varphi_{ENE_i} + \varphi_{REN_i} + \varphi_{GDP_i} + \varphi_{GDP_i^2} + \varepsilon_{ij},
\]

where \(Q_{EF_i}\) refers to the \(\tau\)th conditional quantile of ecological footprint given its determining factors; \(a_i\) indicates the regression parameters of the \(\tau\)th quantile of ecological footprint.

By estimating Eq. (4) using the quantile regression method, we can test hypothesis \(H_1\) of the heterogeneous impacts of shadow economy (and also other determining factors) on the ecosystem. A growing literature has developed methods to estimate Eq. (4), including Koenker (2004), Canay (2011), and Galvao (2011), to name a few. The main problem of such methods lies in the difficulties in estimating a large number of fixed effects \(a_i\) and considering incidental parameter problems when the time dimension is short (Powell 2016). To overcome this issue, Powell (2016) proposes a quantile regression estimator of panel data with non-additive fixed effects. Specifically, by using within-group variation for identification purposes and maintaining the no separable disturbance property, the estimation of parameters can be inferred in the same manner as cross-sectional quantile estimates. Moreover, as the individual fixed effects are not estimated, the number of parameters to be estimated is small relative to the other panel regression techniques. Therefore, two methods by Canay (2011) and Powell (2016) are deployed to robustly estimate the environmental effects of shadow economy. Recently, a series of papers in the field of the economic environment have adopted these two approaches to explore the heterogeneous impacts of driving forces on environmental quality (Alvarado et al. 2021; Albulescu et al. 2019; Belaïd et al. 2021; Dogan et al. 2020). The authors of these papers claim that by adopting the quantile regression method, they overcome the shortcomings of traditional regression methods such as system GMM, fixed effects, fully-modified ordinary least squares, and autoregressive distributed lag (Chen et al. 2018; Khan et al. 2021; Nkengfack et al. 2021).

We also conduct the fixed effects with Driscoll and Kraay robust standard errors and full-modified ordinary least squares to see the outcomes derived from conditional mean methods. This framework has been employed by several papers (Akram et al. 2021; Anwar et al. 2021; Dogan et al. 2020; Chu and Le 2021) to facilitate the comparison between the results of quantile regression and mean regression methods.

**Data specification**

This paper focuses on the effect of shadow economy on the ecological footprint of OECD countries. Based on the data availability, 32 countries are included, i.e., Australia, Austria, Belgium, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Japan, Korea, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, UK, and USA. We select the annual data covering the period from 1990 to 2015.

We use two indicators, the ecological footprint of consumption and the ecological footprint of production, to proxy for environmental quality. The consumption ecological footprint indicates the consumption of bio-capacity by a nation while the production ecological footprint measures the consumption of bio-capacity resulting from production processes within a given geographic area. The former is the sum of the latter and the net ecological footprint of trade. The net ecological footprint of trade is defined as the use of bio-capacity within international trade. In this paper, both indicators are measured as global hectare per capita and extracted from the database of the Global Footprint Network (https://www.footprintnetwork.org/).

The shadow economy is expressed as the proportion of informal output (of official gross domestic products). Given the difficulty of measuring informality, a wide range of estimation methods have been developed to capture its size. Such methods can be classified into two groups, one encompassing indirect model-based estimates of the relative scale of informal output another incorporating direct measures gathered from surveys. In the former group, several approaches are employed, including the electricity demand approach, the Multiple Indicators Multiple Causes model, and the Dynamic General Equilibrium model (hereafter DGEM). In this paper, the shadow economy is estimated based on the DGEM by Elgin et al. (2021). According to Elgin et al. (2021), the idea behind DGEM is that rational
households will allocate labor between formal and informal economies in each period to optimize their benefits. While this model has advantages in terms of theoretical basis, data coverage, and applicability (Loayza 2016), it suffers several limitations such as assumptions about the functional form of and the relationship between formal and informal activities as well as base-year estimates from an independent study. The shadow economy data is collected from Elgin et al. (2021) on the Informal Economy Database of the World Bank (https://www.worldbank.org/en/research/brief/informal-economy-database).

In this study, we incorporate export and import into trade openness to capture their aggregated impacts on environmental quality. Energy usage quantifies the kilogram of oil equivalent per capita while renewable energy reflects the renewable proportion in total final energy consumption. Gross domestic product per capita and its square are included in the model to capture the potential of the Environmental Kuznets Curve hypothesis. The data of trade openness, energy intensity, renewable energy, and GDP per capita are obtained from the World Development Indicators database of the World Bank. Because the variables are expressed in different types of units, it is preferable to take their natural logarithm. This transformation also helps to facilitate the interpretation of estimation results as elasticity and control heterogeneity.

Result and discussion

Summary statistics

The empirical results are analyzed as follows: Our analysis starts by providing a breakdown of variable summary statistics and normality test. It then shows preliminary results of cross-sectional dependence, unit root, and co-integration tests. The last and main part presents the results of panel quantile regression.

Table 1 provides the summary statistics of all variables in the natural logarithm. The means of production and consumption ecological footprint are 1.64 and 1.72, which are equivalent to 5.81 and 5.91 global hectares per capita, respectively. The average level of shadow economy is 2.75 (17.03% of official GDP). As of the year 2015, Mexico ranks first in terms of shadow economy (6.94%) while Switzerland ranks last (28.07%).

Figure 2 shows that the relationship between shadow economy and ecological footprint does not follow a linear but instead a non-linear pattern. At each sub-distribution of ecological footprint, an initial increase of shadow economy leads to an escalation in ecological footprint but a further increase reduces ecological footprint. It provokes the idea that there exist different inverted U–shaped relationships between shadow economy and ecological footprint in different sub-distributions of ecological footprint.

Cross-sectional dependence, unit root, co-integration, and normality tests

This section analyzes the cross-sectional dependence test to check the suitability of the unit root and co-integration tests. Table 2 shows the results of the Pesaran (2015) cross-sectional dependence test. The null hypothesis of no cross-sectional dependence is rejected at a 1% significance level for all variables. This finding calls for the adoption of second-generation unit root and co-integration tests.

We adopt the Pesaran (2007) panel unit root test that allows for cross-sectional dependence. The standard augmented Dickey-Fuller regressions are augmented with the cross-section averages of lagged levels and first differences of the individual variables. The results of variables in both level and first difference are reported in Table 3. It is revealed that while ecological footprint and renewable energy are stationary at a level, all variables are stationary at their first differences. Based on this finding, we can proceed with the co-integration test.

As the cross-sectional dependence exists, it is appropriate to employ a co-integration test that deals rigorously with its presence. This paper relies on Westerlund (2007) to verify the long-run relationship between interest variables. According to Table 4, the integration between groups (Gt) and panels (Pt) are confirmed at the 1% significance level.

We check the normality of the variables, which is the basic assumption of a conditional mean regression model, by employing the Shapiro–Wilk and Skewness–Kurtosis test as well as the quantile–quantile plot. First, the test by Shapiro and Wilk (1965) where the null hypothesis that a sample comes from a normally distributed population is adopted. As shown in Table 5 panel A, the null hypothesis is rejected at a 1% significance level. The Skewness–Kurtosis test by Bera and Jarque (1981) in Table 5 panel B also confirms

| Variable | CD test | Mean ρ |
|----------|---------|--------|
| EFC      | 27.482*** | 0.25   |
| EFP      | 28.961*** | 0.27   |
| SHA      | 66.642*** | 0.63   |
| OPE      | 66.395*** | 0.63   |
| ENE      | 23.073*** | 0.22   |
| REN      | 42.268*** | 0.40   |
| GDP      | 91.269*** | 0.87   |

Authors’ calculation based on Stata software

*** < 0.01; ** < 0.05; * < 0.1
the non-normality of the unconditional distribution of variables. Figure 4 exhibits the univariate kernel density for the residuals, which shows the strong deviation from the normal distribution. Second, the quantile–quantile plot is a visual expression of variable distribution around a diagonal line. It is demonstrated from Figure 5 that all scatter diagrams deviate from the diagonal lines. Therefore, no variable follows the normal distribution. Overall, both the results of the quantile–quantile plot and two residual tests imply that the panel data are not normally distributed, suggesting the implementation of panel quantile regressions.

### Conditional mean regression results

The present study proceeds with conditional mean methods before analyzing the panel quantile regression results. Table 6 reports the estimation results of fixed effects with Driscoll and Kraay standard errors and fully modified ordinary least squares. There are several noticeable outcomes. First, although the coefficients of shadow economy and its square are positive and negative, respectively, only those obtained from production ecological footprint by the fixed effect model are statistically significant. Second, the environmental impact of trade openness is inconsistent between the two estimation methods. While the sign of trade openness coefficients is negative in the fixed effects model, they are positive in the fully modified ordinary least square model. Third, similar properties are found for the relationship between economic development and ecological footprint. However, the results consistently produce the harmful effects of energy intensity and beneficial effects of renewable energy. The outcomes on the effects of gross domestic product and its square are considerably different between the two estimation methods. Overall, we find that the sign and magnitude of estimated coefficients are not consistent between fixed effects with

### Table 3  Unit root test

| Variable | Level Without trend | Level With trend | First difference Without trend | First difference With trend |
|----------|---------------------|------------------|-------------------------------|-------------------------------|
|          | Lags(0) | Lags(1) | Lags(0) | Lags(1) | Lags(0) | Lags(1) | Lags(0) | Lags(1) | Lags(0) | Lags(1) | Lags(0) | Lags(1) | Lags(0) | Lags(1) |
| EFP      | -1.777** | 1.829 | -4.517*** | -2.281** | -17.087*** | -8.959*** | -14.751*** | -6.462*** |
| EFC      | -2.211** | 2.704 | -3.713*** | -0.382 | -17.961*** | -8.391*** | -15.546*** | -5.426*** |
| SHA      | 1.574 | 1.680 | 4.651 | 4.771 | -11.399*** | -1.692** | -10.378*** | -0.072 |
| OPE      | 1.549 | -0.052 | 3.717 | 2.129 | -8.403*** | -3.856*** | -6.368*** | -1.640 |
| ENE      | 0.312 | 1.291 | -1.900** | -1.449 | -14.411*** | -8.741*** | -12.048*** | -6.076*** |
| REN      | -2.566*** | -0.612 | -5.920*** | -3.577*** | -16.907*** | -9.726*** | -13.882*** | -6.730*** |
| GDP      | 2.179 | -1.543 | 3.347 | -0.368 | -5.383*** | -3.138*** | -2.287** | 0.049 |

Authors’ calculation based on Stata software

*** < 0.01; ** < 0.05; * < 0.1

### Table 4  Co-integration test

| Statistic | Production ecological footprint | Consumption ecological footprint |
|-----------|---------------------------------|---------------------------------|
|           | Value | Z-value | P-value | Value | Z-value | P-value |
| $G_t$     | -10.491 | -46.563 | 0.000 | -3.045 | -3.550 | 0.000 |
| $G_a$     | -0.744 | 9.766 | 1.000 | -5.287 | 5.662 | 1.000 |
| $P_t$     | -17.445 | -3.721 | 0.000 | -19.494 | -6.777 | 0.000 |
| $P_a$     | -6.212 | 3.465 | 1.000 | -9.003 | 0.226 | 0.589 |

Authors’ calculation based on Stata software

### Table 5  Shapiro–Wilk and Skewness-Kurtosis test for normality

| Variable | W | V | z | Prob > z |
|----------|---|---|---|---------|
| Panel A. Shapiro–Wilk test |
| EFP resi. | 0.919 | 35.596 | 8.700 | 0.000 |
| EFC resi. | 0.868 | 57.988 | 9.888 | 0.000 |
| Panel B. Skewness-Kurtosis test |
| EFP resi. | 0.000 | 0.060 | 49.630 | 0.000 |
| EFC resi. | 0.000 | 0.000 | 50.850 | 0.000 |

The residuals are obtained from estimating Eq. (1) using ordinary least squares. Source: authors’ calculation based on Stata software
Driscoll and Kraay standard errors and fully modified ordinary least squares. The reasons may lie in the problems of non-normal distribution and outliers in the panel data. The conditional mean methods are not effective in dealing with these challenges, which encourages us to adopt the quantile regression methods. Although these findings only act as references for the Canay (2011) and Powell (2016) regressions, they support the implementation of such panel quantile regressions.

**Quantile regression results**

The panel quantile regression is capable of modeling the entire conditional distribution and controls for the unobserved heterogeneity. Thus, we use nine quantiles for a comprehensive understanding of the environmental effects of shadow economy and other decisive factors. This practice facilitates the analysis at the extreme of the distribution, which is very helpful in proposing policy recommendations. The empirical outcomes on the determinants of production ecological footprint are presented in Table 7 while those of consumption ecological footprint are reported in Table 8. The results obtained from Canay’s (2011) and Powell’s (2016) methods are reported consecutively in panels A and B, respectively of each table. At a first glance, we realize that the estimation results of Canay’s (2011) and Powell (2016)’s methods are quite similar.

The results of quantile regression in Tables 7 and 8 indicate that shadow economy has a significant effect on ecological footprint (both production and consumption) as the coefficients of shadow economy and its squares are statistically significant at conventional levels (except for 10th quantile in Canay (2011) estimation). Moreover, the coefficients of shadow economy are statistically positive while those of its squares are statistically negative. It indicates the existence of an inverted U–shaped relationship between shadow economy and ecological footprint. Specifically, an initial increase in shadow economy leads to a degradation in the ecosystem. When the size of shadow economy reaches a certain threshold, a further expansion of informality leads to an improvement in the ecosystem. To check for the existence of non-linearity between shadow economy and ecological footprint, the Lind and Mehlum (2010)’ test is conducted. This test verifies the combined proposition that the slope of the connection is positive (negative) at the left-hand side of the interval and negative (positive) at the right-hand side. The results strongly reject the null hypothesis of no inverse U–shaped relationship between shadow economy and ecological footprint. Specifically, the estimation statistics demonstrate the change in the relative strength of the

---

**Table 6 Estimation results from conditional mean methods**

|       | Production ecological footprint | Consumption ecological footprint | Production ecological footprint | Consumption ecological footprint |
|-------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| **SHA** | 4.224*** (1.151) 0.084 (0.376) 0.138 (0.369) 0.232 (0.957) | **SHA_sq** | −1.012*** (0.276) −0.030 (0.074) −0.029 (0.072) −0.047 (0.229) |
| **OPE** | −0.012 (0.027) −0.087 (0.059) 0.072 (0.049) 0.127*** (0.023) |
| **ENE** | 1.392*** (0.047) 0.496*** (0.110) 0.663*** (0.105) 1.151*** (0.039) |
| **REN** | −0.068*** (0.020) −0.054*** (0.017) −0.055*** (0.018) −0.072*** (0.017) |
| **GDP** | −27.071*** (5.478) 0.317 (0.225) 0.701*** (0.201) 0.138 (4.554) |
| **GDP_sq** | 1.268*** (0.256) −0.011 (0.013) −0.042*** (0.011) −0.015 (0.213) |
| **Constant** | 130.085*** (28.490) −3.922*** (1.387) −6.832*** (1.216) −8.381 (23.685) |

Variables are transformed into natural logarithm before estimation. Standard errors are in brackets. Source: authors’ calculation based on Stata software

*** < 0.01; ** < 0.05; * < 0.1
Panel A. Canay (2011) estimation results

| Variable | Coefficient | Standard Error | p-value |
|----------|-------------|----------------|---------|
| SHA      | 1.553***    | 0.311***       | <0.01   |
| SHA_sq   | -0.299***   | 0.065***       | <0.01   |
| OPE      | -0.037***   | 0.020***       | <0.01   |
| ENE      | 0.933***    | 0.020***       | <0.01   |
| REN      | 0.093***    | 0.017***       | <0.01   |
| GDP      | 0.402***    | 0.017***       | <0.01   |
| GDP_sq   | -0.033***   | 0.065***       | <0.01   |
| Constant | -8.902***   | 0.354***       | <0.01   |

Panel B. Powell (2016) estimation results

| Variable | Coefficient | Standard Error | p-value |
|----------|-------------|----------------|---------|
| SHA      | 1.524***    | 0.055***       | <0.01   |
| SHA_sq   | -0.294***   | 0.049***       | <0.01   |
| OPE      | -0.039***   | 0.093***       | <0.01   |
| ENE      | 0.926***    | 0.065***       | <0.01   |
| REN      | 0.091***    | 0.015***       | <0.01   |
| GDP      | 0.371***    | 0.025***       | <0.01   |
| GDP_sq   | -0.032***   | 0.016***       | <0.01   |
| Constant | -8.641***   | 0.114***       | <0.01   |

Variables are transformed into natural logarithm before estimation. The turning point of shadow economy has been recalculated to its original form. Standard errors are in brackets. Source: authors’ calculation based on Stata software

*** < 0.01; ** < 0.05; * < 0.1

deregulation effect over the scale effect and vice versa by the degree of informality. Initially, the existence of a small-scale shadow economy could not create enough positive environmental externalities to offset the environmental costs of its deregulation effect. Only when the size of the shadow economy reaches a sufficiently high level does the scale effect of underground activities prevail to save energy consumption and create a significant reduction in the ecological footprint. Depending on the shadow export–import structure, the trade-related effect would demonstrate either a negative or positive impact on ecological footprint. This would affect the threshold where shadow economy starts to reduce the ecological footprint but not change the non-linear nature of the informality-environmental quality linkage. Overall, this
finding confirms hypothesis $H_1$ of an inverse U-shaped relationship between shadow economy and ecological footprint. This result is in line with Elgin and Öztunali (2014a, 2014b) and Yang et al. (2021) that claim that a higher shadow economy initially worsens environmental quality, but to a certain threshold, it helps control environmental degradation.

With regard to the heterogeneous impacts of shadow economy, we find that the coefficients of shadow economy and its square are different with varying levels of ecological footprint. The threshold for each quantile can be calculated by taking the exponential of $\frac{q_i}{2\sigma^2}$ and is reported at the end of each panel of Tables 7 and 8. We find that the turning points are different across quantiles of ecological footprint. In the case of production ecological footprint, the shadow economy turning point increases gradually when the ecological footprint moves from the low to the high quantiles.
middle quantiles. The highest turning point is achieved at the 50th quantile. Then, the turning point remains quite stable from the 60th to the 80th quantile before decreasing to the lowest level at the 90th quantile. Concerning the consumption ecological footprint, the shadow economy turning point starts at a low level at the 10th quantile and then rises to achieve the highest level at the 40th quantile. After decreasing considerably at the 50th quantile, it fluctuates moderately when the ecological footprint moves along the 60th to 90th quantile. This may be because a high level of the ecological footprint may imply a high level of industrialization that leaves more environmental costs while awarding more accumulation of capital. Correspondingly, countries with extremely high environmental degradation (as compared to others in our sample) are more likely capital-abundant agents that obtain environmental benefits from international trade under the theoretical framework for the trade-environment nexus (Tayebi and Younespour 2012). For those countries, the trade-related effect supports the scale effect to alleviate the overall ecological footprint. This helps further offset the negative environmental impacts of shadow economy (as resulted from the deregulation effect) and, hence, yield a low level of turning point. On the other hand, an extremely low level of the ecological footprint may imply a low level of industrialization and/or high stringency of regulation and institutions. This strengthens the scale effect while weakening the deregulation effect of underground activities and, therefore, also results in a lower level of turning point. These two trends of turning points support hypothesis H2, that the relationship between shadow economy and ecological footprint is not homogeneous across different levels of ecological footprint.

Concerning the differences in the role of the shadow economy in determining ecological footprint of production and consumption, we find that almost all turning points of shadow economy in the latter case are higher than those in the former case. The exceptional item is the 10th quantile. It means that for production ecological footprint, shadow economy only needs to increase by a lower level to obtain its beneficial effects. In contrast, such favorable effects are obtained only at a higher level of shadow economy in the case of consumption ecological footprint. In addition, the gaps at the 10th to 40th quantiles are significantly higher than those at the 50th to 90th quantiles. This may be because while the ecological footprint of both production and consumption is influenced by the deregulation effect and the scale effect, the consumption ecological footprint is additionally affected by the trade-related effect (as originating from export–import activities). Our findings indicate that, in general, the trade-related effect would, together with the deregulation effect, intensify the ecological footprint of consumption. Consequently, the size of shadow economy needs to expand up to a higher threshold to dominate both the deregulation effect and the trade-related effect and create significant improvement in environmental quality. In this regard, the net ecological footprint of trade of OECD countries is mostly positive. This finding endorses hypothesis H2 that there are differences in the turning points of shadow economy between production and consumption ecological footprint.

For the year end in 2015, most countries with a lower level of environmental quality in terms of ecological footprint (than other countries in our sample), e.g., Luxembourg, USA, Denmark, and Australia, have relatively low levels of shadow economy. By further controlling the informal sector, they can obtain a better environmental quality. For example, the scale of the informal sector in the USA was 7% in 2015, decreasing by 1.71% from 2010. It is lower than the determined threshold at the 90th quantile (USA belongs to the highest quantile of ecological footprint). Consistently, the ecological footprint of production declined from 8.98 global hectares per capita in 2010 to 8.02 in 2015. The corresponding values of ecological footprint were 8.94 and 8.17 global hectares. In contrast, countries with higher levels of environmental quality, e.g., Mexico, Turkey, Hungary, Spain, Portugal, are facing the expansion of the informal sector. In the process of formalizing their economies, these countries need double efforts to reduce shadow economy considerably to fall behind the turning point. Only at the low levels of shadow economy (lower than those of more environmentally degraded countries) can they attain the environmental benefit of controlling the informal sector. We illustrate this point by using the case of Hungary. This country has a low level of ecological footprint, at the 20th quantile. However, the shadow economy accounts for a large position in Hungary with the scale of 20.49% in 2015 (22.82% in 2010). Because of economic transition, the consumption ecological footprint degraded from 3.64 in 2010 to 3.74 global hectares per capita in 2015.

With regard to other explanatory variables, we also find the existence of heterogeneity across the distribution of ecological footprint as well as the differences between their impacts on production and consumption ecological footprint. First, higher energy intensity is detrimental to the quality of the ecosystem as its coefficients are positive and statistically significant at conventional levels. This finding is consistent with the conclusion reported by Akram et al. (2021), Salman et al. (2019), and Zhu et al. (2018). In the case of production ecological footprint, the impact follows an N-shaped pattern where it reaches the high level at the 10th and 70th quantiles. In the case of consumption ecological footprint, the magnitude of the environmental effect of energy intensity reaches the highest level at the 20th quantile before declining along with the degradation of environmental quality.

Second, the coefficients of renewable energy are positive and statistically significant at all quantiles in the production
A  Consumption ecological footprint

B  Production ecological footprint
ecological footprint. In this case, a modern energy structure fails to lessen environmental damage but aggravates it through the rebound effect in production activities. This phenomenon has been explored in several studies (Dogan et al. 2022; Lin and Liu 2012). In contrast, such a rebound effect does not occur in the effect of renewable energy in consumption ecological footprint. The impact of renewable on consumption ecological footprint is negatively significant and similar to the results of Akram et al. (2021), Anwar et al. (2021), and Chen and Lei (2018). The highest benefit of renewable energy on consumption ecological footprint occurs at extremely high quantiles.

Third, international trade helps to reduce the ecological footprint of production, which may be channeled through the import of more friendly products and services as well as the export of polluted ones to foreign trading partners (Khan et al. 2020; Chu and Le 2021). The magnitude of the effect escalates with the degradation of ecological quality. With regard to consumption ecological footprint, we find two contrasting environmental effects of international trade. For low to medium distribution of ecological footprint, higher trade activities with foreign partners significantly degrade environmental quality. This outcome is similar to the finding of Akram et al. (2021), Chen and Lei (2018), and Wang et al. (2018) where these authors find that trade openness causes environmental pollution at the low and medium quantiles of the dependent variable. In contrast, higher international trade helps improve the situation in countries with a high level of environmental deprivation.

Last, the relationship between economic activities and production ecological footprint follows an inverted U–shaped pattern at the low quantiles (10th to 30th quantiles) as the coefficients of GDP and its squares are positively and negatively significant. At the high quantiles (70th to 90th quantiles), this pattern is reverted to be a U-shaped form. The interchange between inverted U-shaped and U-shaped as well as significant and insignificant relationships have been mentioned in several studies (Albulescu et al. 2019; Zhu et al. 2018). In the case of consumption ecological footprint, the relationship between economic development and environmental degradation follows a U-shaped pattern as the coefficients of GDP and its squares are negatively and positively significant. The threshold of GDP per capita where the ecological impact of higher income changes from beneficial to harmful increases with the degradation level of environmental quality. In other words, the turning point increases when the ecological footprint increases among OECD countries. It is noteworthy that as of the year 2015, all countries in our sample have income per capita higher than the turning points at all quantiles. This finding provides vigorous support for the dominant and harmful scale effect of economic development on consumption ecological footprint in OECD countries. Our results are supported by the studies of Anwar et al. (2021) and Salman et al. (2019).

To sum up, we find several distinct heterogeneities existing in the roles of shadow economy and many decisive factors with different quality of the environment. These findings reinforce our adoption of panel quantile regression and explain the reason for the inconsistent and insignificant effects of explanatory variables on ecological footprints found in conditional mean regressions. Figure 3 further illustrates our arguments.

This paper also adopts Dumitrescu and Hurlin (2012) test to assess the Granger causal relationship between interested variables. Table 9 presents the results on a pairwise basis. We find uni-directional associations running from shadow economy to ecological footprint and energy intensity. It implies that the shadow economy can exert its influence on environmental quality directly and indirectly through energy usage. Another one-way relationship exists involving income per capita and ecological footprint. In contrast, ecological footprint, energy intensity, and renewable energy have bi-directional causal linkages. It is noticeable that while the effect from trade openness to consumption ecological footprint is one-way directional, it is a two-way directional effect in the case of production ecological footprint. This result infers that the production activities in OECD countries are more sensitive to environmental changes than the consumption activities, which may be resulted from the environmental regulations, for example. Shadow economy and trade openness, renewable energy, and income per capita have two-way effects. Overall, the causal interaction of shadow economy to all the variables proves that shadow economy is an important factor to consider in abating environmental degradation.

To check the sensitivity of our findings in the case that informal economy and other determinants of environmental quality might be endogenous to pollution,1 we also use a one-period lag of explanatory variables as instruments. This practice has been adopted by Albulescu et al. (2019) and Elgin and Öztunali (2014a). The estimation results using the Powell (2016) method are provided in Table 10. The inverse U–shaped relationship as well as the heterogeneity across quantiles and two indicators of ecological footprint still hold.

---

1 We thank the anonymous reviewer for suggesting this issue.
ways. Although trade openness is found to lessen environmental degradation in most quantiles, it leads to more degradation in countries with a less ecological footprint of consumption. Renewable energy proves effective in reducing consumption ecological footprint but exacerbates the environmental deprivation in terms of production ecological footprint due to the rebound effect. The U-shaped relationship between income and ecological footprint is found in most quantiles, which emphasizes the scale effect of economic development on environmental quality.

Theoretically, this study provides a scientific explanation for the inconsistent evidence regarding the relationship between shadow economy and environmental quality, as found in previous studies. Specifically, the heterogeneity in the informality-environment linkage across countries could be justified by two factors, including the size of shadow economy and the level of environmental degradation. As the relationship between shadow economy and environmental quality follows an inverted U-shaped curve, the positive environmental externalities of underground activities could not be witnessed in countries or in periods where the size of the informal sector is too small. In such cases, the deregulation effect would dominate over the sale effect to demonstrate a negative association between informality and ecological condition. Even when the data coverage in terms of countries and time allows researchers to witness

### Table 9: The Dumitrescu and Hurlin (2012) causality test

| Null hypothesis | $Z$ statistics | Causality flow | Null hypothesis | $Z$ statistics | Causality flow |
|-----------------|----------------|----------------|-----------------|----------------|----------------|
| EFC $\neq$ SHA  | -0.4516        | EFC $\leftrightarrow$ SHA | SHA $\neq$ OPE  | 3.2878***      | SHA $\leftrightarrow$ OPE |
| SHA $\neq$ EFC  | 5.0781***      | OPE $\neq$ SHA | SHA $\neq$ ENE  | 7.9222***      | SHA $\rightarrow$ ENE |
| EFC $\neq$ OPE  | 0.8579         | OPE $\leftrightarrow$ ENE | SHA $\neq$ ENE  | 1.3594         | ENE $\neq$ SHA |
| OPE $\neq$ EFC  | 8.9166***      | ENE $\neq$ SHA | ENE $\neq$ EFC  | 5.5741***      | SHA $\leftrightarrow$ REN |
| EFC $\neq$ ENE  | 5.5741***      | EFC $\leftrightarrow$ ENE | SHA $\neq$ REN  | 5.8481***      | SHA $\leftrightarrow$ REN |
| ENE $\neq$ EFC  | 4.9772***      | REN $\neq$ SHA | SSHA $\neq$ GDP | 2.3231***      | GDP $\neq$ OPE |
| EFC $\neq$ REN  | 3.3895***      | EFC $\leftrightarrow$ REN | SHA $\neq$ GDP  | 2.8668***      | GDP $\neq$ OPE |
| REN $\neq$ EFC  | 7.6612***      | GDP $\neq$ SHA | GDP $\neq$ ENE  | 5.9993         | GDP $\leftrightarrow$ ENE |
| EFC $\neq$ GDP  | 0.8389         | GDP $\neq$ ENE | GDP $\neq$ OPE  | 10.4726***     | OPE $\rightarrow$ ENE |
| GDP $\neq$ EFC  | 5.9782***      | GDP $\neq$ ENE | GDP $\neq$ SHA  | 0.2982         | OPE $\leftrightarrow$ ENE |
| EFP $\neq$ SHA  | 1.2161         | EFP $\leftrightarrow$ SHA | EFP $\neq$ REN  | 2.2877***      | OPE $\leftrightarrow$ REN |
| SHA $\neq$ EFP  | 7.7784***      | REN $\neq$ SHA | EFP $\neq$ GDP  | 1.9027*        | OPE $\leftrightarrow$ GDP |
| EFP $\neq$ OPE  | 1.7120         | EFP $\leftrightarrow$ OPE | EFP $\neq$ GDP  | 2.4962         | GDP $\neq$ OPE |
| OPE $\neq$ EFP  | 10.0714***     | GDP $\neq$ OPE | GDP $\neq$ SHA  | 5.5762***      | SHA $\leftrightarrow$ ENE |
| EFP $\neq$ ENE  | 7.8205***      | EFP $\leftrightarrow$ ENE | EFP $\neq$ REN  | 5.1796***      | REN $\neq$ ENE |
| ENE $\neq$ EFP  | 2.5746***      | ENE $\neq$ ERE | ENE $\neq$ GDP  | 15.0223***     | REN $\leftrightarrow$ GDP |
| EFP $\neq$ REN  | 2.9393***      | EFP $\leftrightarrow$ REN | EFP $\neq$ GDP  | 1.2006         | GDP $\rightarrow$ REN |
| REN $\neq$ EFP  | 13.6311***     | GDP $\neq$ ENE | GDP $\neq$ SHA  | 9.3060***      | GDP $\leftrightarrow$ REN |
| EFP $\neq$ GDP  | 0.8956         | EFP $\leftrightarrow$ GDP | GDP $\neq$ OPE  | 2.8011***      | GDP $\leftrightarrow$ GDP |
| GDP $\neq$ EFP  | 7.3235***      | GDP $\neq$ ENE | GDP $\neq$ SHA  | 8.2011***      | GDP $\leftrightarrow$ GDP |

Authors’ calculation based on Stata software

*** < 0.01; ** < 0.05; * < 0.1

### Conclusion and policy implications

This study presents the first attempt to track the heterogeneous impacts of shadow economy and other determinants of environmental quality across various levels of environmental degradation where the ecological footprint of the consumption and production sources are separated. Our paper also features the first research on the non-linear relationship between shadow economy and ecological quality for OECD countries. By employing quantile regression for panel data of 32 OECD countries from 1990 to 2015, the findings show that the environmental effects of shadow economy, trade openness, energy intensity, renewable energy, and income are not homogeneous across ecological footprint levels. The shadow economy and ecological footprint nexus follow an inverted U-shape. Initially, the higher size of the informal economy leads to more ecosystem degradation. When the shadow economy increases to certain thresholds, the environmental impact reverts to benefit. Such threshold changes with the state of ecological footprint. Specifically, it first rises then decreases along with the degradation of the ecosystem. The significant relationships between ecological footprint and its determining factors are also established. While higher energy intensity causes harm to the ecosystem with unequal influence degrees, the environmental impact of international trade varies between harmful and beneficial
both positive and negative forces in this relationship, there
is no common threshold of shadow economy where under-
ground activities could turn to be environmentally benefi-
cial. Instead, such turning points would vary by the degree
of environmental degradation across countries.

From the societal perspective, our empirical findings enrich
the dilemma about the trade-off between the shadow economy
and sustainability targets. The growth of the underground sec-
tor has been widely referred to as a wicked problem due to
both negative and positive impacts of the shadow economy on

Table 10 Robustness test (endogeneity issue)

| 10th | 20th | 30th | 40th | 50th | 60th | 70th | 80th | 90th |
|------|------|------|------|------|------|------|------|------|

Panel A. Consumption ecological footprint

| SHA  | 0.071 | 0.270*** | 0.550*** | 0.525*** | 0.900*** | 0.963*** | 1.492*** | 1.289*** | 1.537*** |
|------|-------|----------|----------|----------|----------|----------|----------|----------|----------|
| SHA_sq | -0.015 | -0.044*** | -0.092*** | -0.083*** | -0.158*** | -0.171*** | -0.263*** | -0.230*** | -0.281*** |
| OPE  | 0.058*** | 0.042*** | 0.034*** | 0.026*** | 0.013 | -0.027*** | -0.045*** | -0.025*** | -0.035*** |
| ENE  | 0.457*** | 0.434*** | 0.408*** | 0.427*** | 0.438*** | 0.444*** | 0.461*** | 0.449*** | 0.381*** |
| REN  | -0.046*** | -0.037*** | -0.030*** | -0.027*** | -0.028*** | -0.028*** | -0.018*** | -0.044*** | -0.071*** |
| GDP  | -0.361*** | -0.765*** | -0.904*** | -1.004*** | -0.926*** | -1.346*** | -1.540*** | -2.001*** | -2.004*** |

Panel B. Production ecological footprint

| SHA  | 1.534*** | 0.847*** | 2.078*** | 1.935*** | 2.521*** | 3.073*** | 3.638*** | 4.094*** | 3.968*** |
|------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| SHA_sq | -0.298*** | -0.166*** | -0.388*** | -0.356*** | -0.464*** | -0.554*** | -0.613*** | -0.754*** | -0.801*** |
| OPE  | -0.026*** | -0.099*** | -0.138*** | -0.138*** | -0.110*** | -0.138*** | -0.147*** | -0.146*** | -0.190*** | -0.275*** |
| ENE  | 0.939*** | 1.153*** | 1.054*** | 1.055*** | 0.937*** | 0.961*** | 0.852*** | 0.791*** | 0.742*** |
| REN  | 0.095*** | 0.137*** | 0.140*** | 0.153*** | 0.147*** | 0.163*** | 0.150*** | 0.121*** | 0.074*** |
| GDP  | 0.460*** | 0.771*** | 0.306*** | 0.215*** | -0.339 | -0.254*** | -0.595*** | -0.813*** | -0.623*** |
| GDP_sq | -0.037*** | -0.054*** | -0.027*** | -0.020*** | 0.010 | 0.007*** | 0.026*** | 0.039*** | 0.026*** |
| Constant | -9.188*** | -11.168*** | -9.868*** | -9.600*** | -6.721*** | -8.223*** | -6.132*** | -5.329*** | -4.142*** |

Variables are transformed into natural logarithm before estimation. Standard errors are in brackets. The turning point of shadow economy has been recalculated to its original form. Source: authors’ calculation based on Stata software

*** < 0.01; ** < 0.05; * < 0.1
society at large. On the one hand, scholars such as Bajada and Schneider (2009) and Hatipoglu and Ozbek (2011) argue that some level of informality could function as either salvage for the unemployed or the poor. Moreover, the shadow economy could offer an outlet for the vulnerable segment of the business community to foster entrepreneurship and create new markets (Schneider and Enste 2000). On the other hand, at the macroeconomic level, downsizing the shadow economy is necessary to prevent substantial loss of tax revenue and ensure the provision of sufficient public goods and services, tax morale, and compliance (Žukauskas 2019). Our empirical findings further add that the growth of informal sectors could also endanger the ecological conditions. However, from a sufficiently high level of the shadow economy, the expansion of underground economic activities could negate the ecological footprint through its scale effect. Correspondingly, for society’s sake, there are two alternative strategies. Specifically, a natural rate of shadow economy is maintained to support the vulnerable segment in the society and obtain some scale effect. At the same time, more stringent environmental regulation is introduced and supervised to negate the deregulation effect of underground activities. Alternatively, the informal sectors should be restrained for more sustainable socioeconomic and environmental achievements.

On the policy front, it is suggested that reducing shadow economy and controlling environmental quality are two complementary actions that can provide a win–win solution for governments to pursue sustainability goals. Moreover, the finding of the heterogeneity in the relationship between shadow economy and ecological footprint across various levels of environmental degradation implies that each country, given specific ecological conditions, should tailor their strategies aiming at downsizing the shadow economy for better environmental quality. Countries with higher levels of environmental quality and a relatively lower level of shadow economy, e.g., Luxembourg, USA, Denmark, and Australia, may be positioned in the first half of the inverted U-shaped curve. Therefore, they could immediately witness the positive changes in ecological conditions when downsizing the shadow economy. In contrast, countries with lower levels of environmental quality and a relatively higher share of informal sectors, e.g., Mexico, Turkey, Hungary, Spain, Portugal, may be positioned in the second half of the inverted U-shaped curve. These countries need double efforts to reduce shadow economy considerably to fall behind the turning point. The reason is that they can attain the environmental benefit of controlling the informal sector only at the significantly lower levels of the informal sector. At the end of the day, countries at all levels of environmental quality should prioritize measures that reduce the level of informality to achieve better environmental quality.

On the other hand, the finding that the turning point in the inverted U-shaped relationship between shadow economy and ecological footprint of consumption occurs at the higher share of shadow economy, as compared to that for production ecological footprint, also provides valuable implications about policy priorities. Specifically, it would require more time and effort to witness the positive changes in the ecological footprint of production rather than that of consumption by downsizing the informal sectors. Therefore, it is recommended that OECD governments should give priority to policies aiming at restricting unofficial cross-border trade, such as smuggling, trade fraud, and tax evasion practices to quickly alleviate consumption ecological footprint. Further efforts are then required to continue narrowing the shadow economy in the production sector to the extent where ecological footprint from the production sources could be significantly reduced. Given the inter-relationship between informal activities and environmental quality, the abovementioned actions should be introduced together with environmental protection policies. The government should enforce more stringent environmental regulations as well as provide incentives for the research, development, and demonstration of green technologies. It is noted that the contribution of such regulations to environmental preservation depends greatly on the implementation of relevant regulations and follow-up supervision.

From a broader perspective, our findings suggest that while trade openness, economic growth, and the rebound effect of renewable energy in the production sector could lead to more environmental degradation, in the long run, formalization of the informal sector is a viable strategy to save the planet and achieve sustainable targets across countries regardless of their ecological conditions. However, given the importance of shadow economy to the vulnerable segments of the society and business community, simply preventing the shadow economy from spreading or reducing it to a lower proportion without solving the fundamental causes is far more than enough. Specifically, better and more accessible education and training are essential to help workers move into better-paid formal jobs. This measure should be implemented along with the political and fiscal reforms, which facilitate the transition from the informal to the formal sector. The policymakers also need to expand the small and start-up firms’ access to market and finance to foster their productivity and growth. In addition, it is required to safeguard people who are in the transition process from informal to formal sector because of their inherent vulnerabilities. The social security system and the government’s ability to intervene to support vulnerable groups should be upgraded to ensure an enhanced safety net.

Despite the significant methodological and policy contributions, this paper suffers from some limitations. One of the limitations is our reliance on the Dynamic General Equilibrium model while there are several approaches to measure shadow economy, such as the Multiple Indicators Multiple Causes model. Future research may extend to other measures.
of the underground economy to bring additional facts on the interested relationship. Second, the conclusions and policy recommendations do not take into account the specificities of each country. In fact, there are still several differences in the environmental quality and informal economy in OECD countries. Apart from the role of shadow economy, the impacts of economic structure, institutional quality, and environmental regulations can be further investigated to get further insights into the effectiveness of these policy actions. Accordingly, forthcoming studies can be carried out using other variables that affect the role of shadow economies on environmental quality, including knowledge sophistication, institutional quality, fiscal policies, and environmental stringency index, to name a few. Last, the scope of this research framework can be extended for other country groups or any individual country if relevant data exist.

Appendix

Figs. 4 and 5

Fig. 4 Kernel density estimated and normal density. Note: Variables are in natural logarithm. Source: author’s calculation based on Stata software
Fig. 5 Quantile–quantile plot. Note: variables are in natural logarithm. Source: author’s calculation based on Stata software

**Author contribution** Conceptualization: Lan Khanh Chu; methodology: Lan Khanh Chu; formal analysis and investigation: Lan Khanh Chu, Dung Phuong Hoang; writing — original draft preparation: Dung Phuong Hoang; writing — review and editing: Lan Khanh Chu; supervision: Lan Khanh Chu.

**Data availability** All data analyzed during this study are available and freely collected from public sources.

**Declarations**

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

**References**

Abid M (2015) The close relationship between informal economic growth and carbon emissions in Tunisia since 1980: The (ir) relevance of structural breaks. Sustain Cities Soc 15:11–21. https://doi.org/10.1016/j.scs.2014.11.001

Ahmed K, Long W (2012) Environmental Kuznets curve and Pakistan: an empirical analysis. Procedia Econo Finance 1:4–13. https://doi.org/10.1016/S2212-5671(12)00003-2

Ahmed K, Long W (2013) An empirical analysis of CO2 emission in Pakistan using EKC hypothesis. J Int Trade Law Policy 12(2):188–200. https://doi.org/10.1108/JITLP-10-2012-0015

Akram R, Chen F, Khalid F, Huang G, Irfan M (2021) Heterogeneous effects of energy efficiency and renewable energy on economic growth of BRICS countries: a fixed effect panel quantile regression analysis. Energy 215:119019. https://doi.org/10.1016/j.energy.2020.119019

Albulescu CT, Tiwari AK, Yoon SM, Kang SH (2019) FDI, income, and environmental pollution in Latin America: replication and...
 extension using panel quantiles regression analysis. Energy Econ 84:104504. https://doi.org/10.1016/j.eneco.2019.104504
Ali U, Li Y, Yáñez Morales VP, Hussain B (2021) Dynamics of international trade, technology innovation and environmental sustainability: evidence from Asia by accounting for cross-sectional dependence. J Environ Planning Manage 64(10):1864–1885. https://doi.org/10.1080/09640568.2020.1846507
Allard A, Takman J, Uddin GS, Ahmed A (2018) The N-shaped environmental Kuznets curve: an empirical evaluation using a panel quantile regression approach. Environ Sci Pollut Res 25(6):5848–5861. https://doi.org/10.1007/s11356-017-0907-0
Alm J, Embaye A (2013) Using dynamic panel methods to estimate shadow economies around the world. 1984–2006. Public Finance Rev 41(5):510–543. https://doi.org/10.1111/j.1071-1411.2013.1482353
Álvarez-Herránz A, Balsalobre D, Cantos JM, Shabbaz M (2017) Energy innovations–GHG emissions nexus: fresh empirical evidence from OECD countries. Energy Policy 101(June 2016):90–100. https://doi.org/10.1016/j.enpol.2016.11.030
Antweiler W, Copeland BR, Taylor MS (2001) Is free trade good for the environment? Am Econ Rev 91(4):877–908. https://doi.org/10.1257/aer.91.4.877
Anwar A, Siddique M, Dogan E, Sharif A (2021) The moderating role of renewable and non-renewable energy in environment-income nexus for ASEAN countries: evidence from Method of Moments Quantile Regression. Renew Energy 164:956–967. https://doi.org/10.1016/j.renene.2020.09.128
Apergis N, Payne JE (2009) Energy consumption and economic growth in Central America: evidence from a panel cointegration and error correction model. Energy Econ 31(2):211–216. https://doi.org/10.1016/j.eneco.2008.09.002
Bajada C, Schneider F (2005) The shadow economies of the Asia-Pacific. Pac Econ Rev 10(3):379–401. https://doi.org/10.1111/j.1468-0106.2005.00280.x
Bajada C, Schneider F (2009) Unemployment and the Shadow Economy in the OECD. Review Economique 60(4):1011–1033
Baksh K, Rose S, Ali MF, Ahmad N, Shabbaz M (2017) Economic growth, CO 2 emissions, renewable waste and FDI relation in Pakistan: new evidences from 3SLS. J Environ Manag 196:627–632. https://doi.org/10.1016/j.jenvman.2017.03.029
Baksi S, Bose P (2016) Informal sector, regulatory compliance, and leakage. J Dev Econ 121:166–176. https://doi.org/10.1016/j.jdeveco.2016.03.008
Bali Swain R, Kambhampati US, Karimu A (2020) Regulation, governance and the role of the informal sector in influencing environmental quality? Ecol Econ 173:106649. https://doi.org/10.1016/j.ecolecon.2020.106649
Baloch A, Shah SZ, Rasheed S, Rasheed B (2021) The impact of shadow economy on environmental degradation: empirical evidence from Pakistan. GeoJournal. https://doi.org/10.1007/s10708-020-10354-6
Belaid F, Elsayed AH, Omri A (2021) Key drivers of renewable energy deployment in the MENA Region: empirical evidence using panel quantile regression. Struct Chang Econ Dyn 57:225–238. https://doi.org/10.1016/j.strucde.2021.03.011
Bera AK, Jarque CM (1981) Efficient tests for normality, homoscedasticity and serial independence of regression residuals. Econ Lett 7(4):313–318. https://doi.org/10.1016/0165-1765(81)90035-5
Bi K, Huang P, Ye H (2015) Risk identification, evaluation and response of low-carbon technological innovation under the global value chain: a case of the Chinese manufacturing industry. Technol Forecast Soc Chang 100:238–248. https://doi.org/10.1016/j.techfore.2015.07.005
Biswa AK, Farzanegan MR, Thumb M (2012) Pollution, shadow economy and corruption: theory and evidence. Ecol Econ 75:114–125. https://doi.org/10.1016/j.ecolecon.2012.01.007
Bowles S, Park Y (2005) Emulation, inequality, and work hours: was Thorsten Veblen right? Econ J 115(S07):F397–F412. https://doi.org/10.1111/j.1468-0297.2005.01042.x
Busenitz LW, Gómez C, Spencer JW (2000) Country institutional profiles: unlocking entrepreneurial phenomena. Acad Manag J 43(5):994–1003. https://doi.org/10.5465/1556423
Canay IA (2011) A simple approach to quantile regression for panel data. Economet J 14(3):368–386. https://doi.org/10.1111/j.1368-432X.2011.00349.x
Canh NP, Thanh SD, Schinkcus C, Bensemann J, Thanh LT (2019) Global emissions: a new contribution from the shadow economy. Int J Energy Econ Policy 9(3):320–337. https://doi.org/10.32479/ijeep.7244
Canh NP, Schinkcus C, Thanh SD, Chong FHL (2021) The determinants of the energy consumption: a shadow economy-based perspective. Energy 225:120210. https://doi.org/10.1016/j.energy.2021.120210
Caravaggio N (2020) A global empirical re-assessment of the Environmental Kuznets curve for deforestation. Forest Policy Econ 119:102282. https://doi.org/10.1016/j.forpol.2020.102282
Chaudhuri S, Mukhopadhyay U (2006) Pollution and informal sector: a theoretical analysis. J Econ Integr 21(2):363–378. https://doi.org/10.11173/jei.2006.21.2.363
Chen W, Lei Y (2018) The impacts of renewable energy and technological innovation on environment-energy-growth nexus: new evidence from a panel quantile regression. Renewable Energy 123:1–14. https://doi.org/10.1016/j.renene.2018.02.026
Chen H, Hao Y, Li J, Song X (2018) The impact of environmental regulation, shadow economy, and corruption on environmental quality: theory and empirical evidence from China. J Clean Prod 195:200–214. https://doi.org/10.1016/j.jclepro.2018.05.206
Cheng C, Ren X, Dong K, Dong X, Wang Z (2021) How does technological innovation mitigate CO2 emissions in OECD countries? Heterogeneous analysis using panel quantile regression. J Environ Manage 280:111818. https://doi.org/10.1016/j.jenvman.2020.111818
Chu LK (2021b) Economic structure and environmental Kuznets curve hypothesis: new evidence from economic complexity. Appl Econ Lett 28(7):612–616. https://doi.org/10.1080/13504851.2020.1767280
Chu LK, Hoang DP (2020) How does economic complexity influence income inequality? New evidence from international data. Econ Anal Policy 68:44–57. https://doi.org/10.1016/j.eap.2020.08.004
Chu LK, Hoang DP (2021) The complementarity of income equalization and innovation for more effective emission reduction. J Environ Manage 284:112007. https://doi.org/10.1016/j.jenvman.2021.112007
Cole MA (2006) Does trade liberalization increase national energy use? Econ Lett 92(1):108–112. https://doi.org/10.1016/j.econlet.2006.01.018
Copeland BR, Taylor MS (2013) Trade and the environment: theory and evidence. Princeton University Press, Princeton
Costantini V, Crespi F (2008) Environmental regulation and the export dynamics of energy technologies. Ecol Econ 66(2–3):447–460. https://doi.org/10.1016/j.ecolecon.2007.10.008
Dada JT, Ajide FM (2021) The moderating role of institutional quality in shadow economy–pollution nexus in Nigeria. Manag Environ Qual: an Int J 32(3):506–523. https://doi.org/10.1108/MEQ-10-2020-0238
Danish, Uluçak R, Khan SUD (2020) Relationship between energy intensity and CO2 emissions: does economic policy matter? Sustain Dev 28(S5):1457–1464. https://doi.org/10.1002/sd.2098
UNEP (United Nations Environment Program) (2019). The Emissions Gap Report 2019. United Nations Environment Programme (UNEP): Nairobi, Kenya.
Dauda L, Long X, Mensah CN, Salman M, Boamah KB, Ampom-Wireko S, Kofi Dogbe CS (2021) Innovation, trade openness and CO₂ emissions in selected countries in Africa. J Clean Prod 281:125143. https://doi.org/10.1016/j.jclepro.2020.125143

Demiral M, Akça EE, Tekin I (2021) Predictors of global carbon dioxide emissions: do stringent environmental policies matter? Environ Dev Sustain. https://doi.org/10.1007/s10668-021-01444-7

Destek MA, Uluçak R, Dogan E (2018) Analyzing the environmental Kuznets curve for the EU countries: the role of ecological footprint. Environ Sci Pollut Res 25(29):29387–29396. https://doi.org/10.1007/s11356-018-2911-4

Dietz T, Rosa EA (1994) Rethinking the environmental impacts of population, Affluence and Technology. Hum Ecol Rev 1:277–300

Dietz T, Rosa EA (1997) Effects of population and affluence on CO₂ emissions. Proc Natl Acad Sci 94(1):175–179. https://doi.org/10.1073/pnas.94.1.175

Dinda S (2004) Environmental Kuznets curve hypothesis: a survey. Ecol Econ 49(4):431–455. https://doi.org/10.1016/j.ecolecon.2004.02.011

Dogan E, Taspinar N, Gokmenoglu KK (2019) Determinants of ecological footprint in MINT countries. Energy Econ 30(6):1065–1086. https://doi.org/10.1016/j.eneco.2020.105908

Dogan E, Madalen M, Inglezis-Lotz R, Taskin D (2022) Race and energy poverty: Evidence from African-American households. Energy Econ 108:105908. https://doi.org/10.1016/j.eneco.2022.105908

Dogan B, Madalen M, Tiwari AK, Hammoudeh S (2020) Impacts of export quality on environmental degradation: does income matter? Environ Sci Pollut Res 27(12):13735–13772. https://doi.org/10.1007/s11356-019-07371-5

Dogan B, Ghosh S, Hoang DP, Chu LK (2022) Are economic complexity and eco-innovation mutually exclusive to control energy demand and environmental quality in E7 and G7 countries? Technol Soc 68:101867. https://doi.org/10.1016/j.technosoc.2022.101867

Dumitrescu E-I, Hurlin C (2012) Testing for Granger non-causality in heterogeneous panels. Econ Model 29(4):1450–1460. https://doi.org/10.1016/j.econmodel.2012.02.014

Elgin C, Öztunali O (2014a) Pollution and informal economy. Econ Syst 38(3):333–349. https://doi.org/10.1016/j.econsys.2013.11.002

Elgin C, Öztunali O (2014b) Environmental Kuznets curve for the informal sector of Turkey (1950–2009). Pannoeconomicus 61(4):471–485. https://doi.org/10.2298/PAN140447E

Font Vivanco D, Kemp R, van der Voet E, Heijungs R (2014) Using LCA-based decomposition analysis to study the multidimensional contribution of technological innovation to environmental pressures. J Ind Ecol 18(3):380–392. https://doi.org/10.1111/jiec.12118

Franco C, Marin G (2017) The effect of within-sector, upstream and downstream environmental taxes on innovation and productivity. Environ Resource Econ 66(2):261–291. https://doi.org/10.1007/s10640-015-9948-3

Galvao AF (2011) Quantile regression for dynamic panel data with fixed effects. Journal of Econometrics 164(1):142–157. https://doi.org/10.1016/j.jeconom.2011.02.016

Ghosh S (2010) Examining carbon emissions economic growth nexus for India: a multivariate cointegration approach. Energy Policy 38(6):3008–3014. https://doi.org/10.1016/j.enpol.2010.01.040

Gyamfi BA, Adedoyin FF, Bein MA, Bekun FV, Agozie DQ (2021) The anthropogenic consequences of energy consumption in E7 economies: juxtaposing roles of renewable, coal, nuclear, oil and gas energy: evidence from panel quantile method. J Clean Prod 295:126373. https://doi.org/10.1016/j.jclepro.2021.126373

Haidar Zaidi SA, Zafar MW, Shahbaz M, Hou F (2019) Dynamic linkages between globalization, financial development and carbon emissions: evidence from Asia Pacific Economic Cooperation countries. J Clean Prod 228:533–543. https://doi.org/10.1016/j.jclepro.2019.04.210

Hatipoglu O, Ozbek G (2010) On the political economy of the informal sector and income redistribution. Eur J Law Econ 32(1):69–87. https://doi.org/10.1007/s10657-010-9179-6

Hatipoglu O, Ozbek G (2011) On the political economy of the informal sector and income redistribution. European Journal of Law and Economics 32(1):69–87. https://doi.org/10.1007/s10657-010-9179-6

Helpman E (1998) Explaining the structure of foreign trade: where do we stand? Rev World Econ 134(4):573–589. https://doi.org/10.1007/bf02773288

Herring H, Roy R (2007) Technological innovation, energy efficient design and the rebound effect. Technovation 27(4):194–203. https://doi.org/10.1016/j.technovation.2006.11.004

Huynh CM (2020) Shadow economy and air pollution in developing Asia: what is the role of fiscal policy? Environ Econ Policy Stud 22(3):357–381. https://doi.org/10.1007/s10018-019-00260-8

Imamoglu H (2018) Is the informal economic activity a determinant of environmental quality? Environ Sci Pollut Res 25(29):29078–29088. https://doi.org/10.1007/s11356-018-2925-5

Jalil A, Mahmud SF (2009) Environment Kuznets curve for CO₂ emissions: a cointegration analysis for China. Energy Policy 37(12):1567–1572. https://doi.org/10.1016/j.enpol.2009.07.044

Javid M, Sharif F (2016) Environmental Kuznets curve and financial development in Pakistan. Renew Sustain Energy Rev 54:406–414. https://doi.org/10.1016/j.rser.2015.10.019

Jenkins J, Nordhaus T, Shellenberger M (2011) Energy emergence: rebound and backfire as emergent phenomena. Breakthrough Institute, USA

Jiang X, Liu Y (2015) Global value chain, trade and carbon: case of information and communication technology manufacturing sector. Energy Sustain Dev 25:1–7. https://doi.org/10.1016/j.esd.2014.12.001

Khan I, Hou F (2021) The dynamic links among energy consumption, tourism growth, and the ecological footprint: the role of environmental quality in 38 IEA countries. Environ Sci Pollut Res 28(6):5049–5062. https://doi.org/10.1007/s11356-020-10861-6

Khan H, Khan I, Binh TT (2020) The heterogeneity of renewable energy consumption, carbon emission and financial development in the globe: a panel quantile regression approach. Energy Rep 6:859–867. https://doi.org/10.1016/j.egyr.2020.04.002

Koenker R (2004) Quantile regression for longitudinal data. J Multivar Anal 91(1):74–89. https://doi.org/10.1016/j.jmva.2004.05.006

Koc S, Bulus GC (2020) Testing validity of the EKC hypothesis in South Korea: role of renewable energy and trade openness. Environ Sci Pollut Res 27(23):29043–29054. https://doi.org/10.1007/s11356-020-09172-7

Köksal C, İşık M, Katircioğlu S (2020) The role of shadow economies in ecological footprint quality: empirical evidence from Turkey. Environ Sci Pollut Res 27:13457–13466. https://doi.org/10.1007/s11356-020-07956-5

Kongbuamai N, Zafar MW, Zaidi SAH, Liu Y (2020) Determinants of the ecological footprint in Thailand: the influences of tourism, trade openness, and population density. Environ Sci Pollut Res 27(32):40171–40186. https://doi.org/10.1007/s11356-020-09977-6

Lin B, Liu X (2012) Dilemma between economic development and energy conservation: energy rebound effect in China. Energy 45(1):867–873. https://doi.org/10.1016/j.energy.2012.06.077
Shahbaz M, Shahzad SJH, Mahalik MK, Hammoudeh S (2018) Does globalisation worsen environmental quality in developed economies? Environ Model Assess 23(2):141–156. https://doi.org/10.1007/s10666-017-9574-2
Shahbaz M, Raghuta C, Chittedi KR, Jiao Z, Vo XV (2020) The effect of renewable energy consumption on economic growth: evidence from the renewable energy country attractive index. Energy 207:118162. https://doi.org/10.1016/j.energy.2020.118162
Shao J, Tillaguango B, Alvarado R, Ochoa-Moreno S, Alvarado-Espejo J (2021) Environmental impact of the shadow economy, globalisation, trade and market size: evidence using linear and non-linear methods. Sustainability 13(12):6539. https://doi.org/10.3390/su13126539
Shapiro SS, Wilk MB (1965) An analysis of variance test for normality (complete samples). Biometrika 52(3–4):591–611. https://doi.org/10.1093/biomet/52.3-4.591
Sinha A, Shahbaz M, Balsalobre D (2017) Exploring the relationship between energy usage segregation and environmental degradation in N-11 countries. J Clean Prod 168:1217–1229. https://doi.org/10.1016/j.jclepro.2017.09.071
Sohail MT, Ullah S, Majeed MT, Usman A, Andlib Z (2021) The shadow economy in South Asia: dynamic effects on clean energy consumption and environmental pollution. Environ Sci Pollut Res 28(23):29265–29275. https://doi.org/10.1007/s11356-021-12690-7
Straub S (2005) Informal sector: The credit market channel. J Dev Econ 78(2):299–321. https://doi.org/10.1016/j.jdeveco.2004.09.005
Sun J, Shi J, Shen B, Li S, Wang Y (2018) Nexus among energy consumption, economic growth, urbanization and carbon emissions: heterogeneous panel evidence considering China’s regional differences. Sustainability 10:2383. https://doi.org/10.3390/su10077283
Suri V, Chapman D (1998) Economic growth, trade and energy: implications for the environmental Kuznets curve. Ecol Econ 25(2):195–208. https://doi.org/10.1016/S0921-8009(97)00180-8
Tamazian A, Chousa JP, Vadlamannati KC (2009) Does higher economic and financial development lead to environmental degradation: evidence from BRIC countries. Energy Policy 37(1):246–253. https://doi.org/10.1016/j.enpol.2008.08.025
Tawiali VK, Zakari A, Khan I (2021) The environmental footprint of China-Africa engagement: an analysis of the effect of China – Africa partnership on carbon emissions. Sci Total Environ 756:143603. https://doi.org/10.1016/j.scitotenv.2020.143603
Tayebi SK, Younespour S (2012) The effect of trade openness on environmental quality: evidence from Iran’s trade relations with the selected countries of the different blocks. Iran Econ Rev 16(32):19–40. https://doi.org/10.22059/IER.2012.32736
Torras M, Boyce JK (1998) Income, inequality, and pollution: a reassessment of the environmental Kuznets Curve. Ecol Econ 25(2):147–160. https://doi.org/10.1016/S0921-8009(97)00177-8
Wang Z, Dear K (2017) Region and firm level determinants of environmental regulation violations: an empirical study in Chongqing, China. J Clean Prod 141:1011–1022. https://doi.org/10.1016/j.jclepro.2016.09.090
Wang N, Zha H, Guo Y, Peng C (2018) The heterogeneous effect of democracy, political globalization, and urbanization on PM2.5 concentrations in G20 countries: evidence from panel quantile regression. J Clean Prod 194:54–68. https://doi.org/10.1016/j.jclepro.2018.05.092
Westerlund J (2007) Testing for error correction in panel data. Oxford Bull Econ Stat 69(6):709–748. https://doi.org/10.1111/j.1468-0084.2007.00477.x
Xie Z, Wu R, Wang S (2021) How technological progress affects the carbon emission efficiency? Evidence from national panel quantile regression. J Clean Prod 307:127133. https://doi.org/10.1016/j.jclepro.2021.127133
Yang L, Li Z (2017) Technology advance and the carbon dioxide emission in China – empirical research based on the rebound effect. Energy Policy 101:150–161. https://doi.org/10.1016/j.enpol.2016.11.020

Yang J, Tan Y, Xue D, Huang G, Xing Z (2021) The environmental impacts of informal economies in China: inverted U-shaped relationship and regional variances. Chin Geogra Sci 31(4):585–599. https://doi.org/10.1007/s11169-021-1210-z

York R (2007) Demographic trends and energy consumption in European Union Nations, 1960–2025. Soc Sci Res 36(3):855–872. https://doi.org/10.1016/j.ssresearch.2006.06.007

Zhang Y-J, Jin Y-L, Chevalier J, Shen B (2016) The effect of corruption on carbon dioxide emissions in APEC countries: a panel quantile regression analysis. Technol Forecast Soc Chang 112:220–227. https://doi.org/10.1016/j.techfore.2016.05.027

Zhu H, Duan L, Guo Y, Yu K (2016) The effects of FDI, economic growth and energy consumption on carbon emissions in ASEAN-5: evidence from panel quantile regression. Econ Model 58:237–248. https://doi.org/10.1016/j.econmod.2016.05.003

Zhu H, Xia H, Guo Y, Peng C (2018) The heterogeneous effects of urbanization and income inequality on CO2 emissions in BRICS economies: evidence from panel quantile regression. Environ Sci Pollut Res 25(17):17176–17193. https://doi.org/10.1007/s11356-018-1900-y

Alvarado R, Tillaguango B, Dagar V, Ahmad M, Işık C, Méndez P, & Toledo E (2021) Ecological footprint, economic complexity and natural resources rents in Latin America: empirical evidence using quantile regressions. J Clean Prod, 318(March) https://doi.org/10.1016/j.jclep.2021.12885

Chu LK (2021a) Determinants of ecological footprint in OCED countries: do environmental-related technologies reduce environmental degradation? Environ Sci Pollut Res, in press https://doi.org/10.1007/s11356-021-17261-4

Chu LK, & Le NTM (2021) Environmental quality and the role of economic policy uncertainty, economic complexity, renewable energy, and energy intensity: the case of G7 countries. Environ Sci Pollut Res, 2019. https://doi.org/10.1007/s11356-021-15666-9

Elgin C, Kose MA, Ohsnorge F, & Yu S (2021) Chapter 2: understanding the informal economy: concepts and trends. In The long shadow of informality: challenges and policies, edited by Ohsnorge, F. and Yu, S. Washington, DC: World Bank.

Grossman GM, & Krueger AB (1991) Environmental impacts of a North American free trade agreement. National Bureau of Economic Research No. 3914. http://www.nber.org/papers/w3914.pdf. Accessed 3 Jan 2022

Khan H, Wei Li, Khan L, & Han L (2021) The effect of income inequality and energy consumption on environmental degradation: the role of institutions and financial development in 180 countries of the world. Environ SciPollut Res 0123456789https://doi.org/10.1007/s11356-021-17278-9

Massagony A, & Budiono (2022) Is the Environmental Kuznets Curve (EKC) hypothesis valid on CO2 emissions in Indonesia? Int J Environ Stud 1–12. https://doi.org/10.1080/00207233.2022.2029097

OECD (2001) OECD Environmental Strategy for the First Decade of the 21st Century. http://www.oecd.org/dataoecd/33/40/1863539.pdf. Accessed 3 Jan 2022

OECD (2015) Aligning Policies for a Low-carbon Economy. OECD. https://doi.org/10.1787/9789264332394-en

OECD (2017) Shining Light on the Shadow Economy: Opportunities and Threats. https://www.oecd.org/tax/crime/shining-light-on-the-shadow-economy-opportunities-and-threats.pdf. Accessed 3 Jan 2022

OECD (2020) How’s life? 2020. OECD Publishing, Paris. https://doi.org/10.1787/9870c393-en

OECD (2022) An outsized ecological footprint: humanity’s ecological footprint by land type against Earth’s biocapacity, global hectares (gha), 1961-2021, In Trends Shaping Education 2022. OECD Publishing, Paris. https://doi.org/10.1787/2da3b402-en

OECD (n.d.) Greenhouse gas emissions. https://stats.oecd.org/Index.aspx?DataSetCode=AIR_GHG, Accessed 3 Jan 2022

OECD (n.d.) OECD environmental data and indicators. https://www.oecd.org/env/indicators-modelling-outlooks/data-and-indicators.htm

Opschoor JB, & Vos H (1989) Economic instruments for environmental protection. Organization for Economic Cooperation and Development, Paris, France

Panayotou T (1993) Empirical tests and policy analysis of environmental degradation at different stages of economic development, Paris, France

Policies. Lithuanian Free Market Institute.

Panayotou T (1993) Empirical tests and policy analysis of environmental degradation at different stages of economic development, Paris, France

Policies. Lithuanian Free Market Institute.

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