



Investigating the causal relationship between environmental degradation and selected economic factors: evidence from G20 countries

Piyali Kumar¹ · Soumyendra Kishore Datta¹

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Abstract

In the course of rapid economic development, attainment of environmental sustainability and climate change mitigation issues have received considerable attention in the G20 countries in the twenty-first century. The socio-economic driving forces behind environmental performance in these countries involve long-run interconnection between environmental quality and economic achievement. This study attempts to re-investigate the impact of real gross domestic product (RGDP), foreign direct investment (FDI), urban population (UP) and energy consumption on ecological footprint (EF) and CO₂ emission by applying panel PMG/ARDL estimation technique for the period 1990–2018. First, it is observed that real GDP and non-renewable energy consumption (NREC) are the driving factors behind both ecological footprint and carbon emissions in both short and long run. In addition, FDI has a negative effect on EF, while it positively affects air pollution in the long run. Lastly, urban expansion is found to contribute to improve environmental quality in the long run, while renewable energy consumption (REC) is projected to reduce carbon emission in both periods. The outcomes of Granger causality test do not reveal the existence of an error correction mechanism but the direction of short-run causality supports bidirectional effect of EF with RGDP and NREC, and CO₂ with RGDP, UP and NREC. Several policy measures are suggested to put the pressure on EF and CO₂ emission on hold, consistent with the spirit of sustainability.

Keywords Ecological footprint · Climate change · Economic growth · ARDL · G20 countries

JEL Classification O40 · Q53 · Q54

✉ Piyali Kumar
kumarpiyali92@gmail.com

Soumyendra Kishore Datta
soumyendra_d@rediffmail.com

¹ Department of Economics, The University of Burdwan, Golapbag, Burdwan 713104, West Bengal, India

Introduction

Human needs for energy, fiber, water, timber, land, infrastructure and other developmental ingredients exert huge ecological pressure, which in turn leads to climate change, loss of biodiversity, and land erosion. Over the last 5 decades, the global population had quadrupled and their taste and preference, high material living standards have been enhanced simultaneously. To satiate material demand, tremendous pressure has been put on ecological and environmental resources which is also having deleterious impact on climate. Therefore, the focal issue among the natural scientists is to recover the natural resource misused arbitrarily in the name of economic growth in both advanced and less advanced economies as well as to overcome the harmful effect of climate change (Sayegh 2023).

Among several measures of resource degradation, the most comprehensive measure of humanity's overall impact is considered to be ecological footprint (Wackernagel and Yount 2000). Soil erosion, water depletion, nutrient depletion, mineral extraction and forest loss are the main upshots of unbridled development and also the reasons for degradation of more than a quarter of the world's land surface (Steer 2014). Several previous studies (Lenzen and Murray 2001; Wackernagel et al. 1999; Omri et al. 2015; Samreen and Majeed 2022) have considered ecological footprint as a proxy indicator for environmental degradation. Li and Zhang (2022) tried to measure the ecological pressure due to industrial development in the Yangtze River Economic Belt (YREB) in China. They fitted a panel regression to find the industrial ecological footprint due to industrial development. According to their study although the region still suffers from huge ecological pressure, there has been a downtrend in its value and improved ecological benefits due to environmental regulation. Based on selected EU economies, Wang and Razzaq (2023) used fully modified ordinary least square (FMOLS), dynamic ordinary least square (DOLS), and fixed effect ordinary least square (FE-OLS) for finding the role of technological innovation, environmental governance, and institutional quality in reducing resource footprints.

CO₂-driven climate change represents a dominant phenomenon due to anthropogenic GHG emission resulting from human activities. CO₂ is the major contributor to total GHG emission and majority of the studies (Diakoulaki et al. 2006; Papagiannaki and Diakoulaki 2009; Floros and Vlachou 2005; Paravantis and Georgakellos 2007) are based on carbon-growth nexus. In many previous studies (Saleem et al. 2020; Magazzino 2017; Arminen and Menegaki 2019; Kim 2019), we see that CO₂ is very closely related to financial development and energy-use-related issues. Further, Chen et al. (2019) applied a novel decomposition analysis to study the driving factors of CO₂ emissions in China for period 2011–2015 and analyzed the inequality characteristics of such emission. Using dynamic VAR modeling approach in the context of China, Xu and Lin (2017) found that economic growth resulting from asset investment and exports, urbanization and energy structure acted as drivers of CO₂ emission.

In this context, it may be mentioned that organization G20 consists of largest developed and developing economies which have experienced resource-intensive

growth and are constantly under pressure to reduce air pollutant specially CO₂ emissions. G20 nations accounting more than two-third world population promote international cooperation through informal dialog based on equality and for laying a foundation to achieve sustained development and common progress (Van de Graaf and Westphal 2011). G20 group of countries are endowed with diverse natural resources but suffer from several environmental degradations largely driven by climate change challenges. Compared to the world average, it is important to note that G20 countries cover more 86% of GDP and 76% of CO₂ emissions by extracting 80% of energy in global economy (Rogelj et al. 2016). Without lowering the economic productivity amid the persistent increase in CO₂ emissions, this country group is faced with their bargain of the Paris Agreement. According to Rijsberman et al. (2019), climate change constitutes the major threat in G20 countries today. Radical shift to decarbonization policies is considered by them to be of utmost importance to limit global warming below 2 degrees Celsius coherent with Paris agreement. Access to clean and more sustainable energy instead of fossil fuel is also kept as one important ecological priority (Solikova 2022). Land degradation, biodiversity loss, ecosystem and marine pollution, resource overuse, CO₂ emission, and lack of waste assimilation are some of the basic environmental threats faced by these countries as emphasized in India's presidency of G20 nations. Much concern is put on the restoration of ecosystem as 23% of global land area happens to be no longer suitable for farming activity because of resource depletion and waste accumulation. To thwart the untoward effects of climate change and resource degradation, responsive strategies in such countries are expected to focus on achievement of food security, stability in global supply chain, trade and investment cooperation, fiscal sustainability and stable international financial system together with energy transition as emphasized in G20 leaders meet in Bali last year. What is most important in this context is to understand the relevant factors that affect resource degradation and GHG emission in these countries.

Empirical analysis (Bhat et al. 2022) reveals positive impact of economic growth, non-renewable energy and urbanization on CO₂ emission in G20 nations. The elasticity coefficient of renewable energy is, however, found to be negative. The paper by Yan et al. (2022) considers variables that account for the impact of economic growth, energy consumption, and technological advancement on CO₂ emission in three economic sectors of G20 countries. Using panel data, they found significant long-run equilibrium relationship between the three sectors (primary, secondary and tertiary) and CO₂ emissions. In their study, Roumiani and Mofidi (2022) used penalized regression (RR) approaches (including Ridge, Lasso and Elastic Net) and artificial neural network (ANN) to forecast ecological footprint indices in the G20 countries covering the period 1999–2018. The aspects of ecological footprint and emission of GHG gases as measurement of resource and environmental degradation in G20 countries were considered together in very few studies. These two variables were considered together in case of BRICS countries (Saleem et al. 2019a, b), in case of Qatar (Mrabet and Alsamara 2016). Most of the previous literatures in respect of G20 nations are limited to GHG pollutant, but our study focuses on the crucial air pollutant—carbon dioxide, coupled with ecological footprint. This study focuses on a unique standing compared to the previous research. This is

a comparative study, which investigates the variation in cause and effect of same explanatory variables on resource use and environmental pollution factors individually for G20 group countries.

Having identified the gaps in extant literatures, this study differs from others by utilizing natural resource as well as climate change long-run and short-run causal nexus across some of the determining variables. Ecological footprint is a robust accounting tool which measures the amount of the earth's biocapacity in terms of air, water, and soil demanded by several anthropogenic activities. On the other side, CO₂ is believed to be a comprehensive indicator of climate damage in most of the existing literatures. Therefore, this study contributes to the existing literature in a number of ways. (1) First, in a single study, both ecological footprint as resource degradation variable and CO₂ emission as environmental degradation/climate change variable have been incorporated. (2) Second, it examines the long-run and short-run linkage of these two variables separately with economic growth alongside several other determining variables including foreign direct investment, urbanization and energy use in G20 countries. (3) Third it also seeks to investigate the multivariate causal relation among the variables for resource degradation model and climate change issues separately.

In the light of the preceding statements, it seems imperative to re-investigate the resource degradation, GHG emission, economic growth nexus for G20 economies via the channels of foreign investment, urbanization and energy consumption.

Literature review

There is no denying the fact that over the past 2 decades, the causality relationships between environmental degradation and the socio-economic factors have been a subject of debate for researchers. Numerous inclusive researches exist that investigated the dynamic nexus between natural resource degradation (ecological footprint)/atmospheric pollution (CO₂ emission), financial investment, non-renewable energy use, urbanization and economic growth. In the empirical literature studies on environmental degradation, we can distinguish two strands. The first strand has focused on ecological footprint and the second on CO₂ pollutant. Some of the existing studies have focused on individual countries (Table 1, panel A) and while others are cross-country panel studies (Table 1, panel B). Here, the conflicting results are the consequence of different econometric methodologies, model framework and time span of data, choice of country, etc. The estimation techniques such as panel cointegration, VECM and Granger causality are used in both individual country studies (Hassan et al. 2018; Hatzigeorgiou et al. 2011) and group of countries (Uddin et al. 2016; Charfeddine et al. 2017). The early studies, Ergun et al. (2020), Ahmed et al. (2020), and Charfeddine et al. (2017) found the bidirectional causal relation between ecological footprint and energy consumption. Mix results were obtained by Agbede et al. (2021) by considering MINT (Mexico, Indonesia, Nigeria and Turkey) countries. The result of Granger causality shows the existence of unidirectional causal interaction between ecological footprint and economic growth in Uruguay (Ergun et al. 2020), South Africa (Nathaniel et al. 2019), Bangladesh (Sultana et al. 2021),

Table 1 Summary of previous empirical studies using ecological footprint

Authors	Time period	Study area	Variables	Methodology	Findings
Panel A: country-specific studies					
Hassan et al. (2018)	1970–2014	Pakistan	EF, GDP, NR, BIO, HC, UR	ARDL, VECM, Granger causality	EF ↔ BIO EF → U
Ergun et al. (2020)	1971–2014	Uruguay	EF, GDP, FDI, EC	ARDL, Granger causality	EF ↔ E EF → GDP, FDI E → GDP
Nathaniel et al. (2019)	1965–2014	South Africa	EF, EC, UR, FD, RGDP	ARDL, DOLS, FMOLS, CCR, Granger causality	E → EF, GDP EF → U GDP → EF
Sultana et al. (2021)	1972–2018	Bangladesh	EF, GDP, UR, TO, HC	ARDL, FMOLS, Granger causality	EF → GDP, U, TO, HC
Hussain et al. (2021a, 2021b)	1970–2018	Thailand	EF, GDP, NR, G	NARDL, Granger causality	N ↔ EF
Khan et al. (2021)	1990–2017	Pakistan	EF, GDP, REC, FE	ARDL, Granger causality	EF → GDP
Panel B: multi-country studies					
Uddin et al. (2016)	1961–2011	20 countries	EF, GDP	VECM, Granger causality	GDP → EF
Ahmed et al. (2020)	1971–2014	G7 countries	EF, EC, GDP, UR, FDI, HC	cointegration, D-H causality	EF ↔ E EF → GDP, U, HC
Agbede et al. (2021)	1971–2017	MINT countries	EF, EC, UR, RGDP, BIO	PMG/ARDL, D-H causality	Mixed result
Charfeddine et al. (2017)	1975–2007	MENA countries	EF, RGDP, EC, UR	FMOLS, DOLS, VECM, Granger causality	EF ↔ RGDP EF ↔ E U → EF

Pakistan (Khan et al. 2021), G7 countries (Ahmed et al. 2020) and MENA countries (Charfeddine et al. 2017).

The second strand of existing literature has focused on the CO₂, economic growth, financial investment and energy nexus reported in Table 2; panel A has been set up with individual economy studies (Hdom et al. 2020; Zubair et al. 2020; Durkó 2020; Hatzigeorgiou et al. 2011), and panel B is based on panel data studies (Wang et al. 2014; Kiviyiro et al. 2014; Kasma and Duman 2015; Nosheen et al. 2021; Ozcan 2013). For instance, a growing body of research has investigated the bidirectional causal interaction between CO₂ and energy consumption (e.g., Hatzigeorgiou et al. 2011; Wang et al. 2014), and unidirectional causal relationship from energy consumption to CO₂ is found in some studies such as Nosheen et al. (2021) and Ozcan (2013). Durkó (2020) explores the causal relationship between CO₂, gross domestic product and energy consumption in Hungary for the period of 1974–2014 using the ARDL model and Granger causality test. The result indicates bidirectional causal relation between GDP and carbon emission while urbanization and energy consumption Granger causes to GDP and CO₂ emission.

Some recent studies have incorporated the causal effects in examining the link between air pollution, i.e., CO₂ emissions and unconventional energy adaptation progression (Yazdi and Shakouri 2018; Sahoo et al. 2022; Qiao et al. 2019; Belaïd and Zrelli 2019; Khan et al. 2022) in some group of countries. Further, Zoaka et al. (2022) explained the relation across financial development, clean energy use, economic growth and CO₂ emissions in BRICS countries. While economic growth acted as a triggering factor for carbon emission in the long run, financial development, industrialization, trade openness, and renewable energy use contributed towards environmental quality.

Using data corresponding to 30 sub-Saharan countries over the period 1980–2018, Yilmaz (2023) tried to find carbon emissions effect of trade and energy factors. Based on application of cointegration method and Granger causality, he observed one-way causality between the variables in the long run. On the contrary, the study finds positive bidirectional causality between trade openness and carbon emissions.

From the extant literature as per our knowledge, it is obvious that G20 countries have been neglected in the resource degradation–climate change research as only a few researchers have focused on this particular group of countries. Hence, we perceive that there is no compromise in the G20 country group, making this study imperative.

Methodology of the study

Data source and description of variables

It uses a panel framework with G20 countries over the time period 1990–2018. Here, the EU national group has been eliminated from G20 countries because it includes more complex situations. Thus, the rest 19 economies, i.e., India, Mexico, Brazil, China, Italy, Germany, France, Japan, Indonesia, Turkey, Canada,

Table 2 Summary of previous empirical studies using CO₂ emission

Authors	Time period	Study area	Variables	Methodology	Findings
Panel A: country-specific studies					
Hdom et al. (2020)	1975–2016	Brazil	CO ₂ , TO, EC, GDP	DOLS, FMOLS, Granger causality	TO → C E → GDP E ↔ TO
Zubair et al. (2020)	1980–2018	Nigeria	CO ₂ , TO, FDI, GDP, GFC	ARDL, Granger causality	C ↔ FDI
Durkó (2020)	1974–2014	Hungary	CO ₂ , EC, GDP, UR	ARDL, Granger causality	GDP ↔ C U → GDP, C E → GDP, C
Hatzigeorgiou et al. (2011)	1977–2007	Greece	CO ₂ , EI, GDP	VECM, Granger causality	E ↔ C
Panel B: multi-country studies					
Wang et al. (2014)	1995–2011	30 Chinese Provinces	CO ₂ , EC, UR	DOLS, VECM Granger causality	E ↔ C U ↔ C
Kiviyiro et al. (2014)	1971–2009	Six Sub-Saharan African countries	CO ₂ , GDP, FDI, EC	ARDL, Granger causality	Mixed result
Kasma et al. (2015)	1992–2010	New EU members	CO ₂ , EC, GDP, TO, UR	VECM, Granger causality	E ↔ C U → C U ↔ C
Nosheen et al. (2021)	1995–2017	Asian economies	CO ₂ , GDP, EC, UR, TO, FD	DOLS, FMOLS, Granger causality	E → C FD, TO, GDP → C GDP, E, C → U
Al-mulaili (2014)	1980–2009	MENA countries	CO ₂ , EC, GDPPC	Panel VECM, Granger causality	E → C C → E
Ozcan (2013)	1990–2008	Middle-east countries	CO ₂ , EC, GDPPC	Panel VECM, Granger causality	E → C
Belaid et al. (2019)	1980–2014	9 Mediterranean countries	CO ₂ , GDP, REC, NREC	CCE-MG, Granger causality	CO ₂ ↔ REC GDP ↔ CO ₂ , GDP NREC ↔ CO ₂
Qiao et al. (2019)	1990–2014	G20 countries	CO ₂ , GDP, REC, AGR	FMOLS, VECM, Granger causality	Mixed result
Khan et al. (2022)	2008–2018	Belt and Road countries	CO ₂ , EX, IM, REC, TE, HC	cointegration, D-H causality	TE, REC → CO ₂ GDP ↔ CO ₂
Yazdi et al. (2018)	1992–2014	13 EU countries	CO ₂ , GDP, REC, UR, EI	DOLS, FMOLS, Granger causality	Mixed result

Table 2 (continued)

Authors	Time period	Study area	Variables	Methodology	Findings
Sahoo et al. (2022)	1990–2018	14 developing countries in Asia	CO ₂ , REC, GDP, G, TE, UR	FMOLS, PCSE, FGLS, D-H causality	CO ₂ , ↔ REC, GDP, UR, G
Zoaka et al. (2022)	1980–2018	BRICS countries	GDP, CO ₂ FD, REC	Panel cointegration, PMG-ARDL, PDOLS, Granger causality	GDP → CO ₂
Yilmaz (2023)	1980–2018	30 sub-Saharan countries	CO ₂ , NREC, TO	VECM, Granger causality	CO ₂ , ↔ TO

EF, ecological footprint; *BIO*, biocapacity; *UR*, urbanization; *EC*, energy consumption; *GDP*, economic growth; *RGDP*, real GDP; *FDI*, foreign direct investment; *FD*, financial development; *TO*, trade openness; *HC*, human capital; *NR*, natural resources; *G*, globalization; *GFC*, Gross fixed capital formation; *EI*, energy intensity; *REC*, renewable energy consumption; *NREC*, non-renewable energy; *AGR*, agricultural value-added; *EX*, export; *IM*, import; *TE*, technology transfer; *ARDL*, autoregressive distributed lag; *NARDL*, non-linear autoregressive distributed lag; *VECM*, vector error correction model; *DOLS*, dynamic ordinary least square; *FMOLS*, fully modified ordinary least square; *CCR*, canonical cointegrating regression, → denotes unidirectional causality, ↔ denotes bidirectional causality

Australia, Argentina, Russia, Saudi Arabia, United Kingdom, South Africa, United States of America, and South Korea have been considered here. Various resource degradation factors, economic factors and factors relating to human activities are considered in this study. Two variables (ecological footprint and CO₂ emission) were selected here to analyze the interdependence of resource degradation and climate change with economic growth. In addition, foreign direct investment, urban population growth and energy consumption are considered as separate variables impacting on ecological footprint and polluting gas. Ecological footprint has been chosen as a proxy of resource degradation indicator in this study and these data are taken from Global Footprint Network (GFN 2021). Moreover, the pollutant gas CO₂ covers the climate change issue; these are obtained from Emission Database for Global Atmospheric Research (EDGAR 2017). Economic growth is indicated by real GDP at constant national prices (in mil. 2017 US\$) which is available in Penn World Table 10.0 (PWT 2021). Foreign direct investment indicated by net inflows (% of GDP), urban population growth (annual %) data are taken from World Bank Development Indicators (WDI 2021). Data on fossil fuel energy in per capita (kWh) as proxy of non-renewable energy consumption and renewable energy consumption (kWh) are gathered from Our World in Data (OWD 2021). Further, Figs. 1 and 2 demonstrate the spatial distribution of ecological footprint and CO₂ emission of 1990 and 2018 across G20 economies. Figures 3, 4, 5, 6, and 7 summarize the year wise comparison (1990, 2000, 2010, and 2018) of data for the selected independent variables across G20 countries (Table 3).

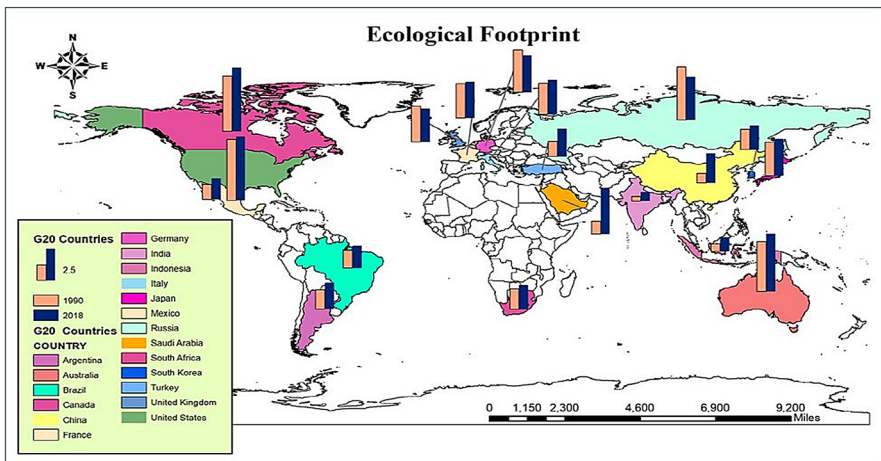


Fig. 1 Map of ecological footprint of G20 countries

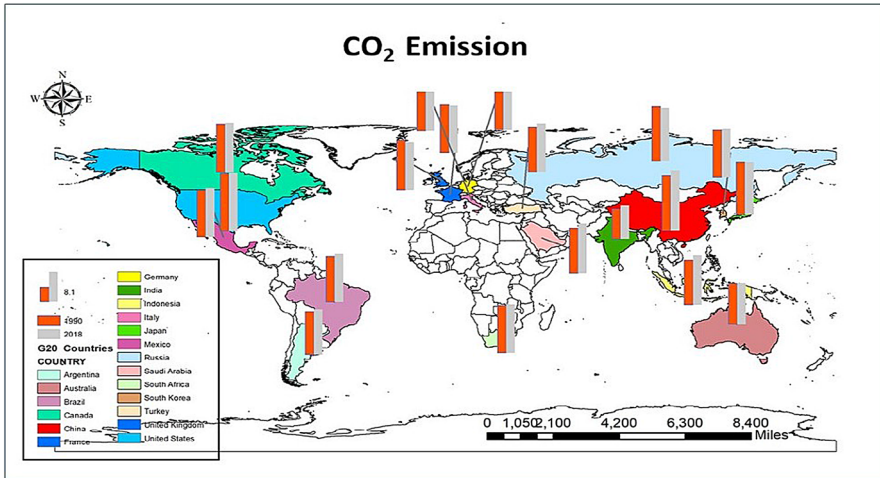


Fig. 2 Map of CO₂ emission of G20 countries

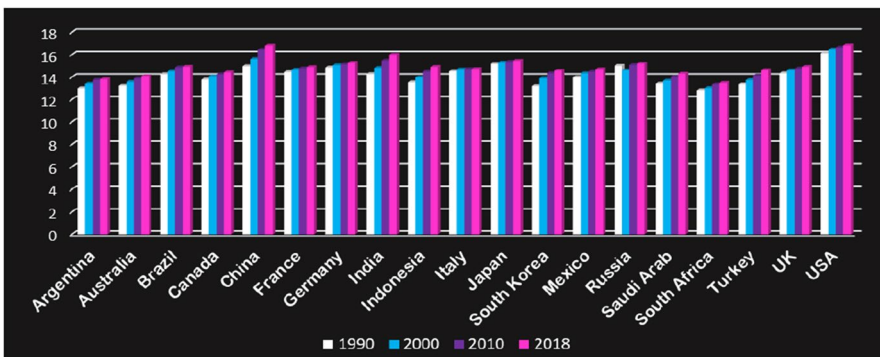


Fig. 3 Trend in real GDP by G20 countries from 1990 to 2018

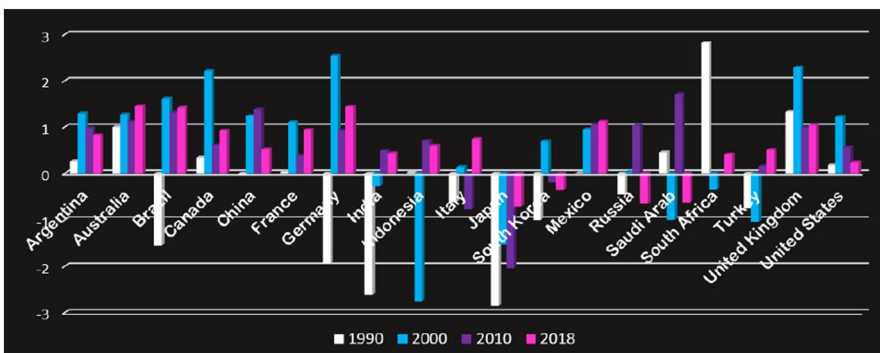


Fig. 4 Trend in FDI by G20 countries from 1990 to 2018

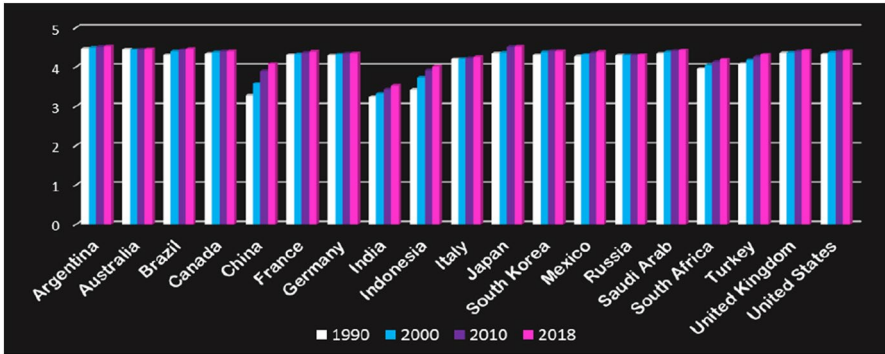


Fig. 5 Trend in urban population growth (annual %) by G20 countries from 1990 to 2018

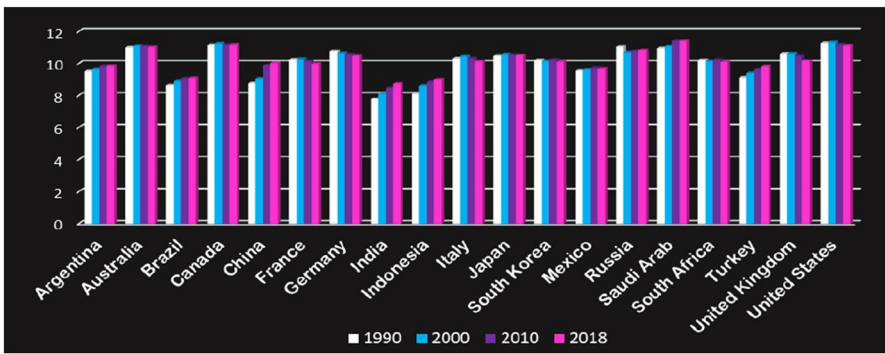


Fig. 6 Trend in non-renewable energy consumption by G20 countries from 1990 to 2018

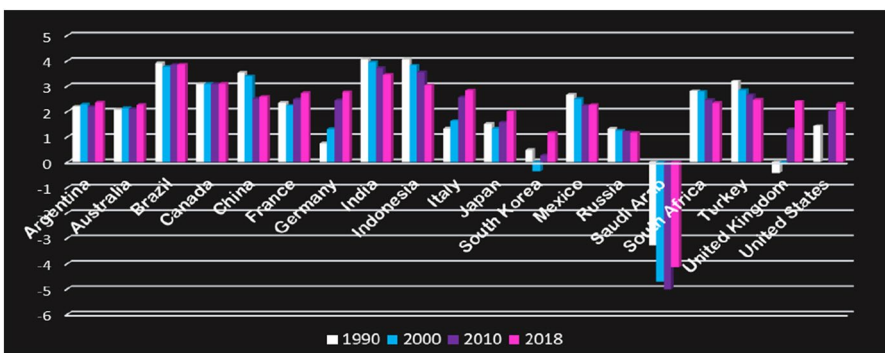


Fig. 7 Trend in renewable energy consumption by G20 countries from 1990 to 2018

Table 3 Data and sources

S/N	Variable	Symbol	Measure and explanation	Source	Expected Impact	
					On EF	On CO ₂
1	Ecological footprint	EF	Global hectares (g/ha) per person	GFN		
2	CO ₂ emission	CO ₂	CO ₂ emissions (Gg) which cover the climate change issue, capture the amount of greenhouse gases in the air	EDGAR v6.0	+	+
3	Real GDP	RGDP	At constant national prices (in mil. 2017 US\$)	PWT 10.0	+	+
4	Foreign direct investment	FDI	Foreign direct investment indicated by net inflows (% of GDP)	WDI	+	+
5	Urban population growth	UP	Urban population growth (annual %)	WDI	+	+
6	Non-renewable energy consumption	NREC	kWh of per capita energy consumption produced from non-renewable energy sources as fossil fuels	OWD	+	+
7	Renewable energy consumption	REC	kWh per capita energy consumption produced from non-renewable energy sources	OWD		-

Explanation for the selection of variables

Ecological footprint

The concept of ecological footprint pioneered by Wackernagel and Rees (1996) is the accounting tool that measures the amount of land and water body needed to produce biological product to meet human needs and mitigate accompanied waste. Ecological footprint is a universally comparable environmental indicator to measure the ecological consequences of human demands, and in many empirical literatures, it has been preferred to CO₂ emissions (Ahmed and Wang 2019; Charfeddine and Mrabet 2017; Rudolph and Figge 2017). People in countries having higher ecological footprint may be causing rapid exhaustion of resources and engendering pollution.

Carbon emission

Climate change is likely to have untoward repercussions on the growth factor in diverse sectors of economy. According to IPCC (2001) and Greenhouse Gas Bulletin (2017), CO₂ emission resulting from burning of fossil energies as an input of production process, is a substantial sponsor to climate change. This anthropogenic CO₂ leads to continuous rise in average temperature of Earth's surface. The continuous feedback hypothesis between carbon emissions and economic activities has received global attention in recent decades.

Real GDP

It is the most common and important proxy of economic growth. Researchers believe that the reason behind the environmental challenges of the present situation is the pursuit of different degrees/aspects of economic development. Alternatively, we can say an increase in output will necessitate more natural resources and then induce more environmental degradation and climate change.

Foreign direct investment

Foreign direct investment is an important tool rather than the others affecting economic development. The contribution of FDI towards the environment of the host countries has also been a subject of debate. Whether FDI is a blessing or a curse for environment depends on the development pattern of the economies, investment promotion strategies and government regulation on environment protection. But the most controversial issue about FDI is whether it significantly contributes to environmental degradation and climate change.

Urbanization

Presently, the most contentious and inconclusive issue is that the process of the rapid demographic transition from rural to urban area has a greater contribution to

resource degradation as well as climate change. Urban form influences the mode of transformation and travel pattern which affects CO₂ emission (Grazi et al. 2008). The corresponding domestic consumer markets and industrial processes in producing commodities in urban area make larger demand on the consumption of natural resources. Rapid increase of heating fuels electricity, gas and gasoline consumption as a sequel to proliferation of urban area, results in increased pollution that harms the environment due to noxious emissions.

Non-renewable energy consumption

Fossil fuel energy widely known as non-renewable energy is indeed a most crucial factor behind the environmental degradation witnessed in the previous research (Chmielewski 2005). Emission of CO₂ is strongly correlated with the consumption of conventional energy. Its effect on environmental degradation depends on the way how and for what purpose it is used. If energy is efficiently utilized in green technologies, it will help to reduce the harmful environmental effects (Stern 2006), while higher amount of energy consumption in terms of higher demand for gas, oil and coal contributes to the pollutant emissions along with the resource degradation that deteriorates the overall environment (Mirza and Kanwal 2017).

Renewable energy consumption

As a sequel to low-pollution economy policies, the use of renewable energy source is gradually rising across the world. It is considered critical for environmental quality and hence considered as achieving energy efficiency and energy saving. It is considered as an effective tool against the incidence of global warming. Electricity based on renewable energy sources produce 90–99% less GHGs in comparison to coal fired plants, which lessens pollution between 70 and 90%. Therefore, focusing on its consideration as an important element other than fossil fuels might help in avoiding environmental impacts from air pollution and GHGs (Raihan and Tuspekova 2022; Hussain et al. 2021a, b).

Models used in the study

This empirical study has been undertaken with two models—(a) natural resource degradation model and (b) climate change model. Ecological footprint has been considered as natural resource degradation indicator, while the major GHG gas—CO₂ that reflect climate change issues, has been taken for the other model. Initially, we shed a light on the natural resource degradation issues by focusing on the model specification:

$$EF = f(RGDP, FDI, UP, NREC) \quad (1)$$

where EF is ecological footprint, RGDP means real GDP, FDI is foreign direct investment, UP is the growth of urban population, NREC means non-renewable energy consumption. These aforementioned variables are the key indicators affecting

ecological footprint of an economy (i.e., Charfeddine 2017; Uddin et al. 2016). As specified in the equation, these are the logarithmic form of the considered variables for sharpness of data and to overcome the chances of heteroscedasticity:

$$\ln EF_{i,t} = \alpha_{11} + \alpha_{12} \ln RGDP_{i,t} + \alpha_{13} \ln FDI_{i,t} + \alpha_{14} \ln UP_{i,t} + \alpha_{15} \ln NREC_{i,t} + \epsilon 1_{i,t} \quad (2)$$

where ‘i’ indicates the countries and ‘t’ indicates the time period from 1990 to 2018. α indicates the slope of the coefficients of corresponding variables.

Apart from these variables, we have considered renewable energy source as an explanatory variable in CO_2 equation as renewable energy plays a key role to control climate change issues and promotes pro-environmental activities (Ahmed and Wang 2019). The estimation of this will enable us to investigate the nexus between economic growth, financial investment, urbanization and the conventional and unconventional energy utilization followed by Sahoo and Sahoo 2020, Hanif 2018, Naz et al. 2019, and Alharthi et al. 2021. The climate change model can be expressed as follows:

$$CO_2 = f(RGDP, FDI, UP, NREC, REC) \quad (3)$$

Here, CO_2 , RGDP, FDI, UP, NREC and REC stand, respectively, for carbon dioxide emission, real GDP, foreign direct investment, urban population growth, non-renewable energy and renewable energy consumption. Considering the logarithmic function of Eq. 3, it can be written as follows:

$$\begin{aligned} \ln CO_{2,i,t} = & \alpha_{21} + \alpha_{22} \ln RGDP_{i,t} + \alpha_{23} \ln FDI_{i,t} + \alpha_{24} \ln UP_{i,t} \\ & + \alpha_{25} \ln NREC_{i,t} + \alpha_{26} \ln REC_{i,t} + \epsilon 2_{i,t} \end{aligned} \quad (4)$$

In Eq. 4, α_{21} presents the intercept, and the all remaining parameters α_{22} , α_{23} , α_{24} , α_{25} , and α_{26} signify the coefficient/elasticity of RGDP, FDI, UP, NREC and REC, respectively.

This study adopted the PMG/ARDL (autoregressive distributed lag/pooled mean group) which provide both the dynamic long- and short-run relationship among the variables and VECM (Vector error correction model) econometric techniques to identify the both long- and short-run causality relationship between the dependent and independent variables. These procedures require some intermediate steps—unit root test, optimal lag selection criteria and cointegration.

The unit root test is the initial necessary step to check whether the mentioned variables are stationary and integrated of the same order or not. We establish three common unit root process across countries such as Levin Lin and Chu (Levin et al. 2002), H-T (Harris and Tzavalis 1999) and Breitung (2001) unit root tests. Apart from this, the study also carries out a group of individual unit root tests, including Im et al. (2003) and ADF-Fisher (Maddala and Wu 1999). Before analyzing the cointegration, the optimal lag selection criteria are to be fulfilled. Among various types of optimal lag length criteria, sequential modified LR test statistic (LR), Final prediction error (FPE), Akaike information criteria (AIC), Schwarz information criterion (SQ) and Hannan–Quinn information criterion (HQ) were followed. To determine the panel cointegration, this paper uses the Pedroni (1999), Kao (1999) and

Fisher (Westerlund 2007) cointegration test. Result of at least two tests must be satisfied, otherwise the criteria of cointegration will not be fulfilled. But the advantage of Pedroni test over Kao test is that Pedroni test considers the heterogeneous coefficients in case of panel model, but the other does not. Fisher test is the system-based test of cointegration for the entire panel sample. For determining the cointegration relation, the PMG/ARDL approach is more statistically significant than other cointegration technique in case of short sample. Further, it investigates whether long-run relationship exists and shows the result of both long-run and short-run model. Another advantage of this technique is that it can be applied irrespective of whether series are $I(0)$ or $I(1)$ or mixed. The ARDL model, specifically, the PMG estimator, provides reliable coefficients despite the potential presence of endogeneity, because it contains response lags and explanatory variables (Pesaran et al. 1999). In PMG over cross-sections, the long-run equilibrium values and error variance are heterogeneous but long-run slope coefficients are homogeneous in nature. Next, we examine the direction of causality between the variables in a panel context. The long-run Granger causality result is based on the coefficient of error correction term (ECT) of VECM. ECT is the one period lag estimation derived from cointegration equation and the coefficient value of ECT must be negative and statistically significant. To identify the short-run causality, Granger causality test can be performed in VECM framework which was developed by Engle and Granger (1987). Next, we examine the direction of causality between the variables in a panel context.

A panel-based VECM model of natural resource degradation model (Eq. 2) can be specified as follows:

$$\begin{aligned} \Delta \ln EF_t = & \Phi_{10} + \sum_{i=1}^p \Phi_{11i} \Delta \ln EF_{t-i} + \sum_{i=1}^p \Phi_{12i} \Delta \ln RGDP_{t-i} + \sum_{i=1}^p \Phi_{13i} \Delta \ln FDI_{t-i} \\ & + \sum_{i=1}^p \Phi_{14i} \Delta \ln UP_{t-i} + \sum_{i=1}^p \Phi_{15i} \Delta \ln NREC_{t-i} + \gamma_{11} ECT_{t-1} + \mu_{11i} \end{aligned} \tag{5}$$

$$\begin{aligned} \Delta \ln RGDP_t = & \delta_{10} + \sum_{i=1}^p \delta_{11i} \Delta \ln RGDP_{t-i} + \sum_{i=1}^p \delta_{12i} \Delta \ln EF_{t-i} + \sum_{i=1}^p \delta_{13i} \Delta \ln FDI_{t-i} \\ & + \sum_{i=1}^p \delta_{14i} \Delta \ln UP_{t-i} + \sum_{i=1}^p \delta_{15i} \Delta \ln NREC_{t-i} + \gamma_{12} ECT_{t-1} + \mu_{12i} \end{aligned} \tag{6}$$

$$\begin{aligned} \Delta \ln FDI_t = & \alpha_{10} + \sum_{i=1}^p \alpha_{11i} \Delta \ln FDI_{t-i} + \sum_{i=1}^p \alpha_{12i} \Delta \ln EF_{t-i} + \sum_{i=1}^p \alpha_{13i} \Delta \ln RGDP_{t-i} \\ & + \sum_{i=1}^p \alpha_{14i} \Delta \ln UP_{t-i} + \sum_{i=1}^p \alpha_{15i} \Delta \ln NREC_{t-i} + \gamma_{13} ECT_{t-1} + \mu_{13i} \end{aligned} \tag{7}$$

$$\Delta \ln UP_t = \beta_{10} + \sum_{i=1}^p \beta_{11i} \Delta \ln UP_{t-i} + \sum_{i=1}^p \beta_{12i} \Delta \ln EF_{t-i} + \sum_{i=1}^p \beta_{13i} \Delta \ln RGDP_{t-i} \tag{8}$$

$$+ \sum_{i=1}^p \beta_{14i} \Delta \ln FDI_{t-i} + \sum_{i=1}^p \beta_{15i} \Delta \ln NREC_{t-i} + \gamma_{14} ECT_{t-1} + \mu_{14i}$$

$$\Delta \ln NREC_t = \pi_{10} + \sum_{i=1}^p \pi_{11i} \Delta \ln NREC_{t-i} + \sum_{i=1}^p \pi_{12i} \Delta \ln EF_{t-i} + \sum_{i=1}^p \pi_{13i} \Delta \ln RGDP_{t-i} + \sum_{i=1}^p \pi_{14i} \Delta \ln FDI_{t-i} + \sum_{i=1}^p \pi_{15i} \Delta \ln UP_{t-i} + \gamma_{15} ECT_{t-1} + \mu_{15i} \tag{9}$$

In addition, the VECM formulas of climate change model (Eq. 4) can be written as follows:

$$\Delta \ln CO_{2t} = \Phi_{20} + \sum_{i=1}^p \Phi_{21i} \Delta \ln CO_{2t-i} + \sum_{i=1}^p \Phi_{22i} \Delta \ln RGDP_{t-i} + \sum_{i=1}^p \Phi_{23i} \Delta \ln FDI_{t-i} + \sum_{i=1}^p \Phi_{24i} \Delta \ln UP_{t-i} + \sum_{i=1}^p \Phi_{25i} \Delta \ln NREC_{t-i} + \sum_{i=1}^p \Phi_{26i} \Delta \ln REC_{t-i} + \gamma_{21} ECT_{t-1} + \mu_{21i} \tag{10}$$

$$\Delta \ln RGDP_t = \delta_{20} + \sum_{i=1}^p \delta_{21i} \Delta \ln RGDP_{t-i} + \sum_{i=1}^p \delta_{22i} \Delta \ln CO_{2t-i} + \sum_{i=1}^p \delta_{23i} \Delta \ln FDI_{t-i} + \sum_{i=1}^p \delta_{24i} \Delta \ln UP_{t-i} + \sum_{i=1}^p \delta_{25i} \Delta \ln NREC_{t-i} + \sum_{i=1}^p \delta_{26i} \Delta \ln REC_{t-i} + \gamma_{22} ECT_{t-1} + \mu_{22i} \tag{11}$$

$$\Delta \ln FDI_t = \alpha_{20} + \sum_{i=1}^p \alpha_{21i} \Delta \ln FDI_{t-i} + \sum_{i=1}^p \alpha_{22i} \Delta \ln CO_{2t-i} + \sum_{i=1}^p \alpha_{23i} \Delta \ln RGDP_{t-i} + \sum_{i=1}^p \alpha_{24i} \Delta \ln UP_{t-i} + \sum_{i=1}^p \alpha_{25i} \Delta \ln NREC_{t-i} + \sum_{i=1}^p \alpha_{26i} \Delta \ln REC_{t-i} + \gamma_{23} ECT_{t-1} + \mu_{23i} \tag{12}$$

$$\Delta \ln UP_t = \beta_{20} + \sum_{i=1}^p \beta_{21i} \Delta \ln UP_{t-i} + \sum_{i=1}^p \beta_{22i} \Delta \ln CO_2 + \sum_{i=1}^p \beta_{23i} \Delta \ln RGDP_{t-i} + \sum_{i=1}^p \beta_{24i} \Delta \ln FDI_{t-i} + \sum_{i=1}^p \beta_{25i} \Delta \ln NREC_{t-i} + \sum_{i=1}^p \beta_{26i} \Delta \ln REC_{t-i} + \gamma_{24} ECT_{t-1} + \mu_{24i} \tag{13}$$

$$\Delta \ln NREC_t = \pi_{20} + \sum_{i=1}^p \pi_{21i} \Delta \ln NREC_{t-i} + \sum_{i=1}^p \pi_{22i} \Delta \ln CO_{2t-i} + \sum_{i=1}^p \pi_{23i} \Delta \ln RGDP_{t-i} + \sum_{i=1}^p \pi_{24i} \Delta \ln FDI_{t-i} + \sum_{i=1}^p \pi_{25i} \Delta \ln UP_{t-i} + \sum_{i=1}^p \pi_{26i} \Delta \ln REC_{t-i} + \gamma_{25} ECT_{t-1} + \mu_{25i} \tag{14}$$

Table 4 Descriptive statistics. Source: author’s calculation based on secondary data

	lnEF	lnCO ₂	lnRGDP	lnFDI	lnUP	lnNREC	lnREC
Mean	0.7905	12.9330	14.5453	0.2084	4.2277	10.1101	1.9293
Std. Dev	0.6016	1.6098	0.8546	1.2212	0.29986	0.8726	1.8347
Max	1.7764	16.2391	16.8176	2.5465	4.5203	11.4602	4.071
Min	- 0.9853	6.6528	12.8155	- 7.1809	3.2405	7.7782	- 5.0206
Skewness	- 0.7983	- 1.3393	0.5750	- 1.8854	- 1.8806	- 0.62110	- 2.1719
Kurtosis	3.3000	6.9920	3.2885	9.4152	5.62054	2.6372	8.3655

$$\begin{aligned} \Delta \ln REC_t = & \sigma_{20} + \sum_{i=1}^p \sigma_{21i} \Delta \ln REC_{t-i} + \sum_{i=1}^p \sigma_{22i} \Delta \ln CO_{2t-i} + \sum_{i=1}^p \sigma_{23i} \Delta \ln RGDP_{t-i} \\ & + \sum_{i=1}^p \sigma_{24i} \Delta \ln FDI_{t-i} + \sum_{i=1}^p \sigma_{25i} \Delta \ln UP_{t-i} + \sum_{i=1}^p \sigma_{26i} \Delta \ln NREC_{t-i} + \gamma_{26} ECT_{t-1} + \mu_{26i} \end{aligned} \tag{15}$$

where Δ is the first difference, p is the optimal lag length, μ is the uncorrelated error terms, and Φ, δ, α, β, π, σ, γ are the coefficients of the polynomial. Error correction term (ECT) is the one period lag estimation derived from cointegration equation.

Results and discussion

Table 4 shows the descriptive statistics of the candidate variables. The primary mean of lnEF is 0.79 with a maximum log score of 1.77, while the lnCO₂ mean score is 12.9330 with a maximum of 16.2391. The results indicate that lnRGDP

Fig. 8 Correlation matrix (Source: author’s calculation based on secondary data)

	lnEF	lnCO ₂	lnRGDP	lnFDI	lnUP	lnNREC	lnREC
lnEF	1.00	0.53	0.16	0.10	0.78	0.91	-0.34
lnCO ₂	0.53	1.00	0.46	0.08	0.38	0.48	-0.17
lnRGDP	0.16	0.46	1.00	0.08	-0.13	0.07	0.12
lnFDI	0.10	0.08	0.08	1.00	0.06	0.03	0.05
lnUP	0.78	0.38	-0.13	0.06	1.00	0.69	-0.40
lnNREC	0.91	0.48	0.07	0.03	0.69	1.00	-0.58
lnREC	-0.34	-0.17	0.12	0.05	-0.40	-0.58	1.00

Table 5 Summary of unit root test. Source: author's calculation based on secondary data

Variable	Common unit root process				Individual unit root process					
	HT		BT		IPS		ADF-Fisher			
	Individual inter-cept	With trend	Individual inter-cept	With trend	Individual inter-cept	With trend	Individual inter-cept	With trend		
<i>Level</i>										
lnEF	-0.343 (0.365)	0.458 (0.676)	0.9082 (0.6817)	4.0438 (1.0000)	0.6254 (0.000)***	-0.5016 (0.308)	0.405 (0.657)	0.467 (0.679)	34.991 (0.609)	36.782 (0.525)
lnCO ₂	-2.998 (0.001)***	-0.002 (0.498)	0.9799 (0.9996)	6.5571 (1.00)	0.8587 (0.9978)	2.8404 (0.9977)	0.636 (0.737)	2.008 (0.977)	41.694 (0.313)	32.607 (0.716)
lnRGDP	-5.011 (0.000)***	-0.922 (0.178)	0.9868 (0.9999)	12.6159 (1.00)	0.806 (0.9125)	2.0558 (0.9801)	1.565 (0.941)	0.587 (0.721)	34.627 (0.626)	33.716 (0.667)
lnFIDI	-7.239 (0.000)***	-5.271 (0.000)***	0.4368 (0.000)***	-3.4467 (0.000)***	0.2907 (0.000)***	-4.6369 (0.000)***	-6.092 (0.000)***	-3.663 (0.000)***	107.101 (0.000)***	76.069 (0.000)***
lnUP	-5.557 (0.000)***	-12.536 (0.000)***	0.9797 (0.9996)	15.632 (1.00)	0.958 (1.000)	12.9138 (1.000)	-0.373 (0.354)	-6.764 (0.000)***	65.870 (0.003)***	39.080 (0.421)
lnNREC	0.005 (0.502)	-0.195 (0.422)	0.9707 (0.998)	5.4469 (1.00)	0.8426 (0.9916)	2.1217 (0.9831)	2.043 (0.979)	1.732 (0.958)	29.506 (0.836)	26.001 (0.930)
lnREC	1.893 (0.970)	0.502 (0.692)	0.9782 (0.9995)	6.2135 (1.0000)	0.7962 (0.8601)	2.4919 (0.9936)	4.565 (1.000)	1.602 (0.945)	19.165 (0.995)	29.233 (0.845)
<i>First difference</i>										
lnEF	-7.609 (0.000)***	-5.482 (0.000)***	-0.288 (0.000)***	-11.2097 (0.000)***	-0.225 (0.000)***	-11.1117 (0.000)***	-11.105 (0.000)***	-9.078 (0.000)***	193.761 (0.000)***	149.878 (0.000)***
lnCO ₂	-3.714 (0.000)***	-2.300 (0.000)***	0.2266 (0.000)***	-11.2696 (0.000)***	0.2967 (0.000)***	-9.9014 (0.000)***	-7.922 (0.000)***	-6.931 (0.000)***	140.843 (0.000)***	123.813 (0.000)***
lnRGDP	-8.132 (0.000)***	-8.164 (0.000)***	0.265 (0.000)***	-6.2519 (0.000)***	0.4257 (0.000)***	-6.7514 (0.000)***	-9.222 (0.000)***	-8.124 (0.000)***	158.292 (0.000)***	135.142 (0.000)***
lnFDI	-10.880 (0.000)***	-8.023 (0.000)***	-0.4377 (0.000)***	-9.9225 (0.000)***	-0.436 (0.000)***	-10.2277 (0.000)***	-15.283 (0.000)***	-13.251 (0.000)***	271.151 (0.000)***	218.077 (0.000)***
lnUP	-0.788 (0.015)**	-59.602 (0.000)***	0.9118 (0.7306)	2.7845 (0.9973)	0.9686 (1.00)	0.1247 (0.5496)	2.226 (0.987)	-19.533 (0.000)***	65.142 (0.004)***	285.392 (0.000)***

Table 5 (continued)

Variable	Common unit root process				Individual unit root process					
	HT		BT		IPS		ADF-Fisher			
	Individual inter-cept	With trend	Individual inter-cept	With trend	Individual inter-cept	With trend	Individual inter-cept	With trend		
LnNREC	-5.102 (0.000)***	-3.408 (0.000)***	0.0455 (0.000)***	0.2378 (0.000)***	-11.1117 (0.000)***	-9.9559 (0.000)***	-8.958 (0.000)***	-7.665 (0.000)***	155.352 (0.000)***	127.977 (0.000)***
lnREC	-7.980 (0.000)***	-6.849 (0.000)***	0.0461 (0.000)***	0.1541 (0.000)***	-9.3209 (0.000)***	-8.8434 (0.000)***	-10.902 (0.000)***	-10.008 (0.000)***	193.855 (0.000)***	171.260 (0.000)***

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

has the highest average score of 14.54 followed by lnNREC with 10.11, while lnFDI has the lowest mean score of 0.20. With the exception of real GDP, the remaining variables are negatively skewed. All the variables except lnNREC are leptokurtic since their kurtosis value is more than three.

Figure 8 shows the correlation between the variables. The correlation between lnEF and that of CO₂ is positive with rest of the variables except lnREC. The positive value of correlation indicates a direct covariation of lnFDI with all other variables. lnRGDP is positively correlated with lnNREC and lnREC, lnCO₂ and lnFDI. Correspondingly, positive value of elasticity of these variables can be calculated. A negative correlation exists between lnRGDP and lnUP and that of lnNREC with lnREC.

Unit root test result

Here, we have employed five-unit root tests LLC, H-T, Breitung, IPS and ADF-Fisher to check the stationarity of the variables which are shown in Table 5. Here, all unit root tests are considered both for individual intercept and trend. The unit root tests show that except lnFDI, all variables have unit root at level. Then, all variables have been further tested for first difference. Finally, the result of panel unit root test indicates that all the variables are stationary at first difference, i.e., integrated at

Table 6 Result of cointegration. Source: author’s calculation based on secondary data

Test statistics		Panel A		Panel B	
		Resource degradation model		Climate change model	
Pedroni test		Stat	Weighted Stat	Stat	Weighted Stat
Within-dimension	Panel v-Stat	-1.4424 (0.925)	-4.0684 (1.000)	5.8691 (0.000)***	-1.2538 (0.895)
	Panel rho-Stat	-0.3059 (0.379)	2.0299 (0.978)	-2.3749 (0.008)***	2.2418 (0.987)
	Panel PP-Stat	-7.5378 (0.000)***	-9.0895 (0.000)***	-11.4251 (0.000)***	-3.2812 (0.000)***
	Panel ADF-Stat	-7.4700 (0.000)***	-7.4025 (0.000)***	-11.4694 (0.000)***	-4.0219 (0.000)***
Between- dimension	Group rho-Stat	2.3475 (0.990)		3.6853 (0.999)	
	Group PP-Stat	-13.2860 (0.000)***		-3.8297 (0.000)***	
	Group ADF-Stat	-8.1760 (0.000)***		-3.9673 (0.000)***	
Kao Test					
ADF (t-statistics)		-1.8182 (0.034)**		-5.5014 (0.000)***	

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

same order 1 and support to proceed for panel cointegration test to analyze long- and short-run relationship among variables. Before cointegration, the secondary step, i.e., optimum lag length criteria are obtained. Accordingly, LR, FPE, AIC, SC and HQ are shown in Table No. A1 (Appendix). Majority of the criteria as LR, FPE and AIC, SC and HQ indicate that the optimal lag length considered for this study is same and that is 2.

Panel cointegration result

The result of cointegration among the variables of natural resource degradation model, i.e., $\ln EF$, $\ln RGDP$, $\ln FDI$, $\ln UP$ and $\ln NREC$ has been displayed in Table 6 (Panel A), indicates that three out of ten statistics of Pedroni cointegration test accept the null hypothesis of no cointegration. Kao test reveals the rejection of null hypothesis, i.e., no cointegration at 1% level. Briefly said, this result determines the absence of no cointegration between ecological footprint, real GDP, foreign direct investment, urban population growth and non-renewable energy consumption. Further, Panel B shows the cointegration result of the series $\ln CO_2$, $\ln RGDP$, $\ln FDI$, $\ln UP$, $\ln NREC$ and $\ln REC$ from climate change model that shows Pedroni test goes against the null hypothesis. Similarly, ADF statistic of Kao test gives significant result at 1% level. Therefore, the two test criteria of cointegration among the employed variables in both the two mentioned models of this study have been satisfied as revealed panel A and panel B. The existence of panel cointegration suggests that there must be long-run

Table 7 Result of PMG/ARDL model. Source: author's calculation based on secondary data

Dependent variable	$\ln EF$ ARDL (1 1 1 1)		$\ln CO_2$ ARDL (1 1 1 1)	
	Coefficient	Prob	Coefficient	Prob
Long run				
$\ln RGDP$	0.243	(0.000)***	0.653	(0.000)***
$\ln FDI$	-0.010	(0.002)***	0.012	(0.003)***
$\ln UP$	-0.019	(0.000)***	-0.288	(0.296)
$\ln NREC$	0.349	(0.000)***	0.103	(0.406)
$\ln REC$	-	-	-0.115	(0.000)***
Short run				
ECT	-0.299	(0.000)***	-0.088	(0.040)**
D ($\ln RGDP$)	0.794	(0.000)***	0.101	(0.050)*
D ($\ln FDI$)	-0.003	0.189	-0.003	0.385
D ($\ln UP$)	0.046	0.251	3.734	0.257
D ($\ln NREC$)	0.172	(0.085)*	0.653	(0.000)***
D ($\ln REC$)	-	-	-0.168	(0.024)**
C	-1.881	(0.001)***	0.316	(0.089)*

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

association among the variables. All the selected variables of the two mentioned models of this study have long-run equilibrium relationship and these can be proceeding to estimate panel ARDL and vector error correction model.

PMG/ARDL model result

Having satisfied the pre-requisites of ARDL method, estimations of long- and short-run parameters for both resource degradation and climate change models are presented in Table 7. The findings identified that income growth has positive and significant contribution towards resource degradation and carbon emission in short run as well as long-run period. This is vindicated by the fact that growth of any economy is associated with degradation of the environment resulting from heavy reliance and consumption of pollutant emitting energy sources (Ueta and Mori 2007).

The above findings can be explained as slow growth of an economy and poor environmental standards have strong causal relation between economic growth and resource degradation. This is supported by the findings of Halicioglu (2009) and Erdogan et al. (2020) who found bidirectional Granger causality in the long run and short run between economic growth and carbon emissions. The present findings also explore that coefficient of two factors i.e., lnFDI and lnUP are negative and significant only in long run. With 1% increase in foreign investment and urban population growth, ecological footprint is decreased by 0.010% and 0.019%, respectively, in the long run. Similar findings are reported by Saud et al. (2020) where EF is observed to decline (at various percentages in Gha) due to increase in financial development and globalization in selected countries.

The intensity of ecological footprint due to foreign investment depends on the types of adopted industries in the economy. Initially, FDI may exacerbate EF by influencing the domestic industrial production but in the long run, scientists and policy makers put stress on eco-friendly production techniques through innovation in advanced resource exploitation technologies which drastically reduce ecological footprint. This finding is consistent with Arogundade et al. (2022), while Chowdhury et al. (2020) found contradictory result. This also finds support in several writings (Danish and Wang 2019; Dogan et al. 2019) who found that urbanization has mitigating effect on environmental degradation/ecological footprint. This is also explained by the fact that, with economic growth, urbanization will reach a level of development at which environmental spoil will begin to be reversed, attendant with positive externalities and greater environmental awareness among the population. Besides this, the rising income of urban people in G20 nations has led them to embrace eco-city with low-carbon urban design such as low-carbon infrastructure, less energy using transportation and waste management, which have a favorable effect on the ecological footprint.

The non-renewable energy consumption significantly contributes to ecological footprint in G20 countries in both long run and short run as expected. This indicates that the nexus between the traditional energy sources as fossil fuel energy and

ecological footprint is consistent with the earlier investigations (Charfeddine 2017; Agboola et al. 2022; Wenlong et al. 2022).

Result of climate change model shows that 1% increase in real GDP significantly enhances CO₂ emission by 0.653% and 0.101% in long run and short run, respectively, which suggests that carbon emission is positively related to economic growth. This particular result found support from previous studies (Zubair et al. 2020; Kasman and Duman 2015; Nosheen et al. 2021) but contradicts with Hdom et al. (2020). It was found that the long-run effect of lnFDI on lnCO₂ is positive and significant, and in the short run, we detected the same sign of the coefficient which is, however, insignificant. Alternatively, we can say that FDI reduces air quality in long time period, while Ahmed et al. (2022) and Kibria et al. (2022) discovered the exact opposite. Study by Huang et al. (2022) in the context of G20 countries reveal that although FDI inflows tend to increase the emissions of carbon dioxide, they are likely to mitigate carbon emissions in countries with higher levels of economic development and regulatory quality. Financial investment leads to carbon emission because FDI influences the domestic industrial production and value-added in wholesale which enhances the over-consumption practice in human nature and makes the atmosphere more polluted. With respect to non-renewable energy consumption, it is found that a 1% rise in NREC leads to 0.653% rise in environmental deterioration in the short-run, while, in the long run, NREC is insignificant. These findings contradict with Agboola et al. (2022) where in the long run only, significant effect is observed from conventional energy, while it is insignificant in short run. This fact can be explained in terms of use of fossil fuel in the energy intensive industries and use of this kind of inputs in the production process is the reason for increasing CO₂ emissions. The coefficients of REC confirm that renewable energy consumption plays an important role in reducing carbon emissions in both short and long run in the selected economies. Therefore, the government authorities and policy maker of G20 nations are on the right path in adaptation of renewable energy technologies to mitigate climate change. Similar observations were made by Agboola et al. (2022) in Russian Federation, Alharthi et al. (2021) in MENA countries, Qiao et al. (2019) in G20 countries, Belaïd et al. (2019) in Mediterranean countries and Raihan and Tuspekova (2022) in Peru.

Table 8 Result of robustness test

Model	Test	Statistics	Coefficient	Probability
Resource degradation model	Serial correlation (LM test)	F-statistic	0.7463	0.751
	Normality	Jarque–Bera	1.524	0.466
	Heteroscedasticity (Breusch–Pagan Godfrey)	F-statistic	0.445	0.232
Climate change model	Serial correlation (LM test)	F-statistic	0.518	0.939
	Normality	Jarque–Bera	1.186	0.100
	Heteroscedasticity (Breusch–Pagan Godfrey)	F-statistic	0.329	0.552

A possible negative consequence in these models is that they may suffer from specification bias or not be homoscedastic or not have a standard normal distribution. To check for these possible modeling errors, standard diagnostic tests are performed to find out if the model is well specified, that is, the regression assumptions are not compromised. The study applies the diagnostic tests including autocorrelation, normality and heteroscedasticity to check the robustness of the results. The long-run model for both resource degradation and climate change, as shown in (Table 8) found to be healthy because the Breusch–Godfrey Lagrange multiplier (LM) test suggests that the model did not suffer serial correlation as the probability value is higher than a 5% significance level. The model is also free of heteroscedasticity as the null hypothesis not dismissed. The normality test concludes that both the model residues have a normal distribution based on Jarque–Bera statistic because the significance value is higher than the 10% level.

Causality analysis using VECM

The PMG/ARDL estimation provide only long-term and short-term parameter estimation, but causal relationship among the selected variables indicates an important step for policy direction. Here, the VECM granger causality method has been used to find out the inter-linkage causal direction among the variables under the two models. For the existence of long-run causality, the value of ECM_{t-1} must be negative and statistically significant.

The results (Table 9) of Granger causality test, based on VECM, for the variables considered in resource degradation model illustrate the short-run effect and long-run effect through error correction coefficients. The F-statistic of short-run dynamics indicate a bidirectional causal impact between EF and RGDP; EF and NREC. This two-way relations reveal that both economic growth and non-renewable energy use Granger cause resource degradation at 1% significance level and vice versa. Further,

Table 9 Result of long-run and short-run granger causality test of natural resource degradation model. Source: author’s calculation based on secondary data

Hypothesis	Short-run causality(F statistics)					Long-run causality (ECT)
	$\Delta \ln EF$	$\Delta \ln RGDP$	$\Delta \ln FDI$	$\Delta \ln UP$	$\Delta \ln NREC$	
$\Delta \ln EF$	–	3.464 (0.002)***	0.503 (0.604)	2.802 (0.061)*	11.166 (0.000)***	–0.00095 (0.395)
$\Delta \ln RGDP$	13.341 (0.000)***	–	0.439 (0.644)	18.954 (0.000)***	10.947 (0.000)***	0.00008 (0.000)***
$\Delta \ln FDI$	1.303 (0.2724)	4.178 (0.015)**	–	0.067 (0.934)	1.050 (0.350)	–0.13071 (0.874)
$\Delta \ln UP$	1.459 (0.233)	1.319 (0.268)	1.793 (0.167)	–	0.546 (0.579)	0.00001 (0.381)
$\Delta \ln NREC$	7.129 (0.000)***	2.969 (0.052)*	0.079 (0.923)	12.50 (0.000)***	–	–0.00081 (0.190)

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

Table 10 Result of long-run and short-run Granger causality test of climate change model. Source: author’s calculation based on secondary data

Hypothesis	Short-run causality(F statistics)						Long-run causality (ECT)
	$\Delta \ln \text{CO}_2$	$\Delta \ln \text{RGDP}$	$\Delta \ln \text{FDI}$	$\Delta \ln \text{UP}$	$\Delta \ln \text{NREC}$	$\Delta \ln \text{REC}$	
$\Delta \ln \text{CO}_2$	–	3.486 (0.031)**	1.180 (0.307)	12.343 (0.000)***	4.034 (0.018)**	2.008 (0.135)	–0.00005 (0.914)
$\Delta \ln \text{RGDP}$	3.932 (0.020)**	–	0.439 (0.644)	18.954 (0.000)***	10.947 (0.000)***	1.815 (0.163)	–0.00013 (0.601)
$\Delta \ln \text{FDI}$	0.474 (0.622)	4.178 (0.015)**	–	0.067 (0.934)	1.050 (0.350)	0.826 (0.438)	0.06145 (0.000)***
$\Delta \ln \text{UP}$	4.155 (0.016)**	1.319 (0.268)	1.793 (0.167)	–	0.546 (0.579)	0.172 (0.841)	–0.000002 (0.817)
$\Delta \ln \text{NREC}$	5.129 (0.006)***	2.969 (0.052)**	0.079 (0.923)	12.509 (0.000)***	–	3.587 (0.028)**	0.00016 (0.259)
$\Delta \ln \text{REC}$	1.526 (0.218)	5.359 (0.005)***	1.630 (0.196)	6.597 (0.001)***	6.955 (0.001)***	–	–0.00145 (0.077)*

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

the bidirectional short-run causal relation between RGDP and NREC indicates the energy-led growth hypothesis and vice versa. A unidirectional causality has been detected flowing from RGDP to FDI and from UP to ecological footprint, real GDP and NREC. This result suggests that economic growth enhances foreign investment but on the contrary, there is no significant effect. Regarding error correction mechanism results, no existence of an adjustment towards long-run causal interaction among the variables is observed.

Table 10 illustrates the result of both long and short-run Granger causality among the variables of climate change model in our study. In the long term, the coefficient of ECT associated with only REC is significant at 10% significance level and has a negative sign. A feedback effect of carbon emission with economic growth, urban population growth and non-renewable energy consumption sources is found in short run. A short-run causal link runs from real GDP to not only FDI but also renewable energy consumption with no feedback. Urban population

Fig. 9 Flow of short-run causality relationship (Natural resource degradation model)

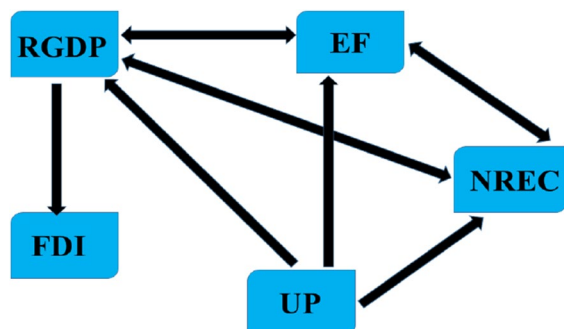
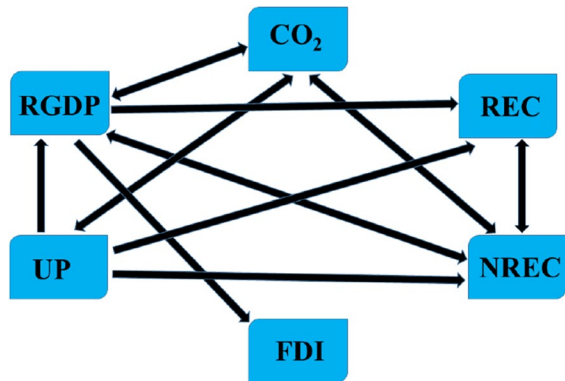


Fig. 10 Flow of short-run causality relationship (climate change model)



growth leads to CO₂ emission, economic growth and energy consumption in short run. Similar study undertaken in the context of India by Pachiyappan et al. (2021) reveal a long-term equilibrium relation across CO₂, GDP, energy use and population growth. Granger causality results show bidirectional causality between GDP and energy use, while unidirectional causality between population growth and energy use, CO₂ emission and population growth, etc. Considering the same four variables in case V-4 countries, Myszczyzyn and Supron (2022) found long-run relation while urbanization affected both CO₂ emission and energy consumption.

The urban lifestyle requires huge transportation, housing demand, and urbanization that also play a deterministic role in higher use of both conventional and unconventional energies. Economic growth and fossil fuel energy has mutual causal interaction. Some additional observations are made from this analysis in the sense that bidirectional causal effect exist between renewable and non-renewable energy use only in short run. The summary of short-run causality results of two models is shown in Figs. 9 and 10.

Conclusion and policy prescription

By far the most controversial issue among environmentalists is that environmental degradation in many developed and developing economies is the consequence of economic growth, foreign direct investment, urbanization, energy use etc. This study shows how economic growth, foreign direct investment, urban population growth, energy consumption influence ecological footprint and CO₂ emission in G20 countries between the period 1990 and 2018. Several econometric techniques such as PMG/ARDL and Granger causality test using panel VECM have been applied to explore the long-run and short-run association among the variables. The result indicates the existence of cointegration among the considered variables. These findings of long-run PMG estimator indicate that economic growth and conventional energy use degrade the environmental quality while urbanization and foreign investment exert the exact opposite. The findings of the short-run causality test reveal

bidirectional causal relationship between ecological footprint, economic growth, and non-renewable energy consumption. The unidirectional causal relation from urban population as well as non-renewable energy consumption to ecological footprint has been detected here. The result reveals that accelerated economic growth and urbanization enhance conventional energy use, and unsustainable production process and consumption behaviors of the inhabitants are the main reason for that. The consumption footprint is more sensitive to domestic income and urban design while the production footprint is more sensitive to domestic natural capital and financial investment. Therefore, both way short-term causality across GDP and EF reflects on the fact that the pressure on resource consumption to meet the demand of consumerist culture needs to be reduced to have more sustained ecological balance.

Furthermore, economic growth is found to accelerate CO₂ emission, side-by-side innovation and adaptation of green energy technologies is a large window to reduce air pollution for these particular economies. In addition, similar bidirectional causal relation of CO₂ with economic growth, urbanization, and non-renewable energy use has been found in climate change model, while one-way causal effect is observed from urbanization and economic growth to renewable energy consumption. From the economic and political point of view, few suggestions have been served corresponding to needed policy initiatives. Policymakers should balance the supply of and demand for natural resources by maintaining the ecological footprint at low level and preserving natural resources through enhanced environmental awareness, investment in vocational training, science and technology, green city development projects, holding more seminars, workshops, etc. The study outcome may enable the G20 country leaders to adopt various stringent environmental regulations which can serve to stop natural resource exploitation and assure environmental sustainability. These might be in the form of imposition of taxes on fossil fuel use, penal measures on high CO₂ emitting industries, provision of severe punishments for those who embark on indiscriminate dumping of refuse, vandalize oil pipe lines, set wild fires, adopt illegal fishing and mining activities, etc. For reduction of erosion and deforestation, environmental policies should include compulsory afforestation laws, wild-life conservation practice and biodiversity initiatives as a comprehensive measure. The government has to implement motivated pro-environmental activities to check over-consumption and promote a sustainable lifestyle for the urban population such as water-harvesting and energy-saving, usage of alternative energy instruments, use of public transportation, consumption of eco-friendly food, and recycling of wastes.

As CO₂ is the most important polluting gas in the atmosphere, the observation of either way causality in short run for the considered group of countries have implications that unless urgent action be initiated to reduce power consumption, by shifting to renewable sources of energy, by walking or cycling short distance, using public transport mostly in place of private cars for long distance, substituting fossil fuel consumption by bio-diesel, etc., the environment is likely to be polluted heavily without allowing any easy reversal. Timely implementation of preservation measures of various ecological resources, introduction of stringent

regulations and atmospheric pollution abatement activities are likely to have significant impact in fulfilling the desired goal of achieving a better sustainable future.

The aspect of resource or material input efficiency and benefit of transition to a circular economy in terms of waste reuse and thus saving resource have not been taken into consideration in the present analysis. Material flow accounts have been established by a number of countries which incorporate indicators of resource efficiency and circular economy. In the absence of these indicators, the perverse impact of material use inefficiency might be reflected in waste generation and land degradation, deforestation, water depletion and pollution, etc. In addition, foreign trade may contribute to material efficiency through inducing innovation, better technique of production and skill formation. There may also be simultaneous relation across some of these variables. These aspects should be taken into consideration in the future studies.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval This article followed all ethical standards for research. The study does not require any contact with human or animal subjects.

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