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RESEARCH ARTICLE

Natural resources, population aging, and environmental quality: analyzing the role of green technologies

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Abstract
Depletion of natural resources and population aging are the two most critical challenges for environmental sustainability. However, the research that integrates natural resources and population aging in the same environmental policy framework is still scant. Therefore, this study investigates the linkage between natural resources, population aging, green technologies, and ecological footprint (EF) of G7 countries. In addition, this study also explores the moderating effects of green technologies on the relationship between natural resources and EF. Drawing on the panel times series data from 1970 to 2017, we employ a cross-sectional autoregressive distributed lags (CS-ARDL) model for short- and long-run empirical estimation. Our empirical analysis indicates that natural resource use exacerbates ecological degradation by increasing EF. By contrast, population aging and green technologies present positive ameliorative effects on EF. Interestingly, the interaction effect of green technologies and natural resources indicates that the damage to ecological quality from natural resources can be effectively improved by means of green technologies, thus maintaining environmental sustainability. Furthermore, the results of panel quantile regression show that the effects of population aging and green technologies on the overall ecological footprint distribution in G7 countries are heterogeneous, while the effects of natural resources on the distribution of all conditions of the ecological footprint are positive. In addition, this paper verifies the causal relationship between the variables using the Dumitrescu and Hurlin test. The findings reveal that the relevant changes in all explanatory variables are bilaterally causally associated with EF. Based on these results, this paper provides some feasible policy recommendations.

Keywords Natural resources · Population aging · Ecological footprint · CS-ARDL · Quantile regression

Introduction

The environmental consequences of economic growth have been a major challenge affecting sustainable development processes (Balsalobre-Lorente et al. 2021). These consequences include climate warming, biological extinction, and irreversible damage to ecological resources, among others. Over the past few decades, economies, regions, and individuals around the globe have paid the price for the environmental damage they have caused. At the same time, many are also taking positive action to mitigate the climate and ecological crisis (Ozcan et al. 2020). Climate change creates severe weather patterns to which all living things cannot adapt. However, the shortage of ecological resources will become the ultimate crisis that is likely to lead to the destruction of the living environment.

Ecological footprint (EF) is an important indicator in mitigating ecological crises and has been studied by many scholars (Chu and Le 2022; Figge et al. 2017; Khan et al.

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2021b; Solarin et al. 2021). Moreover, EF is also an effective tool for measuring multifaceted ecological resource occupation activities, for example, carbon footprint, land, agricultural fields, fishing grounds, forests, and agricultural cropland (Lyu et al. 2021). The global EF has risen by 190% over half a century, indicating that the relationship between humans and ecological resources has become unbalanced (Ahmad et al. 2021). Specifically, in 2017, the global ecological footprint reached 2.77 global hectares (GHA) per capita (GFN 2021). To give a more visual indication of resource occupation, the Global Footprint Network also uses another calculation metric: the earth equivalent. The earth equivalent states that if every citizen of the world depended on ecological resources to live a normal life, those citizens would need at least 1.73 earths to meet the footprint they occupy. However, it is obvious that we only have one earth. If ecological resources are not sufficient to meet human needs, it will trigger a global ecological deficit, which will further exacerbate the ecological crisis facing the planet and its inhabitants. Therefore, it is crucial to find the factors that induce ecological crises and the means to mitigate them.

It is well known that an abundance of natural resource reserves is an important pillar of a country's national economy (Khan et al. 2021b; Pata et al. 2020). For the past half-century, developed countries rich in natural resources have led the economic development of the world. High-income countries, led by the G7 countries, tend to prioritize the economic well-being and spiritual satisfaction they receive in exchange for natural resources. In this regard, the gradual increase in EF reflects the extent to which people consume natural resources to support their needs (Pata et al. 2020). However, rapid economic development without considering the environmental consequences has led to severe environmental degradation. Clearly, this type of consumption also violates the law of intergenerational equity that promotes sustainable development (Demirel et al. 2016).

With regard to G7 countries, the link between natural resources and EF can be categorized into two groups. Countries in the first group, including Canada and the USA, possess an abundance of natural resources but produce the most severe environmental degradation in tandem. For example, the vast territory of Canada has contributed to a global abundance of mineral resources. Canada's production of nickel, zinc, platinum, and asbestos is the highest in the world. In addition, Canada's vast landmass and suitable precipitation allow the country to produce huge timber reserves. However, an over-reliance on natural resources has also led Canada to suffer the most severe environmental degradation of the seven countries. In 2017, Canada's ecological footprint reached 8.08 GHA per person, or 5.05 earth equivalents. In the same contextual model, the USA follows Canada with an ecological resource footprint of 8.04 GHA per person (5.03 earth equivalents). Most of the energy in the USA comes from non-renewable sources (Khan et al. 2020), and its coal, oil, natural gas, phosphate, potash, iron ore, and other mineral reserves are among the largest in the world. The USA is also rich in land resources, containing 12% of the world's total arable land area. In this regard, a progressively increasing EF provides evidence of continuous demand for resources from mankind. The second group of countries, including Germany, France, Italy, and Japan, possesses relatively scarce natural resources. All four economies have less than 0.1% of natural resource rents and produce ecological footprints between 4.2 and 4.7 GHA per capita (as of 2017).

The most notable of the G7 countries is the UK. With considerable oil and shale gas reserves, the UK is also the richest country in the European Union countries in terms of energy resources (Atkinson and Hamilton 2020). The UK has roughly the same share of resource rents as the USA and only one-half the ecological footprint. This is because the UK, as the earliest industrialized country, also introduced very strict environmental protection policies. The UK has been imposing a climate tax since 2001 in response to the climate change crisis. In addition, the UK has developed more advanced technologies for water resource treatment and utilization. As such, the water and soil resources in UK are greatly protected, and its ecological footprint is reduced. This begs the question of whether technological innovation can reduce the global ecological footprint by reducing the use of natural resources among G7 countries. Therefore, based on our exploration of the impact of natural resources on EF, we also examine the interaction between natural resources and green technologies to verify its role on EF.

Nowadays, the dramatic worldwide growth of aging populations has pushed population, an important environmental factor, into a deeper level of discussion. Population aging is a global phenomenon, especially among G7 countries. Japan is the most elderly country in the world, with an aging rate of 28%. Other countries with aging rates above 20% include Italy, Germany, and France. The remaining G7 countries, the USA, the UK, and Canada, all have aging rates of over 16%. The emergence of the aging phenomenon brings many challenges to the new era. It affects many aspects of the world development process, including social security systems, health care levels, financial markets, and economic growth (Menz and Welsch 2010).

From an environmental perspective, the impact of demographic change due to aging on environmental quality is the most visible (Dalton et al. 2008). However, the exact association of this effect is not clear. Most scholars support the positive environmental effects of aging. From the perspective of resource consumption, lower fertility and birth rates reduce population size and may improve environmental degradation by reducing resource use and energy consumption (Bongaarts 1992; Cole and Neumayer 2004). Regarding consumption patterns, elderly populations not only seek higher environmental and air quality but also engage in more energy-saving and environmentally friendly behaviors than younger people. For example, older people are more likely to take public transportation rather than frequently using personal vehicles, thus reducing energy consumption in transportation (Kronenberg 2009; O'Neill and Chen 2002). Considering that the growth of the aging population affects the process of natural resource use, the indicator of carbon emissions is no longer sufficient to support our desired conclusions. Therefore, we include the role of population aging in our study of ecological footprint.

In summary, our study contributes to the existing literature by focusing on the following aspects. First, this paper covers panel data for seven major global economies (G7) from 1970 to 2017. While Yang et al. (2021a) have included population aging in the theoretical framework of natural resource and ecological footprint studies for the first time, the severity of aging is uneven across the 27 Organization for Economic Co-operation and Development (OECD) countries. Taking the 2017 data as an example, 14 of the countries in the sample used by Yang et al. (2021b) are below the average level (18%) of aging in OECD countries, and four countries are less than 10% old. Estimating panel data for different levels of aging may result in bias in the estimated coefficients. Therefore, through data analysis, we used a sample of G7 countries that all have a high level of aging. Not merely that, the above discussion also reveals that the G7 countries are rich in natural resources and meet the conditions for our sample selection. More importantly, our study bridges the gap in the literature on population aging and environmental economics in the G7 countries. Developing a suitable theoretical framework for G7 countries would be useful to emulate in other developed or emerging economies. Second, we have included the green technologies in this model. As per best of authors' knowledge, no previous studies examine the role of green technologies in the relationship between natural resources and ecological footprint. Third, this work also employs the panel quantile regression to examine the heterogeneous effects of vital variables on ecological footprint under different conditional distributions. To our knowledge, this is the first study to explore the heterogeneous impact of population aging on ecological footprint from the perspective of panel quantile regression. Unlike the conditional mean distribution, regression at different quantiles provides a fuller and more extensive characterization of the impact distribution. In tandem, clearer indication of the effects of the independent variables on the dependent variable will offer more detailed and comprehensive advice to decision makers.

In general, the current research intends to contribute to the existing literature and address the following queries:

1. How do natural resource rents affect EF in the G7 countries?
2. What is the impact of population aging on EF in G7 countries?
3. Do green technologies moderate the relationship between natural resources and EF in G7 countries?
4. Do natural resources, population aging, and green technologies have heterogeneous effects on the ecological footprint of different condition distributions?

The remaining sections are as follows: "Literature review" section presents the existing literature, while "Model, data, and methodology strategy" section discusses the methodology and data. In "Empirical results and discussion" section, we give the empirical analysis. In the last section, we conclude the paper and offer some policy implications.

Literature review

This study investigates the linkage between the abundance of natural resources, population aging, green technologies, and EF. For coherence, we divided the review of literature into three segments: natural resources and EF nexus, the nexus between population aging and EF, and the relationship between green technologies and EF.

Natural resources and ecological footprint

The association between an abundance of natural resources and environmental quality is a controversial subject with different arguments. The first strand of the literature suggests that natural resources improved the ecological quality. For instance, a study by Danish et al. (2020) on BRICS countries showed that natural resources improve environmental quality by lessening EF. Similarly, the empirical evidence from the USA reached by Khan et al. (2021a) demonstrated the negative effect of natural resources on EF. An earlier study by Zafar et al. (2019) also reported a positive impact of natural resources on environment quality in the USA. Zhang et al. (2021) examined the impact of natural resources on EF in Pakistan and report that natural resources negatively affect EF. Kongbuamai et al. (2020) found that natural resources have a negative impact on the EF in members of the association of Southeast Asian nations. Their findings support the view that economies with an abundance of natural resources can enjoy better environmental quality than those without such an abundance of resources.

The second strand of the literature suggests a positive effect of natural resources on EF. For instance, Ahmed et al. (2020) probed the relationship between EF and natural resources rent in China from 1970 to 2016. They highlight that natural resource rent significantly increased environmental degradation because China has been putting massive pressure on its ecological resources to fulfill its growing energy demand. Likewise, Zia et al. (2021) argued that natural resources are causing a surge in ecological footprint of China. And Shen et al. (2021) also observed a positive correlation between natural resources and carbon emission using the panel data of 30 provinces in China. Ahmad et al. (2020) investigated the linkage between natural resources, technological innovation, and EF in emerging countries. Using the CS-ARDL model, they disclose the positive effect of natural resources on EF, while technological innovation has a native effect on EF. They also confirmed a similar relationship in the top ten ecological footprint countries. In a recent study on natural resources, Nathaniel et al. (2020) revealed a positive and significant effect of natural resources on EF in BRCIS countries. They further highlight that these countries are endowed with resources but compromise their environmental quality to gain foreign exchange. Muhammad et al. (2021) pointed out that the total amount of natural resources is one of the main factors driving environmental degradation in BRICS countries and other developing or developed areas.

Population aging and environmental degradation

The human population has grown exponentially over the past few decades, placing enormous pressure on ecological resources and the environment (Khan et al. 2021a; Yang and Khan 2022). Numerous scholars have explored the linkage between population and environmental quality, but little attention has been paid to examining the impact of population aging on environmental quality. Therefore, the topics of population aging and environmental quality have gained substantial interest from scholars. For instance, Dalton et al. (2008) studied the linkage between the aging population and carbon emission in the USA. They concluded that population aging reduces carbon emission by almost 40% in the long run because older people prefer to use public transport, thereby reducing the use of private cars and resources and thus lowering pollution levels. Likewise, Hassan and Salim (2015) stated that a 1% increase in the aged population would decrease carbon emissions by 1.55% in the long term. Yang et al. (2021a) and Yang et al. (2021b) also reported on the negative effect of population aging on the degradation of the environment. They further highlight that the elderly population uses fewer commodities than the young population and shows the shift of demand towards a low carbon pattern.

On the contrary, Menz and Welsch (2010) argued that older people use more energy-intensive products and consume more energy, thereby aggravating higher emissions. However, Menz and Welsch (2012) claimed that the relationship between population aging and environmental degradation depends on the country's development level. Liddle (2011) analyzed the impact of age structure on electricity consumption and environmental degradation. Their results indicated young people (20–34) and older populations (70+) have a positive coefficient, whereas middle-aged people (35–49 and 50–69) pose a negative effect, indicating the presence of a U-shaped association between aging and emissions. A recent study of EU-5 countries by Balsalobre-Lorente et al. (2021) reported an inverted U-shaped association between population aging and carbon emission.

Green technologies and environmental degradation

Several empirical results demonstrate that the innovation brought by green technologies promotes environmental sustainability by lessening EF and CO_2 emissions. For instance, Wang et al. (2020) examined the impact of technological innovation on CO_2 emissions in G7 countries between 1990 and 2017. They concluded that technology innovation poses a mitigating effect on carbon emission and can help to improve environmental performance caused by increasing economic activities. Likewise, Ahmad et al. (2021) also reported a similar connection between eco-innovation and EF among G7 countries. Their results further highlight that development level plays a crucial role in the relationship between eco-innovation and EF. They claimed that eco-innovation is more effective at abating emissions among G7 countries than in developing countries. Similarly, Ding et al. (2021) revealed that eco-innovation significantly alleviates consumption-based carbon emission in G7 countries. The mitigating effect of innovation on environmental degradation is also stated by numerous researchers, including Sinha et al. (2020), who researched NEXT 11 countries, Solarin and Bello (2020), who researched the USA, Hashmi and Alam (2019), who researched selected OECD countries, and Zhang et al. (2017) who researched China. On the contrary, Yii and Geetha (2017) concluded that technological innovation is negatively related to carbon emission in the short run while there is no effect that affects the long run. Others argue that innovations in green technologies can reduce environmental degradation only under certain conditions. For instance, Ahmad and Zheng (2021) pointed out that during the economic upturn in BRICS countries, the positive shocks of environment-related innovation can improve environmental quality by minimizing CO_2 emissions. Razzaq et al. (2021) found that green technologies can reduce carbon emissions of BRICS regions only at higher emission levels. These researches have highlighted the direct effect of technological innovation on environmental quality. However, few authors have focused on the indirect effects of technological innovation on environmental quality, especially through the channel of natural resource use.

Research gaps

Summarizing the above literature, we can conclude that there are limited studies that examine the impact of natural resources and population aging on environmental quality and the relationship between the two and do not have a definitive conclusion. Moreover, these studies fail to discuss the relationship between natural resources, population aging, green technologies, and EF. On the other hand, researchers mainly examined the relationship between green technologies and EF, but none of the studies examined the moderating effect of green technologies on the relationship between natural resources and EF. Therefore, this study fills this gap and investigates the linkage between population aging, natural resources, green technologies, and EF in the context of G7 countries. In addition, previous studies concerning the impact of interested variables on EF are all econometric methods using conditional mean estimator. In this respect, they ignore the influence of different degrees of variables and outlier distribution, which is easy to lack of heterogeneity analysis. Therefore, we provide estimates under different conditional quantiles, hoping to show a different perspective for the analysis of existing literature.

Model, data, and methodology strategy

Model construction

This paper follows the models constructed by Ahmad et al. (2020) and Ahmad et al. (2021) and incorporates two key factors, natural resource rent and population aging, into the framework. In addition, control variables include GDP and energy consumption, which are frequently employed to discuss environmental consequences. Therefore, we build the following model:

$$EF = f(NR, PA, EI, GDP, EC) \tag{1}$$

$$lnEF_{it} = \beta_0 + \beta_1 lnNR_{it} + \beta_2 lnPA_{it} + \beta_3 lnEI_{it} + \beta_4 lnGDP_{it} + \beta_5 lnEC_{it} + \tau_{it} \tag{2}$$

To verify the indirect impact of natural resources on EF, that is, whether green technologies have a moderating effect, the interaction term (*ln*NR**ln*EI) between green technologies and natural resources is included in Eq. (2). Therefore, the original model is extended to the following Eq. (3):

$$lnEF_{it} = \beta_0 + \beta_1 lnNR_{it} + \beta_2 lnPA_{it} + \beta_3 lnEI_{it} + \beta_4 lnGDP_{it} + \beta_5 lnEC_{it} + \beta_6 ln(NR * EI) + \tau_{it} \tag{3}$$

where i refers to the seven cross-sections, i.e., seven countries (1, 2, 3, … ,7); t represents the time period (1970–2017) involved in this study; τ represents the error item; NR, PA, and EI denote natural resources, population aging, and green technologies, respectively; economic growth is represented by GDP; and EC denotes energy consumption. To diminish metric error between the data, all variables were transformed by natural logarithm. The measurement of the variables and the data source are proffered in Table 1.

Data

This paper explores the dynamic linkages between natural resources, population aging, green technologies, and ecological footprint in G7 countries. The G7 countries covered include the USA, Japan, the UK, Germany, France, Italy, and Japan. The EF indicates the relevant ecological consequences, and the data are derived from the open platform of the GFN. The data for natural resource rents are obtained from the WDI. It measures the extent to which the seven countries consume and occupy natural resources to meet their living and production needs. The common international view on population aging is that a nation becomes an elderly society if 10% of the total population is over 60 years old or 7% of the total population is over 65 years old (UN 2021). Data on population aging and GDP are also derived from the WDI. Data on green technologies are characterized by the number of environment-related patents. Compared to other alternative innovation indicators, patent data have several attractive features. They are widely available, quantitative, comparable, and output-oriented (OECD 2021). In addition, data on energy consumption are derived from the Statistical Review of World Energy, published by BP in 2020. The study period spans from 1970 to 2017, which is based solely on the available range of related data required for the empirical analysis. The EF only supports data before 2017. And after reviewing the data availability of other variables, we finally settled on 1970 as the starting date. Table 2 contains general information about the data used in this paper, including maximum, minimum, mean, median, and standard deviation. Box charts of our six variables are shown in Figure 1.

Methodology strategy

Before performing the empirical analysis, the panel data requires a number of testing procedures to determine the usability of the model. The flow of the estimation strategy in this paper can be seen in Figure 2. It shows each test session and the econometrics methods used. The methods for testing include the cross-sectional dependency test proposed by Pesaran

Table 1 Variable's description

Variables	Measure	Source
EF	Per capita (global hectares)	GFN: https://data.footprintnetwork.org/#/
NR	Natural resource rents as a percentage of GDP	WDI: https://data.worldbank.org/indicator
PA	Population over 65 years of age (% of the total population)	WDI: https://data.worldbank.org/indicator
EI	Number of patents related to the environment	OECD: https://www.oecd.org/
GDP	Per capita (constant 2010 US$)	WDI: https://data.worldbank.org/indicator
EC	Energy consumption (gigajoule per capita)	BP: https://www.bp.com/

GFN Global Footprint Network, *OECD* Organization for Economic Co-operation and Development, *WDI* World Development Indicators, *BP* British Petroleum

Table 2 Descriptive statistics and pair-wise correlation analysis

	*ln*EF	*ln*NR	*ln*PA	*ln*EI	*ln*GDP	*ln*EC
Mean	1.835	−1.255	2.656	2.062	10.401	5.834
Median	1.733	−1.521	2.677	2.043	10.436	5.592
Maximum	2.404	2.202	3.300	2.734	10.885	7.747
Minimum	1.400	−4.510	1.928	1.295	9.800	4.781
Std. Dev.	0.278	1.634	0.251	0.299	0.266	0.791
Sum	616.42	−421.79	892.57	692.93	3494.70	1960.31
Sum Sq. Dev.	25.82	894.70	21.05	29.95	23.65	209.82
Observations	336	336	336	336	336	336
*ln*EF	1.000					
*ln*NR	0.751	1.000				
*ln*PA	−0.470	−0.468	1.000			
*ln*EI	−0.032	−0.019	0.381	1.000		
*ln*GDP	0.088	−0.112	0.507	0.503	1.000	
*ln*EC	0.606	0.223	−0.163	0.085	0.362	1.000

(2004), the slope homogeneity test proposed by Pesaran & Yamgata (2008), the unit root test raised by Pesaran (2007), the cointegration test of Westerlund (2007), and the causality test presented by Dumitrescu and Hurlin (2012).

Cross-sectional augmented autoregressive distributed lag (CS-ARDL)

The short-term and long-term relationships between natural resources, population aging, green technologies, economic growth, energy consumption, and EF in this paper are determined using the advanced CS-ARDL estimation method (Chudik and Pesaran 2015). Compared to other estimation methods, the CS-ARDL method has three significant advantages. Firstly, it is still able to overcome and give robust results against the CD and heterogeneity problems addressed in the previous subsections. Secondly, it can overcome possible endogeneity problems among variables, eliminating the potential risk of bias in the estimation results. Thirdly, the method is more lenient in terms of data smoothness requirements. This is because CS-ARDL can estimate variables of mixed integration order rather than requiring all variables to be I(0) or I(1) processes. The test equation for CS-ARDL is:

$$\Delta y_{i,t} = \varphi_i + \sum_{j=1}^{p} \varphi_{it} \Delta y_{i,t-j} + \sum_{j=0}^{p} \varphi\prime_{ij} EXV_{i,t-j} + \sum_{j=0}^{p} \varphi\prime_{it} \overline{Z}_{t-j} + \varepsilon_{i,t} \tag{4}$$

where EXV stands for all explanatory variables and $Z_t = (\Delta\overline{y_t}, \overline{EXV_t\prime})\prime$ is the average value of cross-section.

Robustness test (AMG)

As an essential part of the measurement strategy, robustness tests are also incorporated in the estimation step. The augmented mean group (AMG) estimator developed by Eberhardt (2012) is applied in this study. This method can also give long-run estimated coefficients and can overcome some of the common problems with the data mentioned in the above steps. Therefore, the use of the AMG method as a robustness screen is qualified and reasonable.

Panel quantile regression

CS-ARDL and AMG present long-run equilibrium between variables. However, these two methods cannot demonstrate

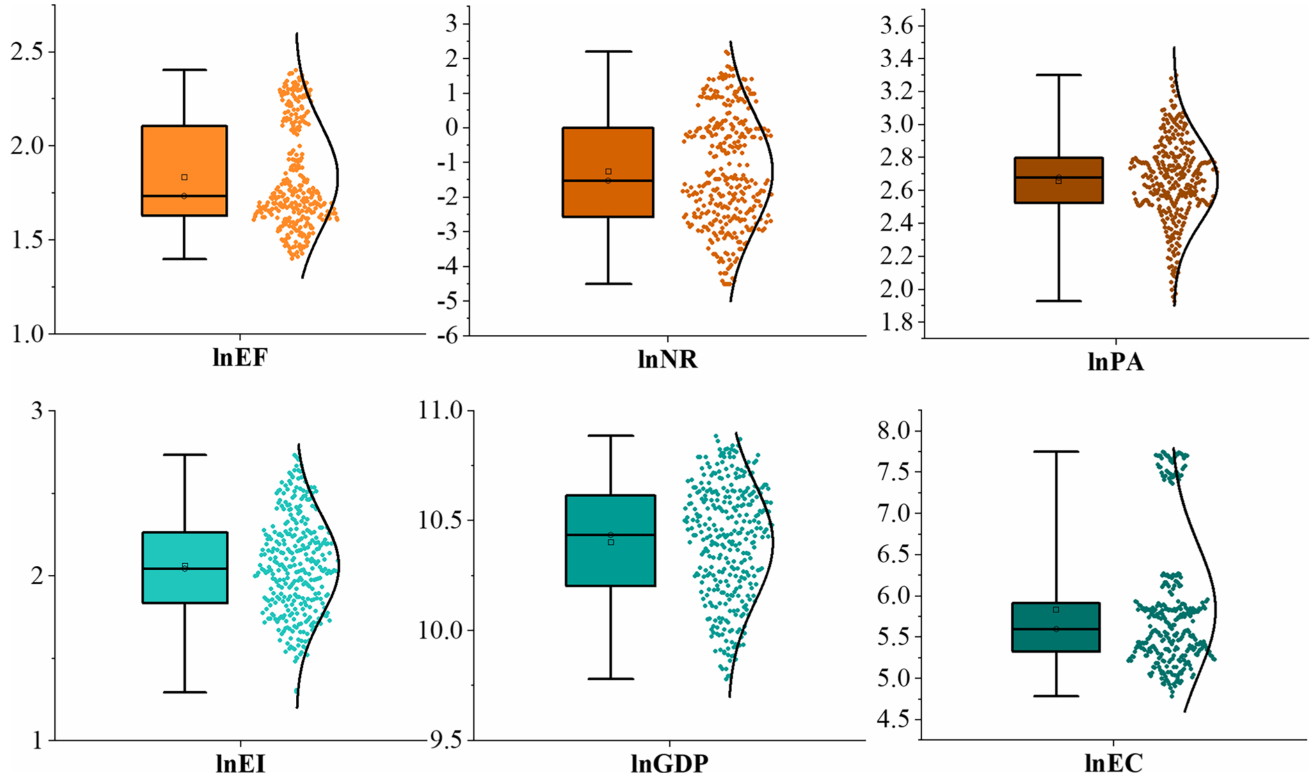
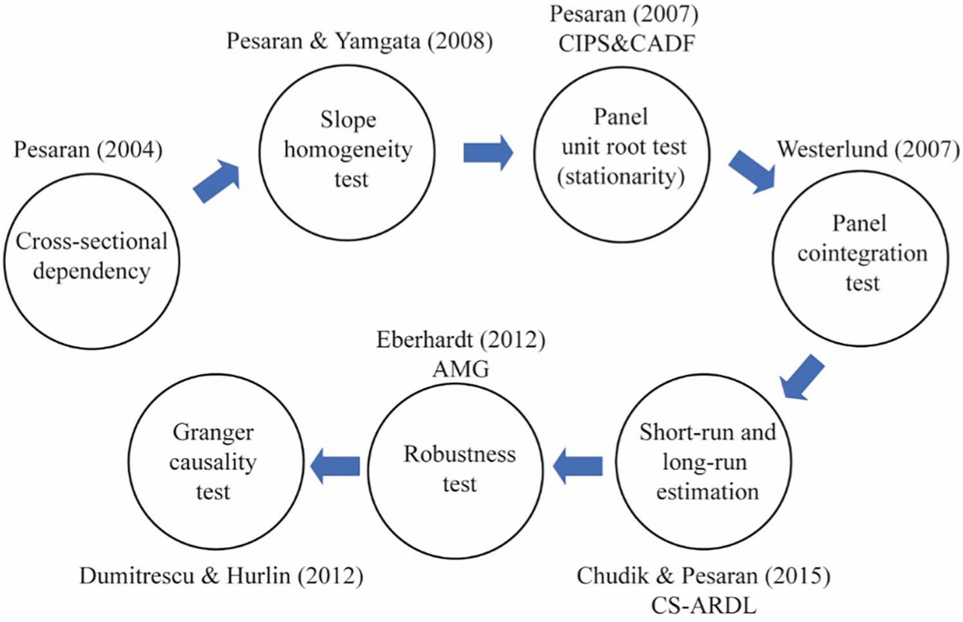


Fig. 1 The box charts of six variables employed in this paper

the heterogeneous effects of the main explanatory variables on the ecological footprint. Therefore, this paper takes a panel quantile regression approach to overcome the effects of outliers and heteroskedasticity and gives the estimated coefficients at different quantile levels. Quantile regression was proposed by Koenker and Bassett (1978). The quantile regression model allows to determine the effect of covariates on the entire conditional distribution of the dependent variable (Opoku and Aluko 2021). For the panel quantile regression, we use the non-additive fixed effects proposed by Powell (2016), an estimate that should be useful in environments where differential identification is required and where

Fig. 2 The flow chart of estimation strategy



the effects of the variables are believed to be heterogeneous across the distribution of outcomes. Moreover, non-additive fixed effects allow for the presence of endogeneity as it is developed in the framework of instrumental variables. In the case of dealing with a large number of variables, Powell (2016) requires other optimization methods such as Markov chain Monte Carlo (MCMC). The quantile regression model used in this paper is as follows.

$$lnEF_{it} = \alpha_{\tau} X'_{it} + \eta_{it}, 0 < \tau < 1 \tag{5}$$

$$Quant_{\tau}(lnEF_{it}|X_{it}) = \alpha_{\tau} X'_{it} \tag{6}$$

where X'_{it} is the vector consisting of natural resources, population aging, green technologies, economic growth, and energy consumption; α is the coefficient vectors to be estimated; τ indicates a quantile between 0 and 1; and η is a random perturbation term.

Empirical results and discussion

The panel test results

We obtain the cross-sectional correlations between countries, as shown in Table 3. All variables meet the 1% significance requirement, indicating a strong rejection of the original assumption. The interpretation of this result is that although there are asynchronies in economic growth, population planning, and policymaking across countries, it is inevitable that the decisions and progress of any one country will indirectly affect other economies. The reflection in statistics shows the problem of cross-sectional correlation. Again, the slope homogeneity test in Table 4 provides further evidence: the values of $\widetilde{\Delta}_{SH}$ and adjusted $\widetilde{\Delta}_{adjusted}$ in two models reject the presence of homogeneity at 1% significance. Therefore, the current panel data are heterogeneous.

Next are the outcomes of the unit root tests which are displayed in Table 5 and the results show that unit root problems exist at the level for EF, GDP, and EC. However, all three variables get stationary after performing the first-order difference. Moreover, NR, PA, and EI are I(0) processes. The mixed integration order is equally sufficient for the cointegration test and coefficient estimation steps. Therefore, the cointegration test results are given in the results in Table 6. Results for model 1 show significant cointegration equilibrium properties between natural resources, population aging, green technologies, GDP, energy consumption, and EF Similarly, among the results of the extended model 2, we find that when the cross term of natural resources and green technologies (*ln*NR**ln*EI) is added, the model also has a strong long-run covariance. Thus, there is evidence that the individual variables vary and move together with EF.

Table 3 Cross-sectional dependency test results

Variables	Statistic	*p* value	Abs (corr)
*ln*EF	14.142***	0.000	0.512
*ln*NR	18.535***	0.000	0.592
*ln*PA	28.950***	0.000	0.912
*ln*EI	26.548***	0.000	0.836
*ln*GDP	30.826***	0.000	0.971
*ln*EC	15.894***	0.000	0.543

The symbol *** indicates the significance level at 1%

Table 4 Slope heterogeneity test results

Test	Model 1		Model 2	
	Value	*p* value	Value	*p* value
$\widetilde{\Delta}_{SH}$	21.538***	0.000	19.282***	0.000
$\widetilde{\Delta}_{adjusted}$	23.304***	0.000	21.122***	0.000

The symbol *** indicates the significance level at 1%

The long-run and short-run results

After ensuring some basic requirements before estimating the panel data, we estimate the long-run and short-run associations between the variables. Table 7 shows the regression results for CS-ARDL. Natural resources (NR) significantly stimulate EF in both the short and long term. In terms of data, the average short-term EF increase of 0.023% (model 1: 0.010%; model 2: 0.036%) is due to the role of natural resources. In the long run, 0.01% (model 1: 0.006%; model 2: 0.023%) of the increase in EF is caused by natural resources. The reason for the unsustainability of natural resources may be the inadequate management system of the resource-related sector. Once a natural resource is "leased," it will lead to overexploitation of natural resources if the economy is not guaranteed to receive the corresponding rent or tax. This type of resource use not only costs the economy economic benefits but is likely to create a resource curse for the region, leading to slow or even stagnant regional economic growth (Ulucak et al. 2020). The present conclusions are in agreement with Ahmad et al. (2020), Balsalobre-Lorente et al. (2021), Danish et al. (2020), Pata et al. (2020), Shen et al. (2021), and others. However, the conclusions are not shared by Khan et al. (2021a) and Zafar et al. (2019), who argue that natural resources improve environmental quality by reducing dependence on fossil fuels.

The regression results further indicate that population aging shows a negative relationship with EF in the long term as well as in the short term. Averaging the data from

Table 5 Panel unit root tests results

Variables	Level		First-difference		Order
	Intercept	Intercept and trend	Intercept	Intercept and trend	
CIPS					
*ln*EF	−2.368**	−2.610	–	–	I(0)
*ln*NR	−2.876***	−3.072***	–	–	I(0)
*ln*PA	−3.705***	−4.738***	–	–	I(0)
*ln*EI	−3.486***	−4.401***	–	–	I(0)
*ln*GDP	−1.623	−2.553	−4.823***	−4.680***	I(1)
*ln*EC	−2.072	−2.776*	–	–	I(0)
CADF					
*ln*EF	−2.368**	−2.610	–	–	I(0)
*ln*NR	−2.909***	−3.099***	–	–	I(0)
*ln*PA	−2.715***	−3.259***	–	–	I(0)
*ln*EI	−2.730***	−3.191***	–	–	I(0)
*ln*GDP	−1.885	−2.725	−3.660***	−3.286***	I(1)
*ln*EC	−2.128	−3.033***	–	–	I(0)

The symbols ***, **, and * indicate the significance level at 1%, 5%, and 10%, respectively

Table 6 Westerlund cointegration test results

Statistic	Model 1			Model 2		
	Value	Z-value	*p* value	Value	Z-value	*p* value
G_t	−3.117***	−2.388	0.009	−3.271**	−2.190	0.014
G_a	−12.125	−0.138	0.445	−12.884	0.309	0.621
P_t	−7.491**	−2.056	0.020	−7.901**	−1.908	0.028
P_a	−10.370	−0.778	0.218	−11.59	−0.481	0.315

The symbols ***, **, and * indicate the significance level at 1%, 5%, and 10%, respectively

Table 7 The CS-ARDL estimations

Variables	Model 1		Model 2	
	Coef.	*Std. Err.*	*Coef.*	*Std. Err.*
Short-run results				
*ln*NR	0.010***	0.003	0.036*	0.019
*ln*PA	−0.334**	0.147	−0.348**	0.167
*ln*EI	−0.048**	0.021	−0.059**	0.023
*ln*GDP	0.715***	0.187	0.773***	0.211
*ln*EC	0.484***	0.123	0.430***	0.139
*ln*NR**ln*EI	–	–	−0.025***	0.009
ECM (−1)	−0.657***	0.062	−0.642***	0.070
Long-run results				
*ln*NR	0.006***	0.002	0.023**	0.011
*ln*PA	−0.198**	0.086	−0.204**	0.100
*ln*EI	−0.029**	0.012	−0.037***	0.014
*ln*GDP	0.429***	0.104	0.467***	0.121
*ln*EC	0.301***	0.082	0.269***	0.089
*ln*NR**ln*EI	–	–	−0.016***	0.005

$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

both models, every 1% increase in population aging (PA) will result in a 0.341% decrease in the short-run EF and a 0.201% increase in long-run EF. The negative coefficient of population aging suggests that older age groups are improving the environmental quality of G7 countries by reducing EF, which provides evidence for the third query of this paper. This view is consistent with O'Neill et al. (2010), Yang and Wang (2020), and Yang et al. (2021a). From an economic perspective, economic growth brings high rates of natural resource extraction. Meanwhile, an aging population can cause a shortage of labor supply (Balsalobre-Lorente et al. 2021). This reduces the economic growth rate in tandem with the risk of ecological deficit caused by the overexploitation of resources. From the perspective of industrial structure, aging will promote the development of tertiary industries, such as livelihood security for the elderly, pension systems, and health care industries, thus upgrading and optimizing industrial structures (Yang and Wang 2020). These sectors consume less energy and reduce the level of dependence on natural resources, which in turn improve environmental conditions. Furthermore, in terms of consumption patterns, most elderly people choose resource-saving travel methods and goods (Yang et al. 2021b). Moreover, in terms of attitudes surrounding environmental protection, tolerance for environmental degradation decreases with age due to a more spiritually enriched elderly population who prefer a "green" natural environment and thus actively reduce their ecological footprint consumption.

We also detect a negative effect of green technologies on EF. In the short-term scenario, green technologies (EI) reduce the EF by 0.054% on average (model 1 is −0.048% and model 2 is −0.059%). Similarly, in the long-term scenario, a 1% increase in EI leads to a 0.033% decrease in EF. This is consistent with the results of several studies involving research of green technologies and EF (Ahmad et al. 2020; Ahmad et al. 2021). The implementation of green technologies can increase the productivity of existing societies and improve the production methods based on the consumption of traditional energy sources, thus reducing pollutant emissions. In addition, the development and implementation of cleaner technologies such as more efficient green technologies can reduce energy consumption and pollution emissions per unit of product compared to traditional technologies, thus increasing the value of resources and energy use. When green technologies are developed to a certain extent, they stimulate the replacement of energy-consuming technologies, which in turn expands the share of environmentally friendly technologies. In this regard, the continuous advances in green technologies tools can improve the efficiency of natural resource use, thereby slowing resource depletion and minimizing ecological degradation (Ulucak et al. 2020). We further explored the moderating role of green technologies between natural resources and EF. The cross term (*ln*NR**ln*EI) in model 2 provides the joint impact of natural resources and green technologies. Both the short-run and long-run estimated coefficients of the crossover term are negative, indicating that the moderating effect of green technologies displays a beneficial driving effect on mitigating environmental degradation due to natural resources in G7 countries. Green technologies can provide new and efficient technological support for natural resource management and use, and gradually reduce the ecological burden by reducing the growth path that is highly dependent on natural resources. It also verifies the second hypothesis of this paper: green technologies moderate the relationship between natural resources and EF in G7 countries. Innovative means will replace manual labor to obtain higher rates of resource utilization than obsolete natural resource extraction and exploitation techniques. Innovation, value addition, and reuse of resources will not only reduce environmental degradation but also be in line with the vision of sustainable development (Bekun et al. 2019).

In addition, both GDP and EC contribute to the unsustainability of the ecological environment. On average, each 1% increase in GDP will boost EF by 0.744% (short term) and 0.448% (long term). This result is supported by the conclusions of many recent studies (Ahmed et al. 2021a; Danish et al. 2019; Xue et al. 2022; Zhang et al. 2021). Ahmed et al. (2021c) also found that when economic growth exceeded a threshold, biocapacity would increase. All this evidence points to a link between economic growth and environmental unsustainability. Additionally, energy consumption also increases EF, corresponding to 0.457% (short term) and 0.285% (long term), respectively. This finding is also supported by Baz et al. (2020), Destek and Sinha (2020), among others. G7 countries have been pursuing economic and market leadership for the past few decades at the expense of the environmental consequences they will suffer. As economic activities have become more widespread, energy consumption has risen, further increasing environmental degradation. Khan et al. (2021d) also proved that energy transitions adversely associated with EF and economic growth for another group of developed countries—OECD. Therefore, investing in clean energy and reducing fossil energy consumption will contribute to the realization of environmental sustainability (Ahmed et al. 2021b; Khan et al. 2021c; Rehman et al. 2021).

In response to the above findings, further corroboration is performed using the AMG estimator to increase statistical evidence for the conclusions. The results in Table 8 display that natural resources, GDP, and energy consumption increase EF, while population aging and green technologies decrease ecological consequences. In addition, green technologies play a sustainable role in the linkage between natural resources and EF. The AMG findings also provide us with evidence for the three hypotheses once again.

Table 8 The AMG estimations (for the robustness test)

Variables	Model 1		Model 2	
	Coef.	*Std. Err.*	*Coef.*	*Std. Err.*
Short-run results				
*ln*NR	0.009***	0.003	0.015***	0.005
*ln*PA	−1.283**	0.579	−1.240**	0.588
*ln*EI	−0.052**	0.024	−0.056***	0.021
*ln*GDP	0.758***	0.126	0.727***	0.123
*ln*EC	0.318***	0.080	0.336***	0.083
*ln*NR**ln*EI	–	–	−0.007**	0.003
Constant	−8.206***	1.135	−0.642***	0.005

$^{**}p < 0.05$, $^{***}p < 0.01$

Table 9 The quantile regression results of Powell (2016)

Variables	Low quantile			Median quantile			High quantile		
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
*ln*NR	0.0729^{a}	0.0928^{a}	0.1104^{a}	0.0437^{a}	0.0798^{a}	0.0711^{a}	0.0836^{a}	0.0826^{a}	0.0466^{a}
	[0.0004]	[0.0014]	[0.0008]	[0.0004]	[0.0013]	[0.0014]	[0.0003]	[0.0007]	[0.0160]
*ln*PA	0.0351^{a}	0.0339^{a}	0.2491^{a}	−0.3604^{a}	−0.3627^{a}	−0.4118^{a}	−0.3888^{a}	−0.3958^{a}	−0.1359
	[0.0026]	[0.0111]	[0.0196]	[0.0002]	[0.0218]	[0.0004]	[0.0029]	[0.0049]	[0.0852]
*ln*EI	−0.1515^{a}	−0.1080^{a}	−0.1387^{a}	0.0979^{a}	0.0416^{a}	−0.0265^{a}	−0.0079^{b}	−0.0254^{c}	−0.2943^{a}
	[0.0025]	[0.0063]	[0.0078]	[0.0019]	[0.0066]	[0.0045]	[0.0033]	[0.0139]	[0.1120]
*ln*GDP	0.0674^{a}	0.2076^{a}	−0.3182^{a}	−0.1100^{a}	0.1576^{a}	−0.1773^{a}	0.0956^{a}	0.0847^{a}	−0.0605
	[0.0013]	[0.0064]	[0.0339]	[0.0027]	[0.0116]	[0.0300]	[0.0032]	[0.0168]	[0.0473]
*ln*EC	0.2156^{a}	0.1828^{a}	0.3648^{a}	0.1478^{a}	0.1475^{a}	0.2747^{a}	0.1092^{a}	0.1070^{a}	0.0657^{a}
	[0.0003]	[0.0012]	[0.0120]	[0.0005]	[0.0020]	[0.0152]	[0.0008]	[0.0026]	[0.0444]
Obs.	336	336	336	336	336	336	336	336	336

The symbols a, b, and c indicate the significance level at 1%, 5%, and 10%, respectively. The value in [ ] is for the standard error

The panel quantile regression results

The quantile regression results provided in Table 9 shows that the coefficients of some variables remain constant at different quantiles of the ecological footprint, while the coefficients of individual variables have both positive and negative values, thus showing heterogeneous effects. Specifically, the estimated coefficients for natural resources fluctuate between 0.04 and 0.1, which is not a large range of fluctuation, but the coefficients are always significantly positive at each quantile. This suggests that in G7 countries with high natural resource abundance, natural resource use significantly stimulates an increase in ecological footprint and causes environmental degradation, and this effect is homogeneous across all quantiles. In addition, the quantile regression results capture the heterogeneous effect of population aging on the ecological footprint. Specifically, the effect of population aging on the ecological footprint of the lower quantiles (quantiles 1st, 2nd, and 3rd) is significantly positive. This positive result is identical to the findings of Balsalobre-Lorente et al. (2021) for the EU5 and Menz and Welsch (2010) for OECD countries on the environmental quality impacts of aging. At the same time, this result echoes the previous findings of Yang et al. (2021a) on the short-term effects of aging on the ecological footprint. However, for the fourth to eighth quantiles, the estimated coefficient of population aging is negative and consistently confirmed at the significance level of 0.01%. Notably, at quantile 9th, the estimated coefficient of aging begins to change, not only showing a decrease of 0.26% in the coefficient, but also being insignificant at any level, indicating that the negative impact of aging on the ecological footprint begins to diminish. Similarly, we have observed a heterogeneous effect of green technologies on the ecological footprint. The green technologies coefficient has a significant negative value at quantiles 1st to 3rd. In contrast, the coefficient transforms into a significant positive value in quantiles 4th and 5th. Interestingly, in the remaining quantiles 6th to 9th, the effect of green technologies on the ecological footprint turns negative again, and both are statistically significant. Therefore, green technology can inhibit the degradation of ecological environment at low and high quantiles. The reason for this result might be that the members of the G7 have large differences in the level of development of technological innovation, thus leading to the heterogeneity of the regression results. Moreover, for the control variables, economic growth leads to an increase in the ecological footprint, except in the 3rd, 4th, and 9th quantiles where the effects are negative, thus capturing the fact that the impact of economic growth on the ecological footprint is not perfectly symmetric in the overall distribution. The findings for energy consumption, on the other hand, show that it has a significant positive coefficient in

Table 10 The DH causality test results

Null hypothesis	W-Stat.	Z-Stat.	Prob.	Conclusion
*ln*NR ↮ *ln*EF	4.144***	2.836	0.005	*ln*NR ↔ *ln*EF
*ln*EF ↮ *ln*NR	3.897***	5.420	0.000	
*ln*PA ↮ *ln*EF	2.870***	3.498	0.000	*ln*PA ↔ *ln*EF
*ln*EF ↮ *ln*PA	11.277***	19.227	0.000	
*ln*EI ↮ *ln*EF	5.186***	7.831	0.000	*ln*EI ↔ *ln*EF
*ln*EF ↮ *ln*EI	1.990*	1.852	0.064	
*ln*GDP ↮ *ln*EF	4.167***	5.925	0.000	*ln*GDP ↔ *ln*EF
*ln*EF ↮ *ln*GDP	5.271***	4.327	0.000	
*ln*EC ↮ *ln*EF	2.160**	2.164	0.030	*ln*EC ↔ *ln*EF
*ln*EF ↮ *ln*EC	2.138**	2.130	0.033	

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$

all quantiles. Thus, the growth of energy consumption is associated with ecological degradation in G7 countries.

The causality test results

The causality test is authenticated in Table 10. The results confirm the bidirectional causality between natural resources, population aging, green technologies, economic growth, energy consumption, and EF. Therefore, policymakers in G7 countries need to be aware that any decision regarding natural resources, aging, green technologies innovation, economic growth, and energy relevant use will affect EF, either directly or indirectly through causality, and vice versa. The ecological environment needs to be taken seriously because we observe a causal link from ecology (environment) to population (society). Any change regarding ecological quality does not simply cause environmental changes, but can directly or indirectly affect the population in society. Deterioration of ecological quality may be hazardous to human health by affecting land, water, and air quality. Of course, it is also possible to enhance health through improvements in ecological quality, thereby extending human lifespan. In addition, we found a causal link from ecological footprint to green technology. Ecological degradation is gradually attracting the attention of the whole society, which stimulates countries to accelerate the process of technological innovation development. Actively mitigating environmental degradation and improving the human living environment at the technological level is the best way to achieve sustainable development for both humans and the planet.

Conclusion and policy implications

Conclusion

Pioneering G7 countries, which benefited from high economic leadership and a "demographic dividend," are facing twin challenges of environmental degradation and population aging. Therefore, these countries must find instruments and policy directions that can safeguard their current environmental welfare. With this in mind, this paper investigated the effects of natural resources, population aging, green technologies, economic growth, and energy consumption on the ecological footprint of G7 countries between 1970 and 2017. First, this study identified the presence of cross-sectional correlation and slope heterogeneity across the seven countries. Under this condition, we conducted unit root tests and cointegration tests on the data using a second-generation panel regression technique that considers cross-sectional issues. The results show that all variables except NR, PA, and EI remain stable after first-order differencing. Therefore, the variables used in this paper are of mixed integration order. In the process, this paper also confirms the cointegration between the variables of interest. These outcomes allow the application of advanced CS-ARDL models for the estimation of long-run and short-run relationships between variables. CS-ARDL results reveal that natural resources, GDP, and energy consumption drive a county's long-term and short-term ecological footprint, while population aging and green technologies reduce ecological footprint. Notably, the cross term of natural resources and green technologies also diminishes ecological footprint, suggesting that natural resource use, moderated by green technologies, can mitigate the risk of environmental degradation. To verify the heterogeneous effects of the variables of interest on the ecological footprint, we quantified the coefficients of the effects of natural resources, population aging, and green technologies on the ecological footprint at different quantiles using a panel quantile regression. The quantile regression results show that the impact of natural resources on ecological footprint is positive at each quantile and thus symmetrically distributed in the overall impact. Population aging presents a heterogeneous impact, as evidenced by positive estimated coefficients for the first three quantiles and negative results from quantile 4 to quantile 9. The distribution of the impact of green technologies is more complex, with coefficients ranging from negative to positive to negative again, showing significant heterogeneity.

In addition, to avoid errors in the practical significance of the results, we verify the causal relationships between the explanatory and explained variables. The causal relationships indicate that there is a bidirectional effect between natural resources, GDP, energy consumption, and ecological footprint, while population aging and green technologies are the unidirectional Granger causes of ecological footprint.

Policy implications

In response to the findings, this paper provides the following policy implications: (1) The regression results suggest that natural resource rents deteriorate the environment by increasing the ecological footprint. Relevant departments in G7 countries should strengthen regulations on natural resource management and strictly enforce taxation mandates on natural resource use in order to prevent the use of ecological resources without compensation or at low prices. Whether it is an individual or an enterprise, those who use ecological resources must pay for them. In the case of excessive damage caused to the environment, compensation should be paid in addition to paying the necessary rent to guarantee the sustainable use of resources. (2) Additionally, countries should not only raise awareness for resource conservation among people and enterprises but also try to coordinate the relationship between economic growth, resource use, and the environment to avoid the "resource curse." (3) Green technologies alleviate environmental degradation by moderating the role of natural resources on EF. Therefore, G7 countries should strongly support green technologies projects and screen for new industries that are consistent with sustainable development. Green technology innovation could reduce G7 countries' dependence on polluting energy use and industrial equipment. At present, the research and development of green technology face the dilemma of high investment and low return. However, the G7 still needs to develop measures and policies to encourage companies and enterprises to develop new products and reduce the risks and burdens of emerging industries. In addition, outdated natural resource extraction and utilization equipment often results in high energy consumption and low resource utilization, which wastes limited natural resources. Thus, the government and relevant authorities should replace outdated equipment and compensate companies for the replacement cost. It is well known that the development and diffusion of future green technologies cannot be achieved without the support of human capital. In this respect, G7 countries can cultivate specialized talents for eco-innovation to counteract the ecological crisis. (4) The outcomes further unveil the positive effects of population aging in G7 countries. Aging is both an opportunity and a challenge. Countries should seize the opportunity introduced through the aging era and make efforts to promote and adjust the upgrading and transformation of industrial structures. Pollution-intensive businesses should be outpaced by healthcare markets and social welfare businesses that serve the elderly. Countries should develop a social economy that focuses on the elderly market and strengthen the development and operation of environmentally friendly tertiary industries. In addition, policymakers should encourage young people to learn from the resource-saving consumption patterns and environmental concepts of the elderly. At the same time, society should protect and safeguard the fundamental interests of the elderly, such as labor force participation rate, pensions, and elimination of age discrimination and inequality.

Limitation of the paper

It is necessary to present some limitations of this study. For example, our study sample covers seven countries from 1970 to 2017. Considered comprehensively, these seven countries are significantly representative of developed countries and meet the requirements of high aging, abundant natural resource reserves, and developed technological tools. However, from the perspective of aging, these seven countries are not the top countries in the world with the highest degree of aging. Therefore, in the subsequent study, we will focus on some of the economies with the highest degree of aging to analyze the environmental consequences.

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Data availability All data sources are referred in this paper. Data can be downloaded free of cost.

Declarations

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