Received: 28 February 2022 | Revised: 11 April 2022 | Accepted: 11 June 2022
https://doi.org/10.56946/jeee.v1i1.483
Journal of Environmental and Energy Economics

Review Article

Factors Affecting the Ecological Footprint in The United States: The Influences of Natural Resources, Economic Conditions, Renewable Energy Sources, and Advancements in Technology

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Abstract

Over the recent decades, there has been a lively debate over the relationship between natural assets and the ecosystem level that surrounds them. It is a well-known fact that numerous prosperous countries that are endowed with mineral assets have experienced favorable advancements in both innovations and the economy. In spite of this, the most significant problems are the ways in which sustainable power, natural resources, and technical developments in regions with plentiful ecological assets, such as the United States of America, influence the quality of the environment. This research explores the dynamic consequences of natural resources rent, technological innovation, renewable energy, and economic expansion on the ecological footprint (EF) in the United States of America from 1980 to 2021. The time period covered by this study is from 1980 to 2021. According to the results obtained through the use of the technique known as Autoregressive Distributed Lag (ARDL), the quality of the environment is improved by renewable energy sources, whereas the ecological condition is deteriorated by natural resource rents. Additionally, the findings revealed that there is a significantly favorable association between technological advancements and natural health. The findings have significant legal repercussions for legislators with reference to natural resources and technological development in the direction of biodiversity quality enrichment. These are vital progressions in sustainable development.

Keywords: Ecological footprint, renewable energy, natural resources, technological innovation, sustainable development.

Introduction

In recent years, there has been a growing acknowledgment within the global community regarding the urgent. In recent decades, the most urgent issues confronting the world pertain to climate change and ecological problems [1]. Economic growth often results in heightened energy consumption, which adversely affects the ecosystem [2]. The United States has adopted innovation as a means to attain environmental sustainability and is among the top ten most innovative countries worldwide [3]. The United States has witnessed a rapid increase in technological advancement, as evidenced by patent claims [4]. Researchers have assessed the connection between technological innovation and equitable growth in response to the swift improvement of technology and its beneficial impacts on global ecosystems [5]. Nonetheless, there are numerous contradictory findings concerning this association. Technological innovation improves energy efficiency. Hence, decreasing electricity usage and greenhouse gas (GHG) releases through the introduction of novel, cost-effective instruments and devices [6].

Furthermore, creativity mitigates pollutants by catalyzing monetary change through a transition from an energy-consuming industry to energy-efficient or innovation-stimulated paradigms [7]. Conversely, other experts claim that innovation is detrimental to the environment. Technological development cannot alleviate environmental damage; rather, it is the coordinated strategy of technology-related investments and current technology that does [8]. Innovation can improve resource efficiency, but its marginal impact is diminishing; therefore, significant investments in the sector of mineral wealth are required to accelerate GDP expansion [9]. Therefore, the United States must enhance its investments in renewable energy to mitigate the risk of impending climatic calamities.

Conversely, natural resources are frequently neglected in climate protection dialogues despite their critical importance to any effective strategy for rectifying ecological injustices [10-12]. Natural resources include gas, oil, forests, and minerals. The mining industry exacerbates ecological degradation despite the presence of ample natural resources [13,14]. Similarly, mining, chainsaw activities, and deforestation induce biodiversity decline [15]. Furthermore, the accessibility and reduced expense of fossil fuels render resource-rich nations reluctant to exploit environmentally sustainable energy options [16]. Consequently, to mitigate the adverse impact of natural resource extraction in the United States, it is essential to adopt environmentally sustainable technical advancements.

The conventional belief that the use of earth’s assets is a primary factor in the loss of wildlife deteriorates natural health. Nonetheless, natural resources have the capacity to enhance our surroundings. The results from the implementation of sustainable and modern power technology. Moreover, employing environmentally sustainable innovations in resource extraction and usage will advance the nation's sustainable development objective [17]. Therefore, it is essential to integrate and comprehend the interactions among natural resources. Nevertheless, despite the inconclusive findings, scant empirical information exists about the effects of natural wealth depletion and development in technology on the ecological footprint (EF). Consequently, this investigation aims to examine the evolving impact of natural assets, economic growth, green energy, and innovation in technology on ecosystem deterioration in the United States. The choice of the United States is driven by its ranking as the second among countries rich in natural resources, with lumber and coal constituting over 90% of these resources, and its status as the third-largest exporting economy globally. It is positioned second in technological innovation, following Switzerland. The United States accounts for more than 14% of worldwide releases of carbon dioxide (CO_2), positioning it as the second-greatest polluter globally.

This research seeks to provide many contributions based on this motivation. This is the initial analysis of the impact of technical improvements, renewable energy, and natural resources on the United States' EF from 1980 to 2021. The study employs ecological footprint (EF) as a proxy for environmental impact rather than just relying on carbon dioxide emissions to represent air pollution. This indicator encompasses various environmental indicators, such as developed land, forested areas, carbon emissions, pastureland, arable land, and marine environments. This study provides essential policy insights for the United States about natural resources and technological innovation aimed at enhancing ecological quality, necessitating progress in sustainable development. The analysis may assist authorities in formulating short and sustained objectives to mitigate environmental degradation while improving the exploitation of natural resources alongside emerging technology.

Literature Review

The relationship between the earth's assets, innovation in technology, and clean power concerning the natural world has gathered significant focus over the past decade. Recently, researchers have recognized a link between technological innovation (TI) and the state of the environment. Nonetheless, additional research and inquiry are still necessary in this domain. Furthermore, the relationship demonstrates ambiguity. Certain researchers assert that TI enhances the biodiversity quality. Abbas et al. [18] examined the influence of renewable energy (RE) and TI on CO_2 outputs in the BRICS nations. They utilized both linear and nonlinear ARDL simulations to examine the data from 1990 to 2020. Advancements in technology have been shown to improve air quality. Xin et al. [19] employed the Spatial Durbin Model to explore the influence of clean power technologies on manufacturing carbon intensity, adopting data from 30 provinces in China spanning 2006 to 2020. The data suggested that renewable energy methods reduce carbon intensity. Abid et al. [20] used the FMOLS approach, with data from 1990 to 2019 for G8 regions, to evaluate the impact of technological innovation, foreign direct investment, energy consumption, and urbanization on CO_2 pollution. They indicated that TI reduces pollutants. He et al. [21] implemented the Tobit fixed effect model to analyze data from 25 provinces in China between 2002 and 2015, investigating the relationship between renewable energy technologies and the overall factor carbon performance index within a market framework. The authors discovered that renewable energy technologies improve the total factor carbon performance index; nevertheless, market considerations influenced this outcome.

Similarly, Iqbal et al. [22] asserted that technological innovation enhanced the natural world in 26 OECD regions, adopting information from 1979 to 2019. Shi et al. [23] examined the impact of technological innovation on CO_2 outputs in China's field of transport, utilizing data from 30 cities spanning 2012 to 2018. The results obtained from the geographical and temporal weighted regression (GTWR) model indicated that technological developments have decreased CO_2 emissions in the transportation sector, particularly in the eastern and northeastern areas. Nonetheless, similar improvements were not evident in other geographical territories. A hollow structure approximating an inverted U was noted in the correlation between the factors. Anser et al. [24] employed quantile regression to analyze the correlation between TI and CO_2 emissions from 2000 to 2017 across 26 European Union countries. At different quantiles, TI and CO_2 emissions exhibited a U-shaped relationship. Technological innovation reduces the release of CO_2. Lou et al. [25] employed the Spatial Durbin Model to analyze the correlation between technological innovation and CO_2 outputs in 30 high-tech zones of China from 2005 to 2016. The results indicated a general "inverted N-shaped" nonlinear association between TI and CO_2 pollution.

Nevertheless, several experts contend that TI may be incapable of alleviating environmental deprivation. Chen and Lee [26] examined the worldwide dynamics of technical advancements concerning CO_2 emissions using a spatial panel analysis. Their findings indicated that TI was ineffective in alleviating environmental deprivation in the overall sample, although it did demonstrate some efficacy in specific subsamples, including high-income, advanced-technology, and greater-CO_2 pollution countries. The researchers noted a decline in CO_2 emissions consequently. Adebayo et al. [27] employed the NARDL approach, with data from 1990 to 2018, to examine the influence of TI on CO_2 levels. The results indicated that TI was unable to reduce CO_2 emissions in Chile due to its lack of commitment to manufacturing sustainable innovations. Cheng et al. [28] emphasized that technological innovation exacerbates CO_2 releases in OECD territories.

Numerous studies have associated the influence of earth's assets on CO_2, yet its impact on EF has garnered minimal concern. For example: Erdogan et al. [29] in 23 African areas, Khan et al. [30] in 51 Belt and Road Initiative economies, Khan et al. [31] within the USA, Wang et al. [32] in the G-7, He et al. [33], and Shen et al. [34] concerning China. Kwakwa et al. [35] regarding Ghana; Caglar et al. [36] in BRICS; Awaosusi et al. [37] within Uruguay; Huang et al. [38] in the USA; Li et al. [39] in ASEAN economies. Mehmood [40] across G-11 nations, Ullah et al. [41] in the top 15 green energy usage nations, and Razzaq et al. [17] in extremely resource-intensive zones. They demonstrated that an excess of mineral resources results in the destruction of the surrounding ecosystem.

Majeed et al. [42] utilized the FMOLS and DOLS techniques to examine the correlation between natural wealth and CO_2 releases from 1971 to 2018. They highlighted that the availability of earth's resources enhances the ecosystem health in low- and middle-income regions, whereas it detrimentally affects high-income countries. Xiaoman et al. [43] implemented the continuously updated, fully modified (Cup-FM), and continuously updated bias-corrected (Cup-BC) techniques to analyze data from MENA nations from 1980 to 2018. The results indicate that natural resources diminish ecological quality. Conversely, Danish et al. [44] investigated mineral assets and loss of biodiversity in BRICS nations utilizing data from 1992 to 2016. They indicated that natural resources enhance environmental quality. Zafar et al. [45] emphasized a comparable outcome, which was ascribed to the proliferation of environmentally sustainable technologies.

In summary, numerous research examined the impact of technical advancements, earth's assets, and green electricity on the ecological condition, including Ibrahim et al. [46] within China, Abbasi et al. [47] concerning Pakistan, and Li et al. [12] in OECD regions; nevertheless, their conclusions were inconsistent. The discrepancies in findings can be ascribed to sample size, temporal factors, and methodological variation. Furthermore, the research investigating these links predominantly focuses on CO_2 emissions while overlooking the EF, which serves as a more accurate proxy of ecosystem damage. Moreover, none of this research empirically concentrated on the United States. This study is the inaugural examination of these factors in the USA utilizing the most recent data available. To address the technical limitations, we employed the ARDL approach, which enhances the comprehensiveness of the bound examination cointegration.

Methodology

Data, theoretical framework, and model

Time series data on the United States from 1980 to 2021 is utilized to examine the connection across the study's origins. This study confined this information due to the unavailability of data on technical advancement and renewable energy prior to 1980 and thereafter to 2021. Data regarding the EF (global hectares per capita) is sourced from the Global Footprint Network [48]; conversely, the World Development Indicators (WDI) database [49] is utilized to acquire information on development in technology, sustainable energy, GDP expansion, and natural resources.

Nonetheless, CO_2 has been employed as a proxy for environmental degradation in various research [50-53]. The ecological footprint (EF) simulation adopts a comprehensive technique for tackling temperature rise, surpassing the quantification of CO_2 outputs. The investigation illustrates the comparative effect of pollutants in relation to various human activities on the earth, encompassing food creation, fiber farming, material extraction, and property allotment for homes and transit systems. Consequently, in accordance with prior research [54-57], we employed EF as a substitute for biodiversity loss. Figure 1 illustrates the yearly pattern of EF in the United States.

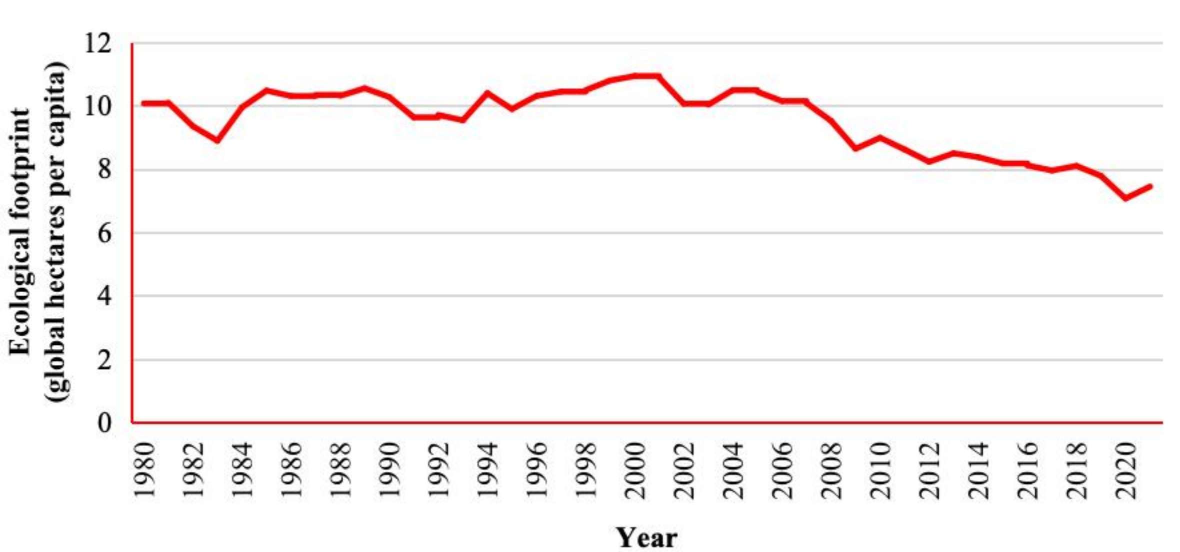

Figure 1. Annual trend of ecological footprint in the United States [48].

Furthermore, renewable energy is regarded as a feasible and cost-effective method for mitigating pollution. The adoption of RE innovations improves natural health by reducing emissions and simultaneously promotes power savings. Thus, promoting the application of alternative energy supplies can improve sustainability and contribute to the creation of a stable and healthy worldwide environment [58]. Therefore, employing it as a criterion for assessing ecosystem quality is suitable. Furthermore, modern evolution theories assert that responsible growth can be attained via technological improvement and heightened expenditure on research and development (R&D) [59]. Technological progress promotes the implementation of energy-efficient procedures and the development of clean technologies, hence diminishing pollution of the environment and energy usage [60]. Therefore, employing it as a criterion for assessing environmental quality is suitable. Figure 2 illustrates the yearly trend of renewable energy in the USA. Besides, Figure 3 shows the yearly pattern of technological innovation in the United States.

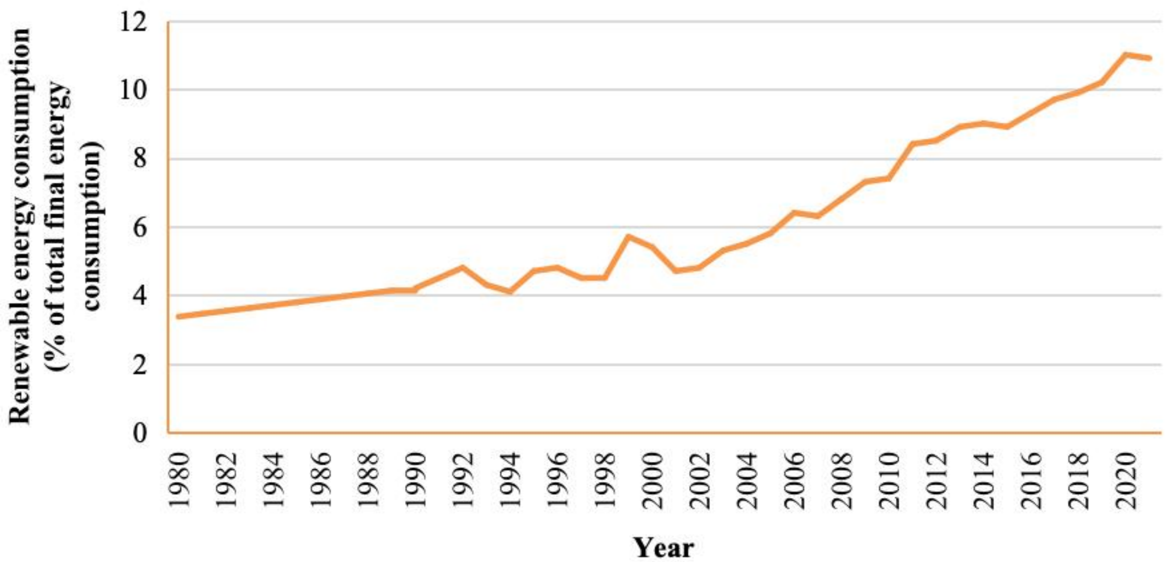

Figure 2. Yearly shift of renewable energy consumption in the United States [49].

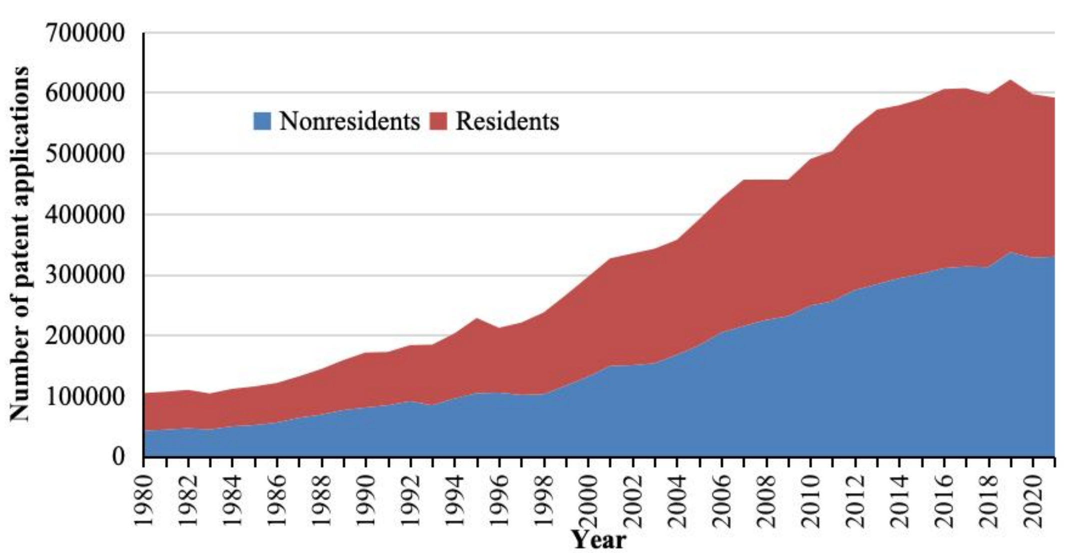

Figure 3. Annual pattern of technological innovation in the United States [49].

The relationship between economic progress and the environment is intricate, mostly due to the persistent environmental stresses resulting from economic growth [61]. Economic growth leads to alterations in the environment, increased resource consumption, and heightened pollution levels [62]. Consequently, employing it as a criterion for assessing environmental quality is suitable. Furthermore, due to the utilization and exportation of internal resources, nations rich in natural resources see rapid economic growth [63]. The ecosystem's sustainability is compromised by the reckless use of natural resources [64]. Therefore, it is essential to utilize mineral assets to assess the ecological criteria inside the United States. Figure 4 demonstrates the yearly tendency of GDP expansion in the USA. Besides, Figure 5 presents the annual shift of earth's resource rents in the USA.

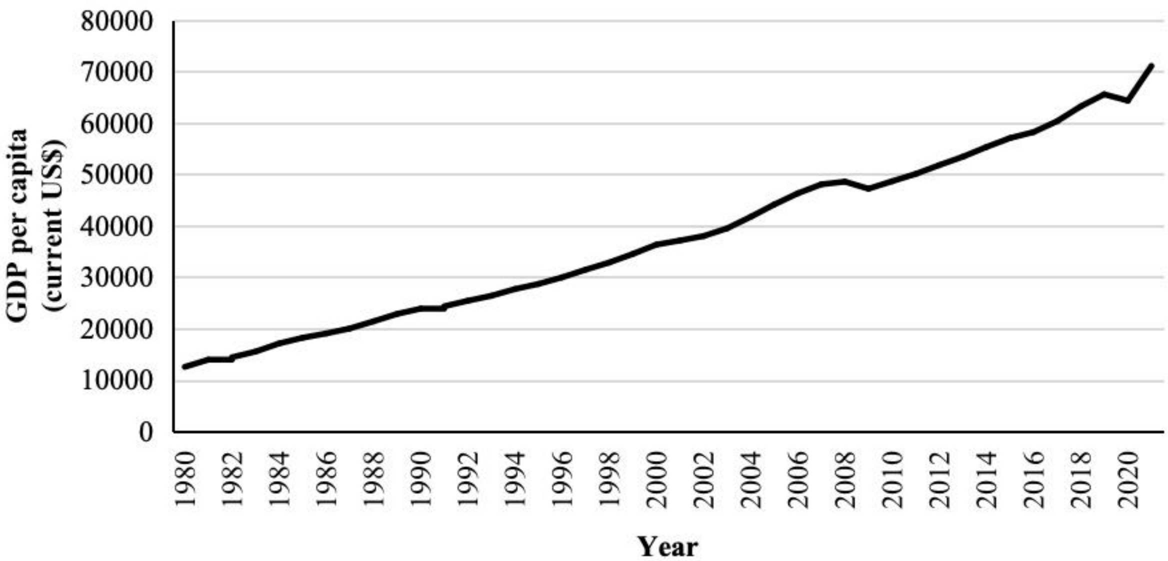

Figure 4. Annual trend of economic growth in the United States [49].

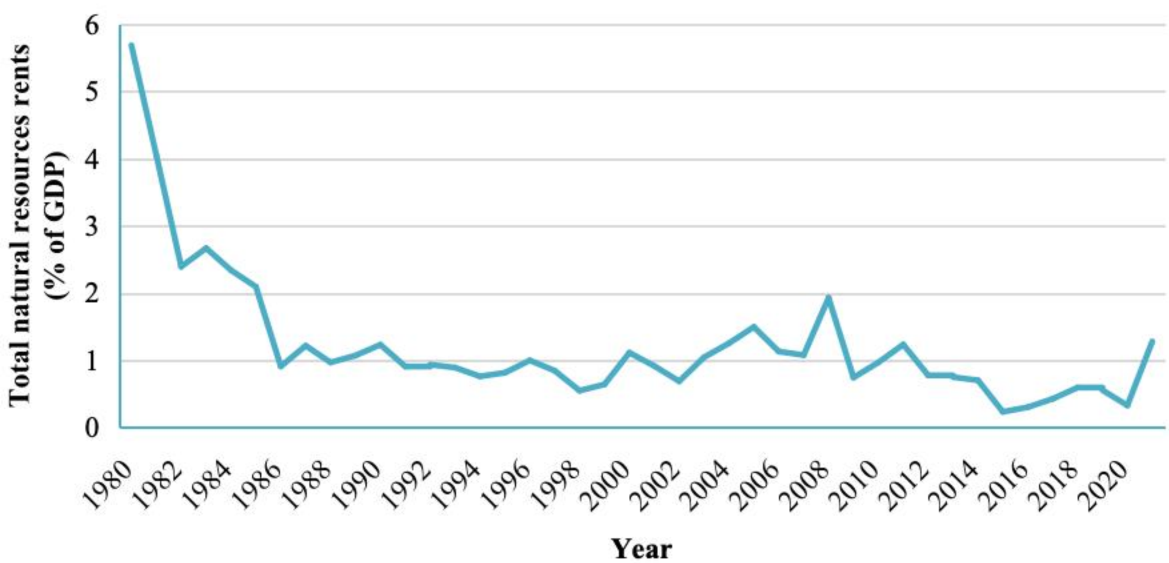

Figure 5. Yearly pattern of natural resource rents in the United States [49].

This research is based on the principles of a sustainable future, which examines the interplay between manmade activity and natural health. The discussion promotes the prioritization of sustainability and highlights the importance of recognizing the probable consequences of human actions on ecological systems. Due to the adverse effects of ecosystem degradation, it is essential to identify the indicative reasons for this and develop proactive strategies. Current scholarly work and advancements in the USA suggest that the extent of the decline in environment in the country depends on several factors, including technological innovation in information technology (IT), the adoption of RE supplies, the rate of GDP rise, and the availability of natural resources (NR). This study aims to analyze changes in the EF of the United States due to technological advancements, increased use of green power, GDP expansion, and NR extraction. The fundamental econometric framework utilized in this study is delineated as follows:

$$EF_t = \tau_0 + \tau_1 Y_t + \tau_2 NR_t + \tau_3 RE_t + \tau_4 TI_t + \varepsilon_t \quad (1)$$

In equation (1), EF denotes the ecological footprint (global hectares per capita) as assessed by the environmental effect. Y denotes economic growth, characterized by an increase in a nation's total production, typically manifested as GDP growth. The metric of evaluation is GDP per capita (current US dollars). NR is defined as the aggregate revenue derived from the sale of oil, natural gas, coal, minerals, and timber. The unit of measurement is the percentage of GDP. Furthermore, RE denotes clean power usage as a percentage of total energy, characterized by energy derived from renewable resources that regenerate at a rate beyond their consumption, hence mitigating environmental hazards such as carbon emissions. Technological innovation (TI), quantified by the total number of patents (including resident and nonresident), is characterized by the modernization of industrial structures and structural adjustments within a cohesive, rigorously controlled market framework, ultimately aimed at reducing pollutant emission intensity. In addition, τ_0 and ε_t are the intercept and error terms. Besides, τ_1, τ_2, τ_3, and τ_4 are the coefficients. All the variables were transformed into their logarithmic forms before conducting the analysis.

Earth's assets encompass minerals, fossil fuels, and forests, and they are essential to economic operations. However, it has numerous repercussions on the ecology, including habitat degradation, pollutants, and global warming. The exhaustion of materials, along with their environmental impact, renewed the necessity to shift to eco-friendly behaviors. Habitat degradation and ecosystem damage occur when surroundings are compromised to enable exploitation, resulting in the demise or dispersion of species and altering landscapes. Contamination is a characteristic consequence of asset exploitation and manufacturing operations, and chemical usage during the extraction process frequently produces harmful substances that contaminate water bodies, air, soil, and aquatic ecosystems. Moreover, the combustion of fossil fuels induces CO_2 emissions, which are a principal contributor to climate issues [65]. Consequently, we posited a positive correlation between NR and EF.

Conversely, technical innovation and renewable energy are crucial in addressing the adverse impacts of Earth's assets on EF. The implementation of novel strategies in materials misuse, power conversation, and trash handling aids in alleviating the adverse impacts linked to the extraction and adoption of natural resources. Advancements accelerate the advancement of greener and more productive technology by promoting green methods and mitigating environmental degradation. Moreover, sources of renewable energy deliver nature-friendly substitutes to fossil fuels, hence reducing CO_2 releases and combating climate change [66]. The evolution of green energy signifies a novel approach to dissociating monetary expansion from environmental degradation [67]. The authors postulate that technological progress and clean power diminish the ecological footprint in the USA.

Econometric strategies

The paper used the ARDL methodology [68] to analyze the dynamic impacts of NR, RE, TI, and GDP on the ecological footprint. Two prerequisites must be met before executing the ARDL simulation on a time series set of data. The endogenous parameter may exhibit non-stationarity at the level I(0) but must achieve stationarity at the first difference, I(1). Secondly, a sustained connection should exist among the examined variables. Three statistical tests were implemented to explore the stationarity of the variables: the augmented Dickey-Fuller (ADF) test [69], the Dickey-Fuller generalized least squares (DF-GLS) test [70], and the Phillips-Perron (P-P) test [71]. These methods are essential to mitigate erroneous regression consequences arising from non-stationary qualities, thus enhancing the model's stability and resilience.

Upon verifying that the variables exhibit stationarity at the initial difference, the cointegration among the variables is subsequently assessed utilizing the ARDL bounds test [33]. Upon verifying the stationarity and cointegration assumptions, it is necessary to estimate the ARDL model for immediate and long-period impacts of the variables. The ARDL simulation effectively captures temporal fluctuations and provides estimates for both long-run and short-run coefficients, facilitating the examination of the distinct effects of the chosen variables and their intricate interactions, hence allowing for a comprehensive analysis of their consequences [68]. The ARDL bounds framework, utilized to illustrate the long-term associations within the selected variables, is delineated as follows:

$$\Delta EF_t = \tau_0 + \tau_1 EF_{t-1} + \tau_2 Y_{t-1} + \tau_3 NR_{t-1} + \tau_4 RE_{t-1} + \tau_5 TI_{t-1} + \sum_{i=1}^{q} \gamma_1 \Delta EF_{t-i} + \sum_{i=1}^{q} \gamma_2 \Delta Y_{t-i} + \sum_{i=1}^{q} \gamma_3 \Delta NR_{t-i} + \sum_{i=1}^{q} \gamma_4 \Delta RE_{t-i} + \sum_{i=1}^{q} \gamma_5 \Delta TI_{t-i} + \varepsilon_t \quad (2)$$

This technique employs the first-difference operator (Δ) to describe temporal variations in the factors and the optimal lag length is denoted by "q."

This investigation demonstrates that the ARDL methodology can provide estimates for both long-run and short-run coefficients of the parameters to facilitate impact comparison. The null hypothesis (H0) under the ARDL bounds posits the absence of cointegration among the variables, whereas the alternative hypothesis (H1) asserts the existence of cointegration amongst all of the variables. After identifying the sustained equilibrium linkages across the chosen parameters, a bounds test is conducted prior to utilizing the ARDL method to ascertain the short- and long-run coefficients. The integration of the error correction term (ECT) in the equation of the ARDL model employed for analyzing short-run dynamics can be expressed as follows:

$$\Delta EF_t = \tau_0 + \tau_1 EF_{t-1} + \tau_2 Y_{t-1} + \tau_3 NR_{t-1} + \tau_4 RE_{t-1} + \tau_5 TI_{t-1} + \sum_{i=1}^{q} \gamma_1 \Delta EF_{t-i} + \sum_{i=1}^{q} \gamma_2 \Delta Y_{t-i} + \sum_{i=1}^{q} \gamma_3 \Delta NR_{t-i} + \sum_{i=1}^{q} \gamma_4 \Delta RE_{t-i} + \sum_{i=1}^{q} \gamma_5 \Delta TI_{t-i} + \theta ECT_{t-1} + \varepsilon_t \quad (3)$$

Here, θ represents the coefficient of the ECT, indicating the rate at which a system reverts to its long-term equilibrium after experiencing short-term disruptions.

Ultimately, multiple diagnostic assessments were conducted to verify the robustness of the ARDL model and the reliability of the statistical findings. For instance, the diagnostic assessments evaluate normality, heteroskedasticity, and correlation inside the model.

Results and discussion

Before initiating any regression analysis, it is essential to thoroughly investigate the underlying properties of the parameters and their relationships. Table 1 shows the results of overall statistics within the factors, in tandem with the values of statistics derived from numerous normality examinations. Skewness values adjacent to zero suggest that all variables deploy a normal distribution. Moreover, the results demonstrate that all series demonstrate a platykurtic distribution, evidenced by their kurtosis values falling below 3. Moreover, the reduced Jarque-Bera statistics and probability values beyond 0.1 suggest that all variables demonstrate a normal distribution.

The conclusions of the unit root testing are displayed in Table 2. It illustrates that the parameters are non-stationary at the I(0) but stationary at the I(1), as the test statistics for ADF, DF-GLS, and P-P at I(1) are significant. Consequently, all variables satisfy the requisite conditions for the application of the ARDL model, thereby validating their integration of order I (1).

Table 1. Summary statistics of the variables.

Variables	EF	Y	NR	RE	TI
Mean	2.25	10.43	-0.01	1.73	12.54
Median	2.30	10.51	-0.05	1.62	12.65
Maximum	2.39	11.17	1.74	2.40	13.34
Minimum	1.95	9.44	-1.45	1.22	11.55
Std. Dev.	0.11	0.48	0.63	0.37	0.62
Skewness	-0.82	-0.38	0.38	0.41	-0.22
Kurtosis	2.52	2.04	2.93	1.80	1.61
Jarque-Bera	4.15	2.64	2.55	3.71	3.69
Probability	0.17	0.27	0.29	0.16	0.16
Observations	42	42	42	42	42

Note: EF = ecological footprint, Y = economic growth, NR = natural resources, RE = renewable energy, TI = technological innovation, *** indicates significance at a 1% level.

Table 2. Results of unit root tests.

Variables		EF	Y	NR	RE	TI
ADF	I(0)	-0.82	-0.56	-0.82	-0.95	-0.86
	I(1)	-7.65***	-5.46***	-7.35***	-4.84***	-5.53***
DF-GLS	I(0)	-0.93	-0.65	-0.54	-1.19	-1.30
	I(1)	-6.75***	-4.07***	-5.93***	-4.32***	-4.98***
P-P	I(0)	-0.83	-0.56	-0.83	-0.93	-0.83
	I(1)	-7.76***	-5.63***	-7.35***	-4.86***	-5.56***

Note: ADF = Augmented Dickey-Fuller test, DF-GLS = Dickey-Fuller generalized least squares test, P-P = Phillips-Perron test, EF = ecological footprint, Y = economic growth, NR = natural resources, RE = renewable energy, TI = technological innovation, *** indicates significance at a 1% level.

Following the confirmation of data stationarity by unit root examinations, this research adopted the ARDL bounds test to analyze the long-term relationship among the variables. Table 3 presents the empirical findings from the application of ARDL limit test methods for cointegration. The computed F-statistic is greater than the upper critical constraint, indicating the presence of long-term cointegration among the variables.

Table 3. Results of ARDL bounds test.

Test statistic	Estimate	Significance levels	I(0)	I(1)
F-statistic	4.79	10%	2.20	3.09
K	4	5%	2.56	3.49
		2.5%	2.88	3.87
		1%	3.29	4.37

Upon verifying the cointegration of the investigated factors, the ARDL simulation for both long- and short-run analysis was implemented. Table 4 represents the outcomes of the work conducted using this model. The findings indicated that GDP exerts a significant and positive influence on the ecological footprint. It observes that a 1% rise in GDP correlates with a 0.86% rise in the EF of the USA in the near term and a 1.11% increase over time. This study also revealed that NR significantly and adversely impacts the EF of the United States economy. For each 1% augmentation in the utilization of NR, ecological damage in the USA will escalate by 0.07% immediately and 0.09% in the long term.

Furthermore, the conclusions of the ARDL examination deployed that RE exerted a considerable adverse effect on the ecological footprint. The study showed that, in the short term, a 1% application in RE decreased the EF of the US environment by 0.13%; however, in the long term, it resulted in a reduction of 0.29%. Additionally, the findings indicate that the coefficients of technical advancements are both inverse and significant, which aligns

with anticipated outcomes. Consequently, technological progress substantially influences the EF of the USA. Each 1% rise in technological innovation will cause a 0.32% reduction in ecological damage in the short term and a 0.48% decrease over time in the United States.
These outcomes demonstrate that sustainable energy usage positively impacts the enhancement of ecological sustainability in the United States. Conversely, research demonstrated that economic expansion negatively impacts the natural health of the USA. The findings of this paper offer valuable recommendations for the USA to enhance its policies promoting renewable energy utilization. A key conclusion is that the USA ought to utilize technical innovation and the development of natural resources to promote environmental sustainability. The present study indicates that the United States ought to formulate power strategies that enhance the utilization of alternative energy while diminishing reliance on polluting sources.
The authors obtain the ECT at -0.65 and find it significant at 1% thresholds, providing solid evidence of a steady relationship between the exogenous factors and the EF. It suggests that shifts in these variables can trace around 65% of durable changes in EF. The R^2 value of 0.96 and the adjusted R^2 of 0.95 reflect the better match of the regression model to the data. A few diagnostic methods, stated in Table 5, declare the model's credibility: The Jarque-Bera test shows that the data is normally distributed; the Breusch-Godfrey LM test shows that there is no serial correlation, the Breusch-Pagan-Godfrey test shows that the data is homoscedastic, and the Ramsey RESET test shows that the model is right for this analysis.

Table 4. Results of ARDL long and short-run analysis

Variables	Long-run			Short-run		
	Coefficient	t-statistic	p-value	Coefficient	t-statistic	p-value
Y	1.11***	3.64	0.00	0.86***	3.75	0.00
NR	0.09***	3.35	0.00	0.07***	3.62	0.00
RE	-0.29***	-4.56	0.00	-0.13***	-4.31	0.00
TI	-0.48***	-4.73	0.00	-0.32***	-4.74	0.00
C	12.34	1.35	0.10	-	-	-
ECT (-1)	-	-	-	-0.65***	-3.92	0.00
R^2	0.96					
Adjusted R^2	0.95					

Note: Y = economic growth, NR = natural resources, RE = renewable energy, TI = technological innovation, ECT = error correction term, *** indicates significance at a 1% level.

Table 5. Diagnostic test results.

Diagnostic tests	Coefficient	p-value	Decision
Jarque-Bera	0.53	0.24	Normal distribution residuals
Breusch-Godfrey LM	0.64	0.56	No autocorrelation
Breusch-Pagan-Godfrey	0.27	0.24	No heteroscedasticity
Ramsey RESET	0.52	0.46	The model is properly specified

Note: LM = lagrange multiplier, RESET = regression equation specification error test.

The results of this investigation indicate that economic expansion has a favorable impact on the EF. The results indicate that the association is likely in the United States, which is experiencing rapid expansion and has demonstrated robust growth in GDP in recent years. The finding aligns with prior research which reported that economic growth increases ecological footprint [72-82]. The United States possesses the largest economy globally, with a GDP of 25.44 trillion USD and an annual GDP growth rate of 1.9% in 2022. Consequently, the findings indicate that the concentrated emphasis on catastrophic climate change enhances the comprehension of the ecological consequences of financial expansion between economists and lawmakers. Consequently, their perspectives transition from the simple pursuit of prosperity to a focus on ecologically sustainable development in the economy. The results affirm that the United States has strategies aimed at sustainable economic development.

The Under Secretary of State for Economic Development, Energy, and Sustainability oversees the State Office's worldwide initiatives on prosperity, power, farming, the sea surroundings, and technological advances.

This analysis also revealed that NR rents adversely affect the ecosystem of the United States. This process is significant as the extraction of natural resources would promptly stimulate economic growth, resulting in heightened environmental degradation. While the escalation of extraction activities may yield certain benefits for economic development, it also presents disadvantages for the ecosystem. The present study's finding aligns with prior investigations [78-91]. The results of this study validate the current environmental policy of the United States. The United States government established the Resource Conservation and Recovery Act, which adopts the Environmental Protection Agency (EPA) to oversee the management of hazardous and non-hazardous waste. Furthermore, it oversees and regulates multiple facets of garbage administration, encompassing the generation of trash, transport, storage, and removal operations. Furthermore, industrialization leads to the overexploitation of the earth's assets, significantly elevating pollutants in the region. The outcomes of the investigation indicate that the extraction of natural wealth, including gas, oil, coal, and other valuable materials, is responsible for environmental degradation, biodiversity loss, deforestation, and soil erosion in the United States. Consequently, effective regulations and strategies are essential to mitigate the harm caused by extraction activities and to safeguard individuals from environmental threats.

This study concluded that renewable energy improves the ecosystem condition of the USA. The utilization of alternative and clean energy sources will reduce the environmental impact in the United States, thereby contributing to the protection of the ecosystem. The discovery aligns with prior research [81,82,91-100]. Pollution-free energy and minimal ecological effects are two defining characteristics of clean and sustainable power supplies. The USA is advancing towards its Sustainable Development Goals (SDGs) by enhancing its clean electricity facilities. It demonstrates that the utilization of renewable and sustainable energies reduces carbon emissions. The findings of the analysis illustrate that the US economy is transitioning from fossil fuels to green and environmentally sustainable power supplies, which may reduce the surrounding effect of individual behaviors. Consequently, it is recommended that the United States augment its renewable energy consumption capacity by investing in advanced, cleaner technologies, fostering a sustainable, healthy ecosystem. A nation rich in minerals is concentrating on attaining greener energy goals by lowering levies, providing money, and enhancing financial assistance for clean energy companies. These results validate the actions implemented by the United States government. The principal aim of the American Clean Power Association is to promote policies that enable the transformation of the power grid of the USA into economical, reliable, and sustainable electricity operations. It seeks to promote the use of clean power technology at the national, regional, and state levels. It emphasizes the promotion and advocacy for the development and implementation of renewable and clean energies in the United States. Implement reforms in legal structures, regulatory processes, and siting procedures to reduce barriers to entry. Furthermore, to promote increased investment and production of renewable energy technology, it is essential to provide a stable market environment.

The study's results indicate a negative correlation between TI and EF. The investigation result reveals that technical development in the USA contributes to diminishing the nation's ecosystem by implementing energy-efficient gadgets. The results of this investigation align with prior studies [18,19,22,23,77,78,101-108]. Furthermore, it is evident that in this nation, technological advancements and environmental legislation are primarily focused on achieving industrial development, taking into account their mitigating effects on ecological footprints. Moreover, empirical evidence substantiates the necessity of enhancing technological processes to mitigate technology obsolescence in response to rising economic expansion and ecological mandates over the long run. Furthermore, to mitigate the impact of ecological contaminants, this nation must enhance the implementation of breakthrough technologies and substitute obsolete technologies through public-private partnerships to advance clean and sustainable energy options. These activities will reduce and mitigate levels of pollutants in the country. Furthermore, the government should bolster the business by establishing a definitive regulatory structure that diminishes ecological impact throughout the ensuing times and continuously endorses innovative technologies that enhance environmental sustainability.

Conclusions and policy recommendations

This study examines the dynamic effects of natural resource rents, innovation in technology, renewable energy, and GDP expansion on the ecological footprint in the United States. This study utilized the ARDL framework, analyzing data from 1980 to 2021. The results indicate that the application of modern technology and clean power supplies is required to minimize environmental damage and promote sustainable growth in the economy of the United States. The nation must leverage greater technical innovation to attain an environmentally sustainable future. Conversely, the findings indicated that natural resource rents in the USA adversely affect environmental quality. The study demonstrates that resource exploitation and extraction result in ecological damage. The extraction of natural resources is significant since it would promptly stimulate economic expansion, resulting in heightened environmental degradation. The environment bears increased extractive activities despite potential fiscal growth. Consequently, regulations and measures are proposed to mitigate the detrimental effects of extraction activities and safeguard individuals from environmental threats.

The empirical data presented in this paper advocates for policy modifications to attain eco-friendly and financial goals. The research endorses the notion that clean energy usage could serve as a crucial and affordable electricity resource for sustained environmental policy and evolution to address increasing worldwide energy demands. Consequently, authorities, conversation agencies, corporate entities, and businesses should be forcefully urged to allocate resources towards the development of green energy infrastructure and initiatives while also reducing constraints on the assessment of alternative energy sources without compromising development prospects. Furthermore, prospective financiers and stakeholders must be encouraged to recognize and participate in viable ways to use greener resources through public-private partnership (PPP) arrangements.

Furthermore, political entities in the USA must promptly prioritize the enhancement of environmental benefits derived from technical developments to bolster ecological sustainability. Consequently, state law should fiscally endorse the proliferation of novel technological initiatives to foster harmony within reduced emissions and accelerated monetary expansion. The credit distribution technique for production units must account for technology advancements when assessing fuel efficiency to promote enhanced technological solutions. Furthermore, lawmakers in the United States must endorse private sector projects aimed at discovering superior, cleaner sources of energy and environmentally sustainable technology, thus facilitating environmental preservation.

Ultimately, the expansion of the mining sector (oil, gas, coal, and minerals) could enhance GDP development. Nonetheless, it also adversely affects the natural world, resulting in a decline in ecology, environmental inequality, forest loss, and erosion of soil in the United States. The paper advocates for states, ecologists, and politicians to formulate plans and regulations aimed at diminishing the extraction of natural resources and soil erosion while identifying the most effective environmentally sustainable alternatives that promote biodiversity. Furthermore, it is advisable for the nation to enhance afforestation efforts to rectify the environmental imbalance. These efforts will assist the United States in achieving the specified targets outlined in SDG 7 (cost-effective and clean energy), SDG 8 (decent work and economic growth), SDG 9 (industry, innovation, and infrastructure), and SDG 13 (climate action).

Nonetheless, the current study possesses certain limitations. The current study utilized the timeframe from 1980 to 2021. The current effort is limited by the unavailability of data on technological innovation prior to 1980 beyond 2021. Consequently, the latest statistics on EF, if accessible, can be utilized in forthcoming investigations. The study additionally employed annual data for the United States. Consequently, new regions may be incorporated in forthcoming scholarly work contingent upon data accessibility. The ARDL approach is employed in the current research to assess the connections among the factors analyzed in the United States. An upcoming analysis should concentrate on exploring how several estimation panel methodologies, along with those of both developed and emerging nations, might be utilized to evaluate the influence of natural resources, renewable energy, and technical advancements on the ecological footprint across a selection of regions.

Funding: Not applicable.
Acknowledgment: Not applicable.
Conflict of Interest: The authors declare no conflict of interest.

Authors' contributions: Asif Raihan contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Filiz Guneysu Atasoy, Murat Atasoy, Asif Raihan, Khayruzzaman, Mohammad Ridwan, Tipon Tanchangya, Junaid Rahman, Md. Shoaibur Rahman, Md. Zia Uddin Foisal, Babla Mohajan, Samanta Islam, Arindrajit Paul, and Abdullah Al Jubayed. All authors read and approved of the final manuscript.
Data availability statement: Data supporting this manuscript will be provided upon reasonable request from the corresponding author.

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