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Pathways to ecological sustainability in the United States: assessing the role of policy stringency and green energy using wavelet quantile correlation

Solomon Prince Nathaniel¹, Emmanuel Uche², Mamello Amelia Nchake³ and Magdalena Radulescu^{4,5,6*}

Abstract

The United States ranks among the most developed countries in the world in terms of economic development, technological innovation, and human capital development. Furthermore, the US is among the countries with the largest ecological footprint (EFP), with its EFP per capita higher than the global average. This questions the stringency of environmental policies in the US as well as the role of green energy in alleviating the country's ecological well-being. The objective of this study is to scrutinize the association between environmental policy stringency (EPS), green energy, and EFP in the United States. To achieve this, innovative methodologies (namely, wavelet quantile correlation and the causality approach) are employed, utilizing data from 1990 to 2022. The findings reveal that EPS warrants a substantial reduction in the EFP in the US. Although notable heterogeneous effects exist, the evidence suggests a strong negative relationship between EPS and EFP. Akin to the impact of EPS, green energy consumption produces a varying negative and positive impact on EFP over the distributions. Nevertheless, a critical observation herein is the predominant negative contribution of green energy consumption to EFP. Except in the lowest and uppermost quantiles, the contributions of green energy thereafter remain insufficient to engender ecological sustainability. Further findings reveal that both green energy and EPS significantly Granger-caused EFP across the time and quantile dimensions. Thus, this research highlights that policymakers consider a combination of market tools such as emission limits, carbon pricing, and waste reduction to optimize environmental outcomes and alleviate environmental stress.

Keywords Environmental policy stringency, Green energy, Technological innovation, Ecological footprint, Wavelet quantile correlation, United States of America

*Correspondence:

Magdalena Radulescu

mag.radulescu@yahoo.com; magdalena.radulescu@upb.ro

¹ Department of Economics, Pan-Atlantic University, Lagos, Nigeria

² Department of Economics, University of South Africa, Pretoria, South Africa, Muckleneuk

³ Department of Economics, Stellenbosch University, Stellenbosch, South Africa

⁴ National University of Science and Technology Politehnica Bucharest, Pitesti University Centre, Pitesti, Romania

⁵ UNEC Research Methods Application Center, Azerbaijan State University of Economics (UNEC), Istiqlaliyyat Str. 6, Baku, Azerbaijan

⁶ BEU Scientific Research Center, Baku Engineering University, Baku, Azerbaijan

Introduction

The world has continued to witness a rapid rise in environmental issues, such as air pollution, biological containments, and carbon emissions [39]. Regrettably, no region or country is immune to global warming or the repercussions of climate change, such as more severe storms, loss of species, increased drought, biodiversity loss, poverty and displacement, health challenges, warming oceans, melting glaciers, and rising carbon emissions levels [3, 33]. Many studies have investigated the possible drivers of climate change as well as its consequences

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on human health and ecological sustainability [18, 31]. Unsustainable consumption is a critical factor in the climate change issues, especially in developed countries that gained economic development at the expense of environmental integrity [25]. This explains why many developed economies, including the United States, harbor an ecologically deficit territory [26].

The EFP in the United States has continued to expand as a result of increased demand for water, food, energy, and other nature’s wealth, leading to dwindling biodiversity and extinction of species. The United States, for instance, has a biocapacity deficit of – 110% [20]. The EF in the United States increased from 7.95 gha in 2017 to 8.09 gha in 2018. It reduced to 7.78 gha in 2019 and to 7.06 gha in 2020. In 2021, it soared to 7.44 gha and rose further to 7.46 gha in 2022. These figures are higher than the world average of 2.7 gha, of which 60% is carbon footprint (GFN, 2024). Figure 1 shows the trend of EFP and biocapacity in the United States. The consequences of ‘EFP overshoot’ are already clear: accumulation of noxious gases in the atmosphere, species and habitat loss, depletion of resources, and infection-linked cognitive impairment [42]. Therefore, gauging the factors contributing to ecological deterioration in the United States is imperative.

The US has twice and seven times the EFP per person in China and India, respectively. The footprint assists countries to enhance quality of life and sustainability. It

helps individuals to realize their global footprint and local authorities to maximize public project return. Arkansas, Wyoming, South Dakota, Montana, and Alaska have the smallest EFP per citizen. However, states like Virginia, Florida, Colorado, California, and Arizona have the largest EFP per citizen.

Stringent environmental policies are required to tackle environmental degradation and eclipse fossil fuel consumption [14]. Carbon pricing systems, like carbon taxes, can increase the cost of fossil fuels and boost the competitiveness of renewable energy sources. Besides, subsidies and tax incentives for renewable energy projects can reduce the upfront costs and make them more attractive to investors [21, 45].

Aside from EPS, it has been argued that green energy can be a solution to EFP expansion in both developed and developing countries. The argument is based on the claim that renewable energy is clean, inexhaustible, and reliable [15, 36]. Although green energy is a solution for climate change and rising emissions, it may not be enough. Coal, oil, and natural gas have the largest share in the country’s energy mix, as shown in Fig. 2. The country introduced major climate and energy policy reforms, placing the country towards an affordable, secure, and clean energy system for a zero-carbon economy.

The US assumes an important role in supporting international energy security as the world’s largest exporter of natural gas and producer of oil. The US is currently the

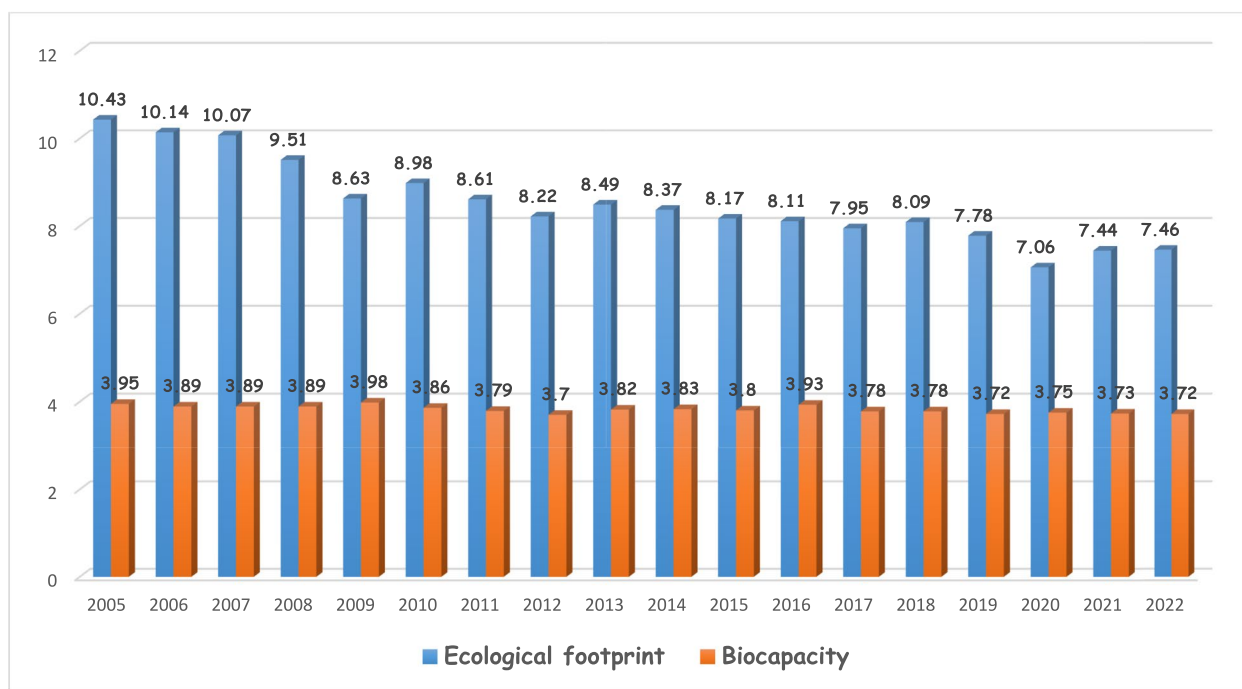


Fig. 1 Ecological footprint versus biocapacity (gha) in the United States. Source GFN (2024)

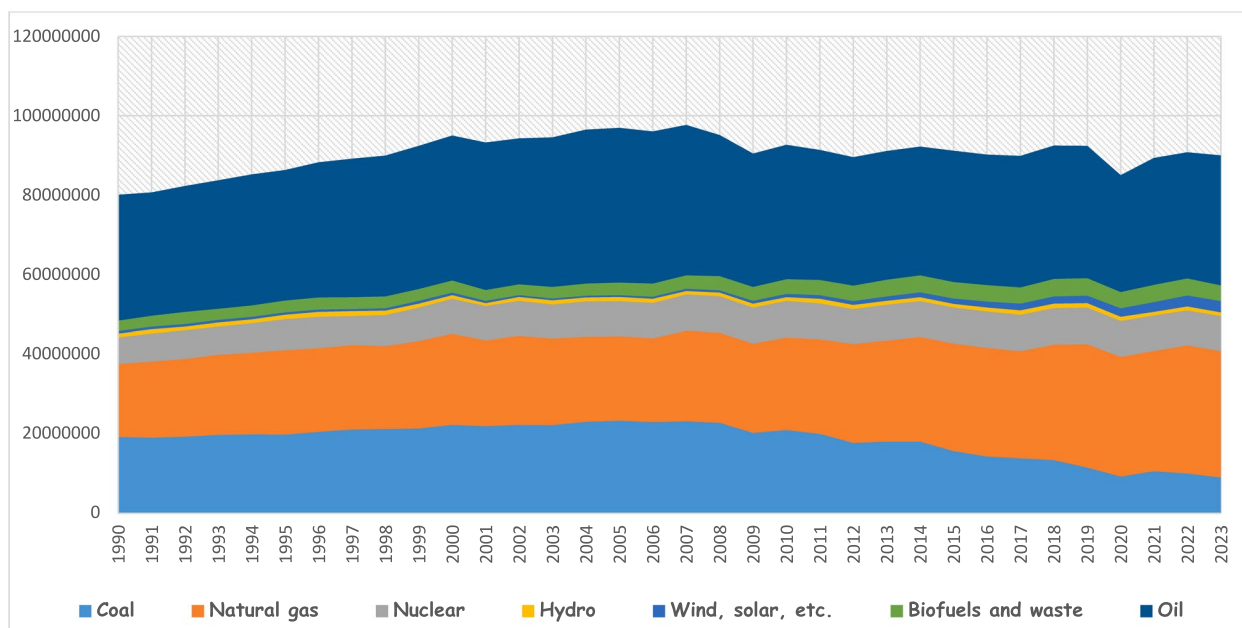


Fig. 2 Total energy supply by source in the United States. Source IEA [24]

third largest market for electric vehicle sales, heat pump manufacturing, and renewable energy investment, allowing green energy transitions around the globe via its leadership in technological innovation [23].

The US accounts for about 15.6% of global annual energy demand, ranking second after China with 25.6%. The country is also the second-highest emitter of carbon after China (British [8]). To overcome some of its environmental challenges, the country’s share of renewable energy in primary energy consumption has also increased significantly from 9% in 2014 to 21% in 2021 [23]. In terms of renewable energy generation, the country ranks second, just behind China, in solar and wind energy generation. Nevertheless, there is no consensus on the effects of EPS and green energy on EFP in the US.

The investigation shows that EPS reduced the EFP in the United States. Although notable heterogeneous effects exist, the evidence suggests a strong negative relationship between EPS and EFP. In addition, green energy produces a varying negative and positive impact on EFP over the distributions. The impact of green energy on EFP was not significant in the medium run. However, technological innovation significantly mitigates the EFP across all quantiles. Moreover, the wavelet-based Granger causality results showed that EPS, green growth, and EFP can predict each other at various frequencies.

This study makes a fourfold contribution to the extant literature on the EPS-green energy-EFP nexus. Firstly, it examines the relationship between EPS, green energy, and EF in the US in the presence of technological

innovation, GDP, urbanization, and natural resource rents using the recently introduced Wavelet Quantile Correlation (WQC) of Kumar & Padakandla. After a careful review of the literature, it was discovered that no existing study has examined the relationship among the aforementioned variables using the WQC method.

Secondly, in addition to the WQC approach, wavelet quantile Granger causality (WQGC) has been used to ascertain the direction of causality among the enlisted variables in the US. This technique is used for the first time for studies on the EPS-green energy-EFP nexus. The WQGC approach allows for detailed inferences as opposed to the classical econometric techniques. Besides, the approach makes it easier to discern the impact of EPS and other variables on EFP for different quantiles of EFP and different time horizons (short, medium, and long run). This clearly differentiates the current study from all other studies on the EPS-EFP nexus in the literature. Thirdly, previous studies focused on carbon emissions, which are primarily concerned with the climate-related effects of greenhouse gas emissions. However, environmental pollution is multidimensional and includes biodiversity conservation, carbon footprint, water pollution, fishing ground pollution, grazing land pollution, etc. To overcome this limitation, EFP was used in this study to achieve a formidable outcome, as it measures human demand on nature. Fourthly, the study carefully linked EPS and green energy consumption to EFP in the US, thereby exposing the country’s ecological deficit level and how

market- and non-market-based policies, technology support, and environmental taxes can help the United States overcome ecological deterioration.

The remainder of this study is structured as follows: Sect. "Literature Review" presents the empirical literature review. Section three discusses the WQC and WQGC methodologies. Sect. "Empirical results and discussions" discusses the various results obtained from the WQC and WQGC approaches. Sect. "Conclusion" concludes with the limitations of the study, relevant policy prescriptions, and direction for future research.

Literature review

Theoretical background

This study extends the Environmental Kuznets Curve (EKC) hypothesis. The EKC hypothesized an inverted U-shaped relationship between growth and the quality of the environment, suggesting that the latter deteriorates at the beginning of economic development and improves in later stages [29, 32]. Bölük and Mert (2014) introduced green energy consumption in the analysis of the EKC hypothesis. Several other studies discovered that green energy consumption significantly mitigates environmental deterioration because they are low in emissions and emanate from sources that cause no harm to the natural environment [16, 44].

Yao et al. [46] proposed the Renewable Energy Environmental Kuznets Curve (RKC) hypothesis, which connects green energy consumption and GDP per capita. According to the RKC hypothesis, the share of green energy decreases in the early stage of development due to increased demand for fossil fuels. After a certain level, and with further increase in growth, the share of green energy will increase and the energy structure will stimulate green development. Moreover, since the turning point of RKC occurs before EKC, it suggests that promoting green energy use could stimulate GDP per capita and reduce pollution [34].

Environmental policies that encourage grid access and integration for green energy sources can trigger the distribution and transmission of renewable energy. The adoption of renewable energy can be improved by setting strict emissions standards for industries [22]. Therefore, because green energies are clean and low in emissions [36], the persistent consumption of green energies would likely mitigate the EFP [15]. The stringency of environmental policies encourages pro-environmental behaviors, including the consumption of renewables, recycling, and proper waste management. These steps would most likely reduce the EFP [33]. In recent times, research on the impact of EPS on the environment has proliferated. Environmental policies are implemented in the United States to address market failures and trigger sustainable

development. Environmental policies in the United States have the prime objective of mitigating pollution, promoting green energy consumption, and enhancing energy efficiency via technological development. Therefore, this study is motivated to investigate the potency of EPS and green energy consumption in impeding the EFP in the US.

The conceptual framework in Fig. 3 portrays the determinants of environmental quality as put forward by the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model, which can be expanded to include EPS. The framework, suggested by Ehrlich and Holden [13], argued that demographic factors, affluence, and technology are the major drivers of environmental degradation. In Fig. 3, demographic factors (e.g., urbanization) encourage habitat loss, drive pollution, alter hydrological cycles, and cause deforestation if not properly managed. EPS promotes pro-environmental behavior, public demand for environmental policies, support for environmental policies, and efficient energy consumption. On the other hand, technological innovation promotes innovation in the energy sector (e.g., smart grids). Energy consumption is a key determinant of environmental quality. REC tends to reduce the EFP because they are low in emissions, while NREC degrades the environment. Figure 4 presents the hypotheses of the study framework.

Empirical review

EPS and EFP

There are lots of studies in the literature that tried to examine the impact of EPS on EFP. Some of such studies include Luo et al. [30], Arjun and Mishra [5], and [12]. The main conclusion in these studies is that EPS has the capacity to reduce the EFP, particularly for developed countries with strong institutions. These studies stressed the importance of strengthening environmental policies across different sectors to avoid pollution spillover and biodiversity loss. Luo et al. [30] examined the effect of EPS on EFP in the world's eleven largest economies from 1992 to 2020 using the fixed effect, OLS, and random effect models. Fiscal policy, economic growth, the openness index, financial development, and FDI were the other dependent variables in the model. The findings of the study revealed that fiscal policy, the openness index, and financial development alleviate the EFP in the selected countries. This is an indication that macroprudential policies are effective in tackling ecological deterioration. Conversely, FDI and economic growth increase the EFP. The quantile results showed that fiscal policy, financial development, and the openness index decrease

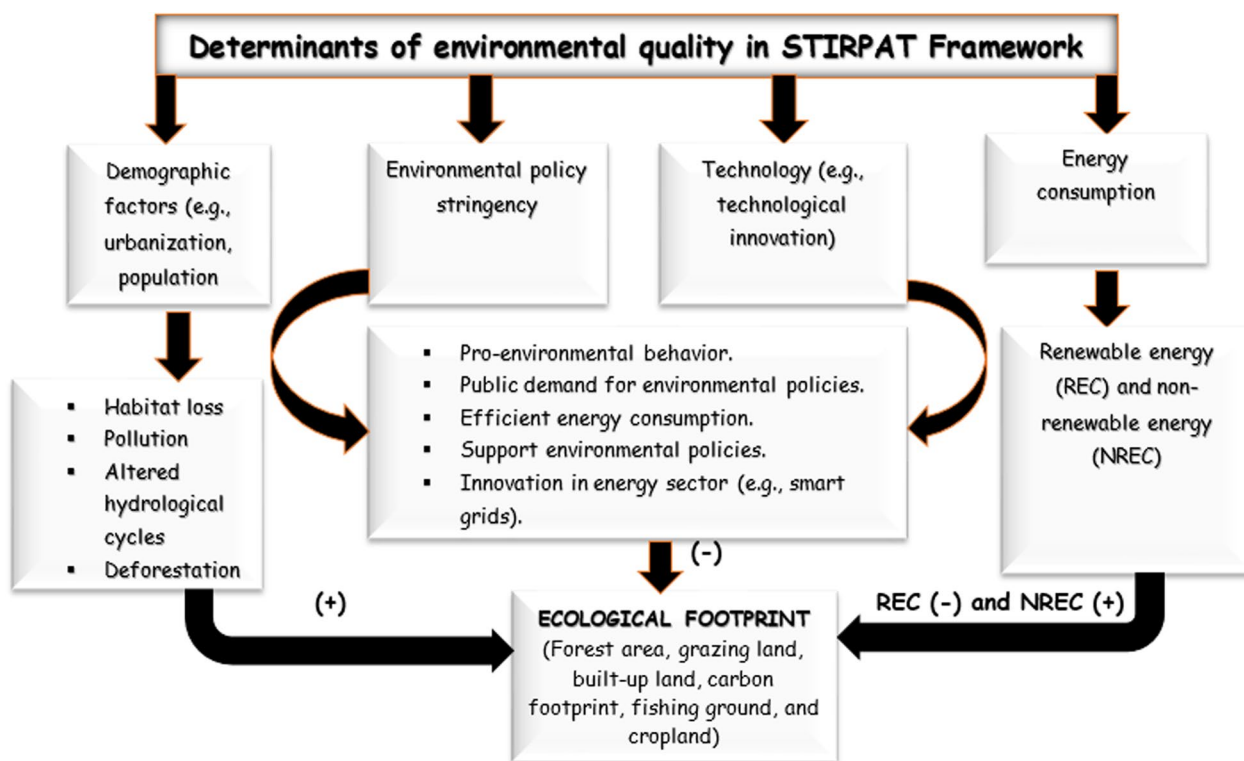


Fig. 3 Conceptual framework of the study. Source Authors construction

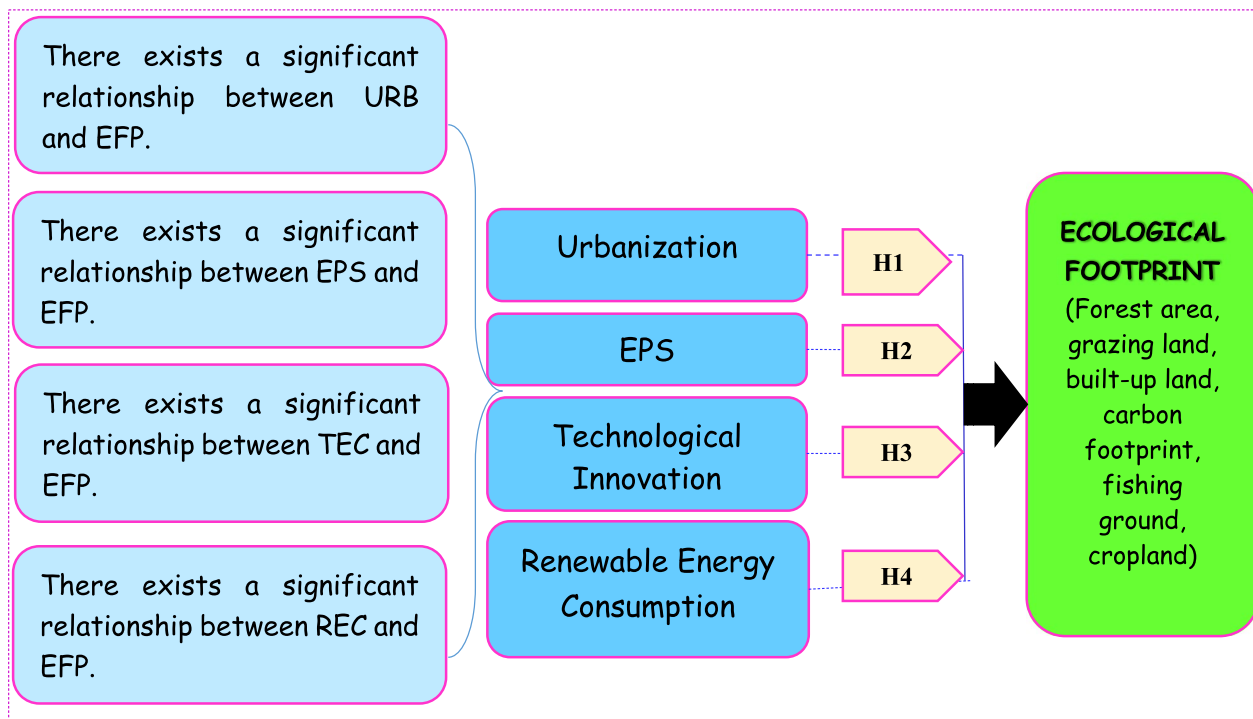


Fig. 4 Hypotheses of the study. Source Authors construction

the EFP across all quantiles, whereas FDI and economic growth exacerbate the EFP figures.

The impact of EPS on EFP has also been examined considering the role of biocapacity surplus within a quantile framework. [4] explored the impact of EPS, technological, and biocapacity surplus on the EFP in twenty-eight OECD countries using the cross-sectional autoregressive distributed lags method. Their results confirmed that EPS and technological innovation impede the EFP, whereas bio-capacity surplus and industrial value-added expand the EFP. The MMQR results confirmed that EPS and biocapacity surplus reduced the EFP only in lower quantiles. In addition, industrial value added and economic growth reduced EFP in the 0.3q, 0.5q, 0.7q, and 0.9q. A bidirectional causality exists between import, urbanization, economic growth, technological innovation, and EFP.

There are also studies that argued the role of fiscal and monetary policies in the EPS-EFP nexus. For instance, Arjun and Mishra [5] investigated the interaction between monetary policy, EPS, fiscal policy, and EFP in BRICS-T countries. Unlike the study of Luo et al. [30], disaggregated energy was introduced as an additional variable. The fixed effect, FMOLS, MMQR, and the DOLS technique were used for data estimation. The results support the claim that fiscal policy and economic growth sustained environmental integrity in BRICS-T countries. Also, monetary policy and EPS mitigate ecological deterioration in all quantile levels. The studies of [12], Bozatli and Akca [7], and [2] discovered that EPS reduced the EFP for OECD countries [27] and [19] reported similar results for BRICS, Australia, and the United States, respectively.

Green energy and EFP

Green energy is mainly derived from natural resources that tend to replenish faster than they are consumed. Some common sources of renewable energy include wind, tidal, solar, geothermal, hydropower, bioenergy, ocean energy, and hydrogen power. The effects of climate change over the years have prompted policymakers and intergovernmental bodies to seek possible solutions to the lasting damage caused by climate change and all its symptoms. Renewable energies have been proposed as a possible solution to environmental degradation as opposed to fossil fuel consumption because they are clean [41], inexhaustible [6], and reliable [47].

For instance, Roy [40] used the ARDL approach to investigate the impact of renewable energy consumption (REC) on the EFP in India while controlling for non-REC, economic growth, trade, and FDI. The results revealed that economic growth, REC, and FDI have a significant negative impact on the EFP. This suggests that REC does not hurt the environment as opposed to non-REC.

Similarly, [28] examined the effect of REC, industrial value added, and non-REC on the EF in Indonesia from 1990 to 2020 using the VECM approach. First, it was discovered that a short-run imbalance exists in REC, industrial value added, and non-REC, causing a rapid adjustment in the EFP. Second, they further discovered that the EFP in Indonesia is mostly influenced by REC in the long run. Third, non-REC will deteriorate the environment by 10.207% in 2060, making it difficult for Indonesia to achieve its carbon neutrality target. Finally, REC reduces the EFP in the long run, whereas industrial value added and non-REC deteriorate the environment.

Nathaniel et al. [33] explored the effects of clean energy on EFP in Bangladesh using the novel ARDL simulation approach. Globalization, financial development, and economic growth served as controlled variables. The study validated the EKC hypothesis and also showed that clean energy, globalization, and financial development reduce the EFP figures in Bangladesh. The FMOLS and DOLS results confirmed the robustness of the findings. Fan et al. [17], and Adebayo et al. [1] confirmed similar results for OECD countries, BRICS-T, and the United States, respectively.

Literature Gaps

The literature section of the current study was executed under two subsections, with the first reviewing studies on the impact of EPS on EFP, while the second subsection reviewed studies on green energy and EFP. Despite significant contributions from these studies, notable gaps remain. In particular, there is a dearth of researchers that integrate WQC and WQGC methodologies within a single investigation while accounting for technological innovation, urbanization, economic growth, and resource richness. These gaps underline the need for further investigation to unveil the relevance of EPS and green energy to biocapacity loss and ecological expansion in the United States.

Materials and methods

Materials

The current study focused on the effect of EPS and green energy on EFP in the US from 1990 to 2022. The beginning date is consistent with data availability of green energy, as comprehensive data on green energy was first reported in 1990 by the World Bank. On the other hand, the data on EFP was last reported in 2022. In addition, the selected period coincides with significant environmental and energy policy shifts that occurred in the United States, which include the 1990 Clean Air Act, the Energy Policy Act of 2005, the American Recovery and Reinvestment Act of 2009, the Clean Power Plan of 2015, the Energy Act of 2020, the Infrastructure Investment

and Jobs Act of 2021, the Inflation Reduction Act of 2022, and the Tax Cuts and Jobs Act of 2017, which contains several provisions impacting the US energy sector. The dataset also covers the periods of ecological deficits in the US. The study considers data on EPS, urbanization, technological innovation, green energy, natural resource rents, and GDP. The datasets are transformed to quarterly frequency with the "quadratic-match-sum" process. Table 1 contains the description of the dataset.

Methods

The WQC is the core econometric procedure adopted in this study. Before embarking on the WQC and the WQGC tests, we proceeded with the descriptive statistics, the linearity test, and the density distribution of the variables. The results of the aforementioned tests are presented in the next section. The WQC is a novel and much superior non-parametric test that is capable of decomposing variables into different time scales. The WQC approach combines the traditional quantile correlation protocol of Li et al. (2015) and the wavelet transformation process of Perciwal and Walden (2000) to decompose variables into different quantile scales. The technique ascertains the total sensitivity of a conditional quantile in a set of dependent and independent variables[11]. By combining these two approaches, the WQC allows for time-specific analysis of the relationship between the predicting and predicted variables over the short-, medium-, and long-term horizons. This approach allows for a nuanced understanding of the

dynamic interactions of the study at a specific time horizon, therefore enabling policy formulations consistent with the peculiarities of each horizon.

By employing the WQC method, EPS, REC, and EFP are investigated in terms of conditional correlation. Nevertheless, since time series data are plagued by seasonal fluctuations in the short- and long-run periods and are greatly impacted by political, economic, and social dynamics, the use of WQC makes it very easy to accommodate the fluctuations in EPS and REC.

As such, applying the time-varying heterogeneity and tail-dependence behavior over different quantiles and time horizons, this study is designed in line with the earlier studies of carried out a pioneering study on quantile correlation, which was extended by Kumar & Padakandla, who proposed the WQC. For the quantile correlation of two variables, let's say, X and Y , assume that $Q_{\tau,X}$ represents the τ^{th} quantiles of X , and $Q_{\tau,Y}(X)$ signifies the τ^{th} quantile of Y conditional on X . $Q_{\tau,Y}(X)$ not depending on X just if $I(Y - Q_{\tau,Y}) > 0$ and X is an independent vector. As such, with $0 < \tau < 1$, the quantile covariance is represented in Eqs. (1) and (2) as;

$$\begin{aligned}
 qcov_{\tau}\{Y, X\} &= cov\{I(Y - Q_{\tau,Y} > 0), X\} \\
 &= E\{\phi_{\tau}(Y - Q_{\tau,Y})(X - E(X))\},
 \end{aligned}
 \tag{1}$$

$$\phi_{\tau}(w) = \tau - I(w < 0)
 \tag{2}$$

The equation suitable to measure the quantile correlation of between X and Y is given below in equation 3:

Table 1 Data description and measurement units

Indicators	Symbol	Definition and Measurement	Source
GDP per capita	GDP	This is the total income derived from the production of goods and services in a particular economic territory in a particular year. The core indicator has been divided by the general population to achieve a per capita estimate. This variable is measured in constant 2015 US\$	WDI (2024)
Ecological footprint	EFP	It is a metric that measures the ecological resource use and resource capacity of nations over time. It is derived by tracking how much biologically productive area it takes to provide for all the competing demands of people. Measurement: (global hectares per capita)	GFN (2024)
Urbanization	URB	This variable refers to people living in urban areas as defined by national statistical offices of the World Bank. Measurement: (% of total population)	WDI (2024)
Green energy	REC	It represents the share of renewable energy in total final energy consumption. Measurement: (% of total final energy consumption)	WDI (2024)
Natural resources rents	NR	Are the sum of coal rents (soft and hard), natural gas rents, oil rents, forest rents, and mineral rents. Measurement: (% of GDP)	WDI (2024)
Environmental policy stringency	EPS	It is an index encompassing thirteen policy instruments, including market based and non-market based sub-indices, focusing on air pollution and climate change mitigation policies. It measures the strength of technology support policies. Measurement: (stringency, index)	OECD (2024)
Technological innovation	TEC		OECD (2024)
		It is the ratio of environment-related inventions of all domestic inventions in all technologies. Measurement: This indicator is measured as a percentage of all domestic inventions in all technologies	

GDP per capita: <https://data.worldbank.org/indicator/NY.GDPPCAP.KD>. Natural resources rents: <https://data.worldbank.org/indicator/NY.GDP.TOTL.RT.ZS>. Urbanization: <https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS>. Green energy: <https://data.worldbank.org/indicator/EG.FEC.RNEW.ZS>. Environmental policy stringency: https://www.oecd.org/en/publications/measuring-environmental-policy-stringency-in-oecd-countries_90ab82e8-en.html. Technological innovation: <https://www.oecd.org/en/data/indicators/patents-on-environment-technologies.html>. Ecological footprint: <https://www.footprintnetwork.org/>

$$qcor_{\tau}(X, Y) = \frac{qcor_{\tau}(X, Y)}{\sqrt{var\{\phi_{\tau}(Y - Q_{\tau,y})var(X)\}}} \quad (3)$$

Furthermore, X_t and Y_t pairs of EPS, EFP, and REC are decomposed by applying the maximum overlapping discrete wavelet transformation, which has been proposed by Percival & Walden (2000) to discuss the effect of circular shifts on the discrete wavelet transformation (eq. 4 and 5).

$$\alpha_1[i] = p_1[i]^*e[i] = \sum_m h_1[i - m]e[m] \quad (4)$$

$$d_1[i] = q_1[i]^*e[i] = \sum_m q_1[i - m]e[m] \quad (5)$$

The same procedure was used to filter $\alpha_1[i]$, although with modified filter $p_2[i]$ and $q_2[i]$. However, the process is repeated in an iterative manner. To get the accurate approximate coefficient where $J = 1, 2, \dots, J_0 - 1$ and $J_0 \leq J$, the formulas in Eqs. (6) and (7) were applied.

$$\alpha_{j+1}[i] = p_{j+1}[i]^*c_j[i] = \sum_m p_{j+1}[i - m]c_j[i] \quad (6)$$

$$d_{j+1}[i] = q_{j+1}[i]^*c_j[i] = \sum_m q_{j+1}[i - m]c_j[i] \quad (7)$$

where $q_{j+1}[i] = U(q_j[i])$ and $p_{j+1}[i] = U(p_j[i])$. By applying an up-scaling function denoted by U , zero is inserted between each pair of subsequent time-series elements. Meanwhile, the $J - level$ decomposition X_t and Y_t are useful in achieving the detail coefficient, which was achieved after applying the quantile correlation to the pair of wavelet details $d_j[Y]$ and $d_j[X]$ for all J , which produces a WQC at each level of J . Therefore, the WQC for any two selected variables is given in Eq. (8) as:

$$WQC_{\tau}(d_j[X], d_j[Y]) = \frac{qcor_{\tau}(d_j[Y], d_j[X])}{\sqrt{var(\phi_{\tau}(d_j[Y] - Q_{\tau,d_j[Y]})var(d_j[X]))}} \quad (8)$$

Following the defined WQC procedures, the data scales comprise 1990–1997 (immediate time horizon), 1998–2005 (short time horizon), 2006–2013 (medium time horizon), and 2014–2022 (long time horizon). The study applied the newly proposed WQGC estimator approach introduced by Ozkan et al. (2024) to provide deeper insights into the causal relationship between the enlisted variables and environmental quality in the US. The newly proposed WQGC econometric protocol provides the pathway to understudy Granger causal effects among variables over time dimensions and quantile distributions (Ozkan et al.,

2024). Essentially, the outcomes of the WQGC serve as a robustness test on the outcomes of the WQC estimator.

Empirical results and discussions

Descriptive statistics, linearity test, and distributions

The pre-estimation evaluations preceding the baseline estimators include summary statistics, nonlinearity tests, and distribution plots. Accordingly, the summary statistics are provided in Table 2, while the nonlinearity test is provided in Table 3. Furthermore, the distributions of the variables via the density plots are illustrated in Fig. 5.

Among other cardinal expositions of the summary statistics, there is overwhelming evidence to infer that all the selected variables deviate from normal distributions. Notably, the probability values of the Shapiro–Wilk Wald test for each variable are less than the 1% significance level. This outcome, which indicates deviation from normal distributions, amplifies the essence of a time-sensitive estimator with the capability to account for the varying trends of the enlisted variables. Besides, Table 3 presents evidence of the nonlinearity test based on the BDS process. Therein, there is also overwhelming evidence to reject the null hypothesis that the series followed a linear trend. More insights captured within the density plots (Fig. 5) exposed the abnormal distributions of the enlisted variables. Overall, the applications of the two novel techniques (WQC and WQGC) that account for the peculiarities of the relevant series within time and quantile dimensionalities are remarkable. Unarguably, applying standard econometrics techniques that are insensitive to these peculiarities would produce biased outputs and eventual policy distortions.

The study implemented novel econometric techniques to understudy the predictors of environmental quality in the US economy. Meanwhile, the study adopted the ecological footprint to measure environmental quality. Likewise, the selected predictors of environmental progress are environmental policy stringency (EPS), renewable energy consumption (REC), urbanization (URB), technological innovation (TEC), natural resource rents (NR), and gross domestic product (GDP). Herein, the novel WQC procedure is selected for updated insights.

The wavelet quantile correlation results

The new insights based on WQC are illustrated in plots 6, 7, 8, 9, 10 and 11, representing the EPS–EFP, REC–EFP, URB–EFP, TEC–EFP, NR–EFP, and GDP–EFP relationships, respectively. In line with Chishti et al. [11] and Uche et al., the effects of the predicting variables on the outcome variable are captured over four horizons, ranging from 1990 to 1997, 1998 to 2005, 2006 to 2013, and 2014 to 2022. These represent the immediate, medium,

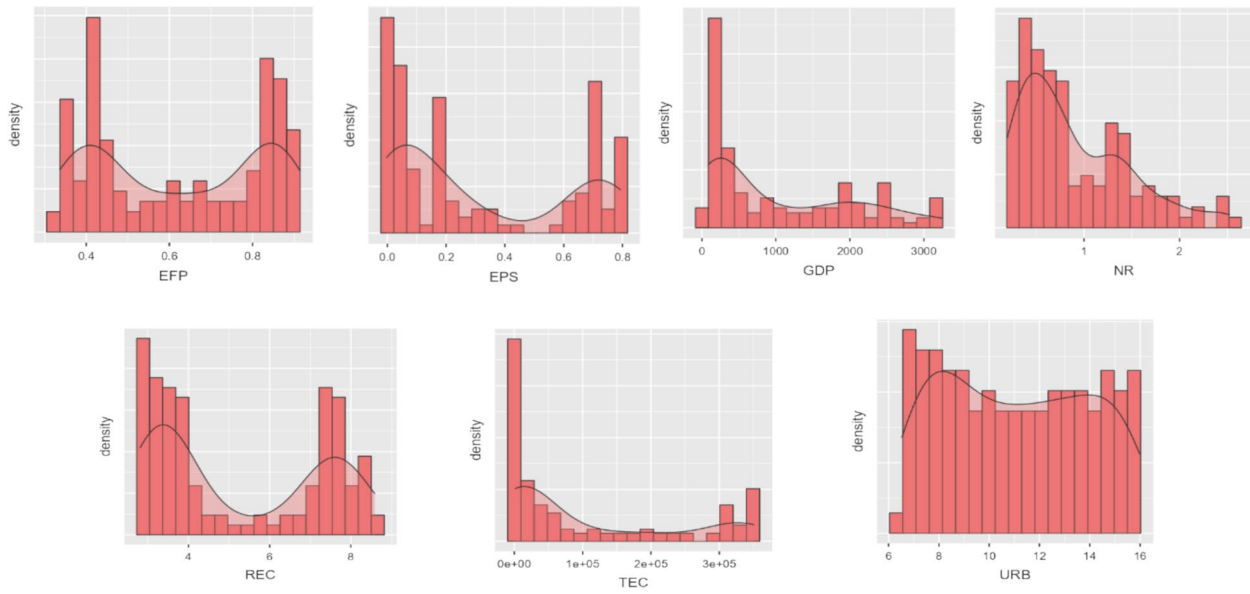


Fig. 5 Density distributions of variables

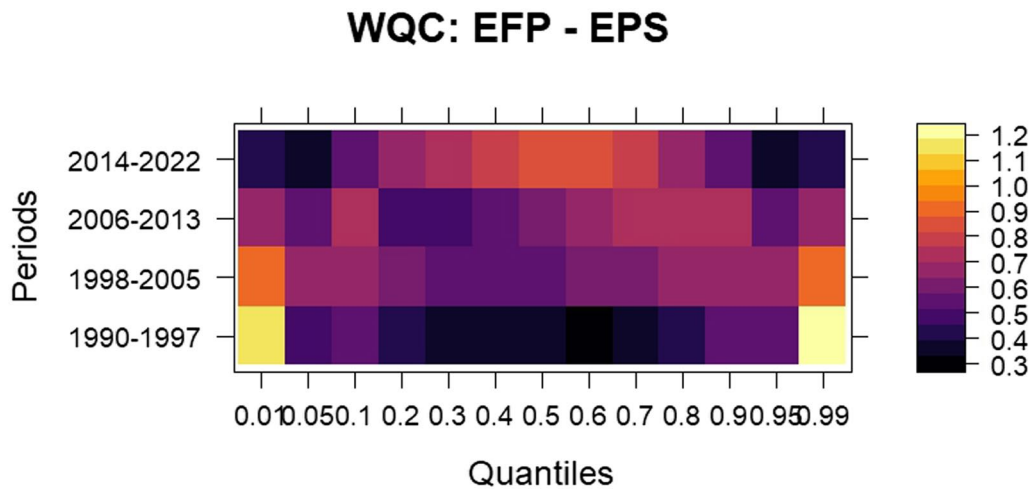
Table 2 Summary statistics

	EFP	EPS	GDP	NR	REC	TEC	URB
Mean	0.622	0.310	1042	0.898	5.20	10,645	11.1
Median	0.617	0.172	523	0.711	4.10	30,565	11.0
Standard dev	0.205	0.302	993	0.576	2.08	13,081	2.90
Minimum	0.337	-0.002	85.9	0.199	2.81	1374	6.53
Maximum	0.914	0.793	3253	2.52	8.58	35,081	16.0
Skewness	0.008	0.529	0.769	1.00	0.306	0.908	0.090
Std. error skewness	0.211	0.211	0.211	0.211	0.211	0.211	0.211
Kurtosis	-1.67	-1.48	-0.798	0.297	-1.69	-0.872	-1.31
Std. error kurtosis	0.419	0.419	0.419	0.419	0.419	0.419	0.419
Shapiro-Wilk W	0.867	0.801	0.839	0.896	0.822	0.747	0.939
Shapiro-Wilk p	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

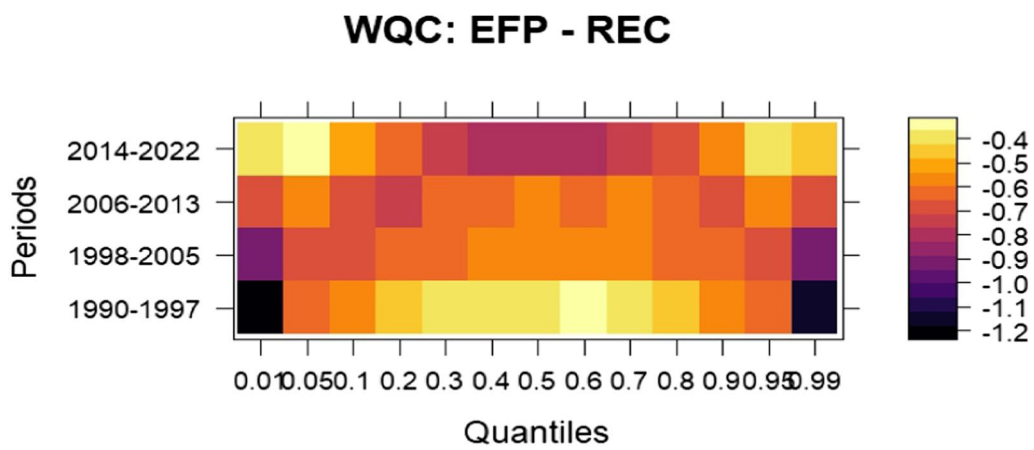
Table 3 BDS nonlinearity results

Dimension	EFP	EPS	GDP	NR	REC	TEC	URB
2	0.205***	0.201***	0.202***	0.178***	0.204***	0.198***	0.205***
3	0.346***	0.337***	0.336***	0.294***	0.346***	0.333***	0.348***
4	0.444***	0.430***	0.429***	0.368***	0.443***	0.424***	0.449***
5	0.511***	0.494***	0.494***	0.412***	0.509***	0.487***	0.521***
6	0.558***	0.538***	0.541***	0.440***	0.553***	0.530***	0.573***

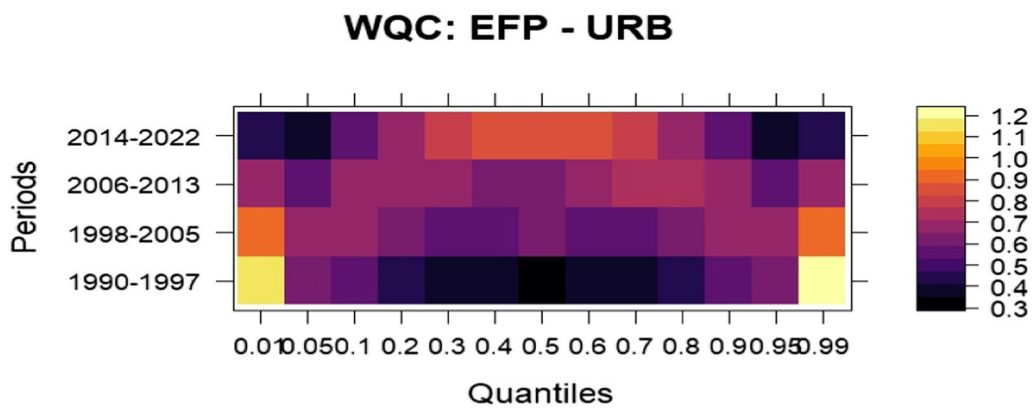
*** implies the rejection of the null hypothesis of linearity at a 1% significance level



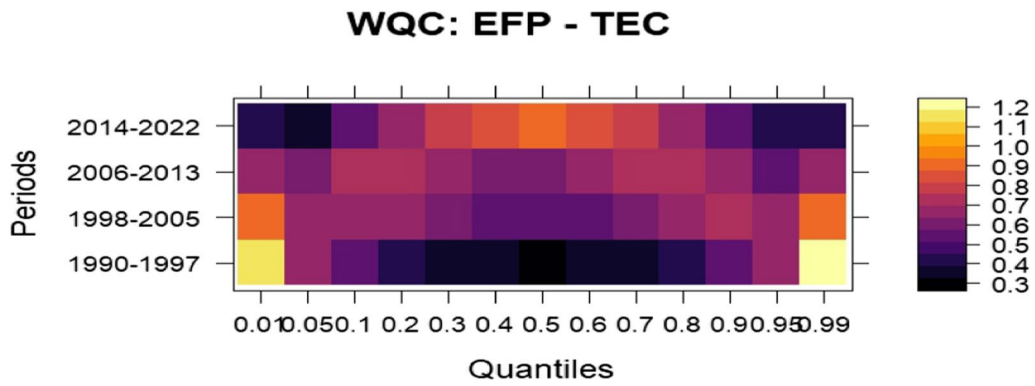
Plot 6 EFP and EPS



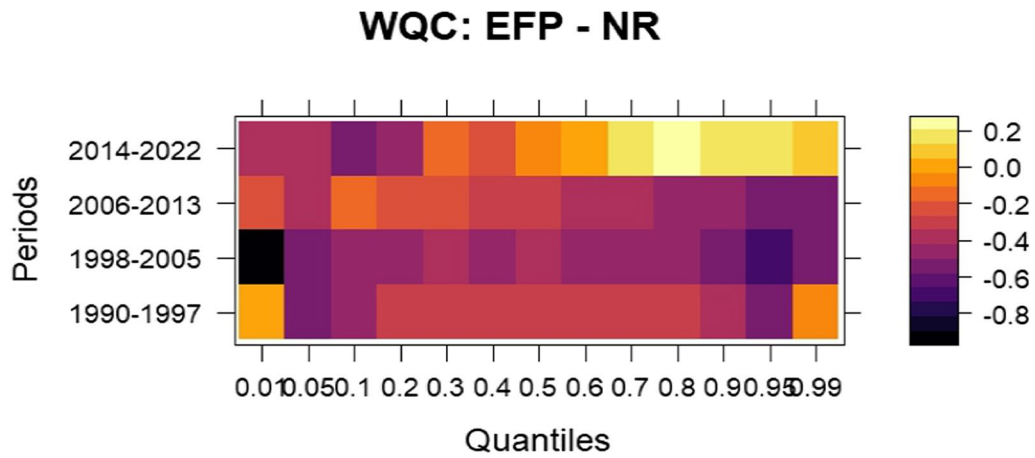
Plot 7 EFP and REC



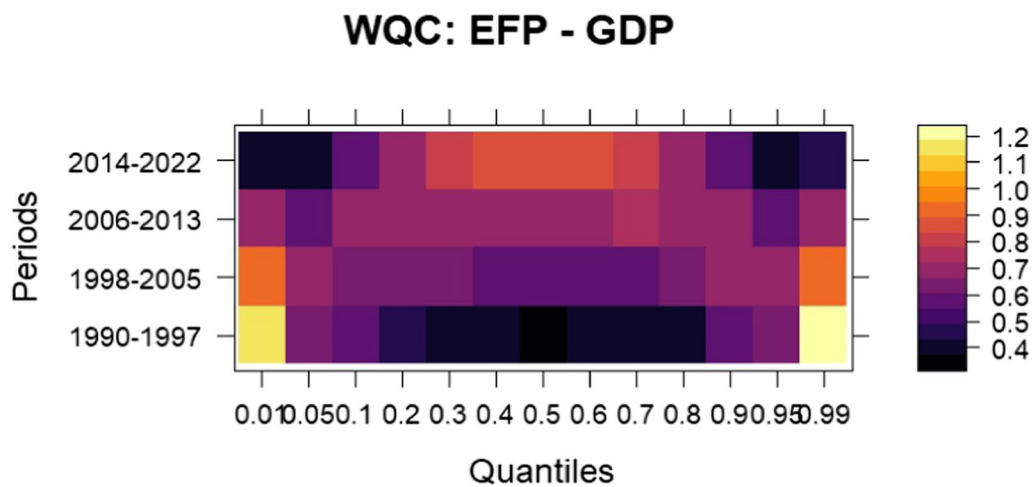
Plot 8 EFP and urbanization



Plot 9 EFP and TEC



Plot 10 EFP and natural resource rents



Plot 11 EFP and GDP

and long-term implications of predictors on response variables. For clarity of understanding, the WQC heatmap exposes extreme positive and negative connectedness between the outcome variable and its predictors. Accordingly, the extreme positive connectedness is represented by the extreme yellow boxes, while the extreme black boxes define the extreme negative connectedness.

Plot 6 illustrates the wavelet quantile connectedness between EFP and EPS in the US. As expected, EPS warranted substantial reductions in EFP in the US over the quantile distributions. Although there are notable heterogeneous effects, the evidence underlines a strong negative relationship between EPS and EFP. At the outset (1990–1997), EPS contributed to the rise in EFP at the lowest and uppermost quantiles. At the same time, EPS produced notable pleasant environmental quality-enhancing effects within the middle quantiles. These varying and heterogeneous associations between EFP and EPS reflect the changing economic dynamics occasioned mainly by uncontrollable economic shocks and policy instabilities. A precise understanding of such dynamics is critical for policy realignment toward improved environments. Over time, economic shocks such as geopolitical restiveness, oil price volatility, and economic policy inconsistencies substantially affect the relationship among economic variables.

During 1998 and recently, there has been a notable decline in the environmental quality-enhancing effects of EPS except for the lowest and uppermost quantiles of the distributions. Overall, EPS produced varying negative and positive effects on EFP during the investigated period. This entails consistent and rightly coordinated environmental control policies that are critical to ensure environmental vitality. Essentially, policymakers must review the existing environmental control policies to identify the immediate causes of the noted deviations from the expected outcomes. Hence, such factors are identified, and some immediate adjustment measures must be rolled out to ensure functional environmental stringency measures.

Accordingly, Plot 7 illustrates the relationship between the US's EFP and REC. Similar to the effects of EPS, REC produced varying positive and negative effects on EFP over the distributions. However, a critical observation herein is the predominant negative contributions of REC to EFP. Except for the lowest and uppermost quantiles during the immediate time when REC produced environmental quality-enhancing effects, its contributions thereafter remain insufficient to engender environmental sustainability. This outcome highlights critical policy insights for environmental sustainability in the US. The outcome connotes that renewable energies might

contribute more to pollution abatement than environmental sustainability (Dam et al. 2024). On this understanding, US policymakers should expand the existing environmental quality policies to include key factors directly affecting environmental sustainability.

Another policy takeaway of the empirical findings is the prevailing energy mix in the US. As noted in existing empirical studies [10], the US energy mix is dominated by traditional energies. Implicatively, the contributions of renewable energy consumption remain very low and insufficient to mitigate EFP. In such cases, policies should be geared towards a holistic transition to renewable energies if the US must attain SDGs 7 and 13. It is also imperative to adequately fund energy-enhancing technologies to boost their contributions to pollution abatement and environmental sustainability.

Plot 8 illustrates the contributions of urbanization over the quantile distributions of EFP in the US during the studied period. As illustrated in the wavelet quantile correlation plot, URB produced heterogeneous effects on environmental quality over the quantiles. Its negative effects are most notable at the uppermost and lowest quantiles of the distributions during the immediate time. However, URB produced sufficient environmental quality-enhancing effects within the middle quantile at the outset. Except for the lowest and uppermost quantiles of the distributions, urbanization could not offer sufficient environmental quality-enhancing effects in the long run. Similar insufficient effects are also observed in the medium term of the quantile distribution.

From the findings, it is imperative to highlight that coordinated, environmentally sensitive urbanization policies remain critical to boost its contributions to ecological footprint reductions. Besides, the heterogeneous effects underscore some inconsistencies in policy coordination towards environmental health. Against this backdrop, policymakers must ensure consistent coordination and administration of urbanization policies to ensure overall environmental quality. Although this finding invalidates that of Opula et al. (2023) in the case of West African countries, it underscores the peculiarities of US urbanization policies with notable environmentally sensitive entries.

In Plot 9, the relationship between EFP and TEC is depicted based on the novel WQC analysis. The plot reveals the heterogeneous implications of technological innovativeness on environmental performance during the 1990Q1–2022Q4 periods in the US. The heterogeneous contributions highlight some policy inconsistencies that certain economic shocks may have influenced. A typical example is the most recent COVID-19 global pandemic that left an indelible impression in all countries,

especially the US. In such situations, technological progress targeted at environmental sustainability is halted, and funds to that effect may be redirected to more compelling health challenges. Nonetheless, TEC remains a critical positive driver of environmental sustainability given its sufficient ecological footprint-reducing attributes within the middle quantiles in the immediate time (1990–1997).

Likewise, TEC produced notable environmental sustainability-enhancing effects at the lower and upper quantiles of the distributions of EFP over the long run. Although there are notable negative contributions, however, as highlighted in several prior studies [35], TEC is a reliable channel to foster environmental sustainability in the US. However, policy inconsistencies must be minimized to ensure maximum environmental quality-enhancing effects. Hence, policymakers must pay adequate attention to factors leading to the observed deviations from policy focus. Likewise, providing more funding for all technological innovations directly affecting environmental sustainability is imperative. Besides, policymakers are encouraged to revisit the existing policy strand to ensure its full compliance with the prescriptions of SDGs 7 and 13.

Natural resource (NR) utilization is another determinant of environmental quality (EFP), as illustrated in Plot 10. The evidence from Plot 10 denoted strong environmental quality-dampening effects of NR in the US. Except for lower quantiles during the middle term, NR remains critically inimical to environmental sustainability during the period of this study. Particularly, its environmental quality-dampening effects are maximized at the middle through the upper quantiles of EFP distributions over the long run. Amidst notable heterogeneous effects, the influence of NR is predominantly inimical to environmental sustainability based on the outcomes of the analysis. This outcome has several policy implications that policymakers must not neglect. Among other things, the environmental quality-dampening effects of NR highlight a situation whereby natural resources are exploited without considering their environmental implications. Such environmentally insensitive activities increase the rising ecological degradation, thereby making the environment unsustainable.

Some prior studies [9, 38] highlighted the negative effects of NR on the environment in West Africa. Hence, policymakers in the US should provide stringent natural resource exploitation policies to quell the negative implications of such activities on the environment. Although the existing environmental policy stringency in the country looks very strong and assertive, it seems that its natural resource exploitation components are misdirected. Such misdirected policies are the leading factors

in minimizing the contributions of EPS to NR. Hence, streamlined natural resource exploitation policies are fundamental to improving its effects on environmental quality.

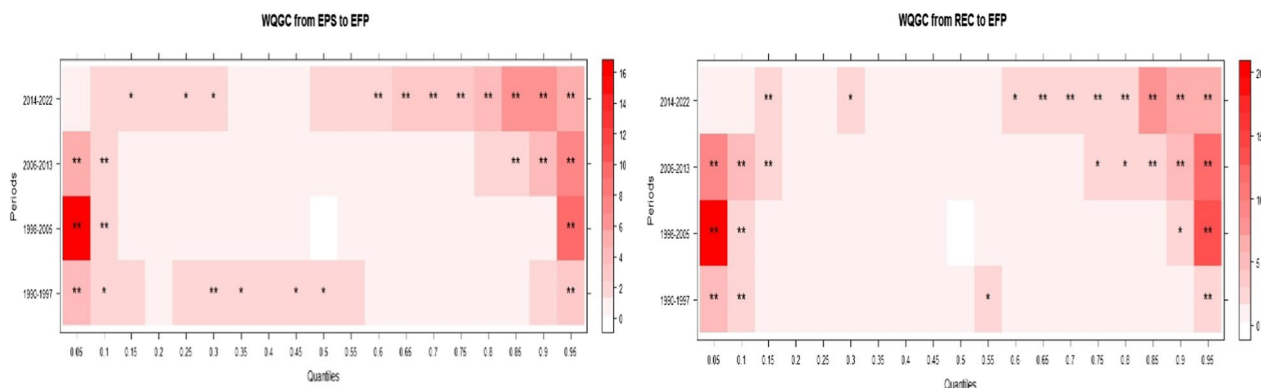
The contributions of economic growth (GDP) to EFP in the US are captured in Plot 11. Like other enlisted determinants, GDP produced varying positive and negative effects on EFP during the studied period. The varying effects underline notable heterogeneity in its contributions to environmental sustainability in the US. As earlier identified, economic shocks and policy misalignments are typical factors heightening such observed heterogeneities. The evidence explains that GDP produced sufficient environmental quality-dampening effects at the lower and upper quantiles of EFP distributions during the immediate time. Still, within the immediate time, GDP produced sufficient environmental quality-enhancing effects in the middle quantiles of the distributions.

Notably, the contributions of GDP remain insufficient across the quantiles during the medium term. In the long run, GDP produced sufficient ecological footprint-reducing effects at the lower and upper quantiles, with some insufficient ecological footprint-enhancing effects at the middle quantiles of the distributions. This outcome reflects a touch of inconsistencies in policy administrations tailored towards environmental sustainability. It shows a case whereby more attention is paid to economic prosperity at the detriment of environmental survival. The outcome also signifies rebound effects whereby the initial environmental sustainability gains are eroded in the long run due to the quest for economic prosperity.

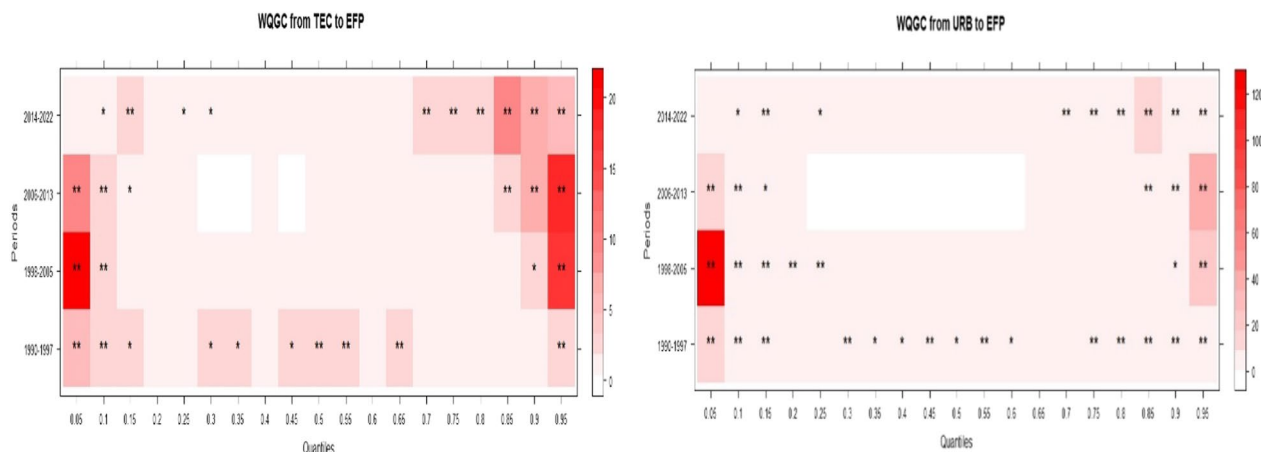
Remarkably, the US is determined to maintain its status as the leading global economy; however, policymakers must pay close attention to the environmental implications of such dispositions. In line with the submissions of prior studies [36, 37], sacrificing environmental quality for economic gains tends to erode such gains in the future. Therefore, policymakers may need to ensure a balance between economic prosperity and environmental progress. To attain this goal, manufacturers must understand the severe negative environmental implications of relying on obsolete production equipment. Rather, they should be encouraged to adopt environmentally friendlier machinery to enhance environmental quality. Meanwhile, introducing some incentives for environmental quality-enhancing compliance is recommended. These are possible steps critical to reducing the negative effects of economic prosperity on environmental sustainability.

Wavelet quantile granger causality results

Following the approach of Ozkan et al. (2024), we implemented the newly proposed wavelet quantile Granger



Plot 12 WQGC from EPS and REC to EFP. **, * imply rejection null hypothesis at 5% and 10% significance levels, respectively



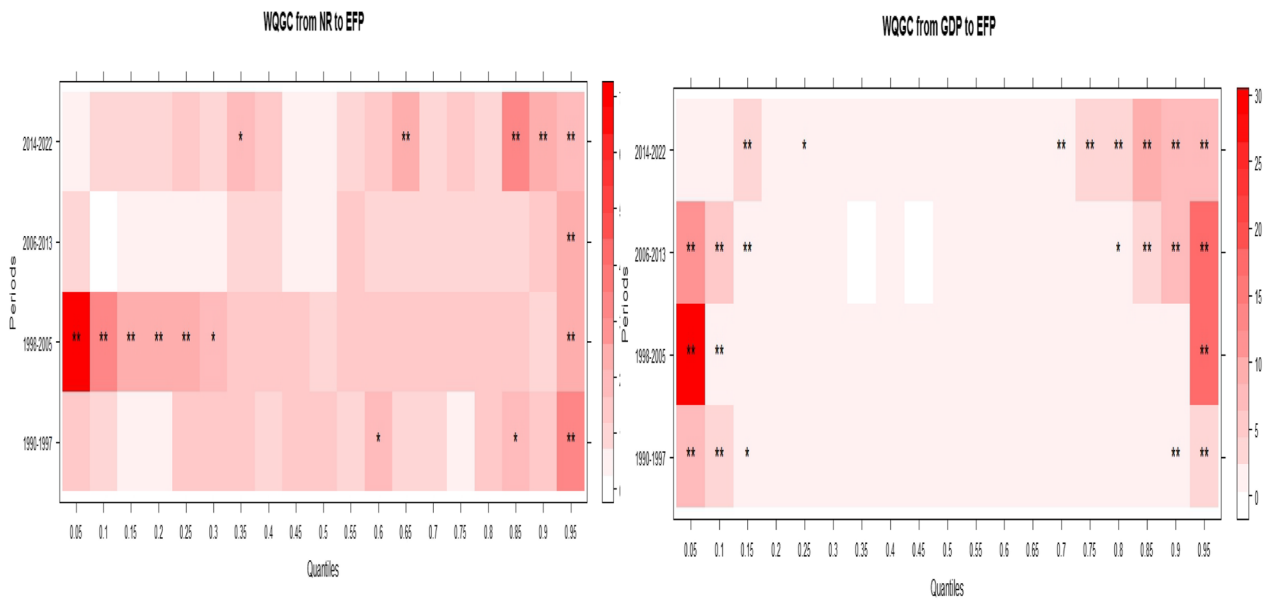
Plot 13 WQGC from TEC and URB to EFP. **, * imply rejection null hypothesis at 5% and 10% significance levels, respectively

causality (WQGC) protocol to provide deeper insights into the causal relationship between the enlisted variables and environmental quality in the US. Herein, Plots 12, 13 and 14 illustrate the causal effects of each variable on ecological footprint across the immediate, middle, and longer terms in the US. This study implemented the WQGC estimator based on insights gained from recent studies, including Ozkan et al. (2024) and Uche [43].

As illustrated earlier, the newly proposed WQGC econometric protocol provides the pathway to under-study Granger causal effects among variables over time dimensions and quantile distributions. By applying this novel technique, this study can generate unique policy insights about the causal relationship between the US ecological footprint and its identified determinants. Moreover, such evidence is conspicuously nonexistent in prior investigations, amplifying this study’s novelty. Herein, the WQGC plots are represented by Plots 12, 13

and 14, accordingly. Specifically, Plot 12 reveals that both EPS and REC significantly Granger-caused EFP across the time and quantile dimensions. However, their causal effects are more remarkable at the lower and upper quantiles during the middle and long term. This further validates the earlier inferences based on the WQC analysis. Thus, the presence of heterogeneous causal effects must be considered in policies pertaining to environmental quality – the EPS and REC nexus in the United States.

Additionally, Plots 13 and 14 consist of the wavelet quantile Granger causal effects of TEC, GDP, NR, and URB on EFP in the US. On closer observation, these variables produced Granger causal effects on the response variable more significantly at the lowest and uppermost quantiles. However, it is worth noting that their causal effects are more pronounced in the middle and long term of the distributions. An exception to this is the NR that significantly Granger-caused EFP at the upper quantile



Plot 14 WQGC from NR and GDP to EFP. **, * imply rejection null hypothesis at 5% and 10% significance levels, respectively

(0.95q) during the short run. Deductively, the evidence portrayed by the WQGC analysis connotes that these variables are relevant predictors of EFP in the US. As such, policymakers must pay closer attention to them in a bid to ensure environmental sustainability. Most importantly, the time and quantile distributional nuances of ecological sustainability and its determinants must be considered to enable the achievement of SDG 13 in the USA.

Conclusion

Summary of findings

This study investigated the association between EPS, green energy, and EFP while controlling for GDP, TEC, URB, and NR in the US. WQC and the WQGC were used for data analysis. The WQC results showed that EPS reduced the EFP in the US across various quantile distributions. Although notable heterogeneous effects exist, the evidence of a strong negative relationship between EPS and EFP confirmed the efforts of the government towards ensuring that the integrity of the environment is not compromised. Furthermore, green energy produced varying positive and negative effects on EFP across different quantiles. Meanwhile, the effects of green energy on EFP remain insufficient to engender environmental sustainability in the medium run. Also, TEC produced obvious environmental sustainability-enhancing effects at the lower and upper quantiles of the distributions of EFP over the long run. These outcomes pave the way for practical policy prescriptions.

Policy implications

The findings suggest that policymakers need to further enhance the efficiency of environmental policies. This could include promoting rigorous pollution control strategies, resource management regulations, and stricter implementation of existing legislation. Given that green energy remains insufficient to engender environmental sustainability in the medium-run, policies aimed at promoting the adoption and expansion of renewables should be encouraged. Green energy can be supported through tax incentives, subsidies, investments in green technologies such as advanced photovoltaics, green hydrogen, grid integration, blockchain, and advanced robotics. Since technological innovation reduced the EFP, it shows that the adoption of green innovation can help reduce the environmental impacts of fossil fuels and other energy-intensive machines. Government funding, grants for startups, and collaboration with technological institutions will help bolster technological innovations. The combination of market tools such as emission limits, carbon pricing, carbon capture, and waste reduction and diversion strategies will optimize environmental outcomes and alleviate environmental stress.

This study is limited by data availability and the inability to consider the subcomponents of the EFP, such as fishing grounds, grazing land, carbon footprint, built-up land, cropland, forest area, etc. Besides, this study focused on environmental deterioration from the demand side, with little or no information on the supply

side. Although the WQC method is a superior non-parametric test that is capable of decomposing variables into different time scales, it is unable to show the effects of structural breaks and asymmetries in the dataset. The combination of EFP and load capacity factor could provide different dimensions of environmental policies and policy recommendations. Therefore, future studies may consider both the demand and supply sides of environmental degradation as well as the potential effect of asymmetries in the EPS-EFP nexus. The need to consider the subcomponents of the EFP, such as fishing grounds, built-up land, cropland, carbon footprint, and forest area, will also help to broaden the policy dimension of the current study.

Author contributions

S.P.N.: conceptualization; formal analysis; writing original draft; E.U.: conceptualization; software; methodology; M.A.N.: data curation; resources; validation; M.R.: conceptualization; investigation; reviewing and editing.

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Data availability

Data will be available on request from the corresponding author.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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