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The impact of natural resource rents on environmental degradation in case of USA: The role of technological innovation and renewable energy consumption

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Abstract

This study explores the impact of natural resource rents on CO_2 emissions in the presence of renewable energy consumption, technological innovation, and gross domestic product (GDP) in the case of the USA from 1990 to 2020. For sustainable development policies and to slow down environmental degradation, it is important to understand the intricate connection between resource rents and carbon emissions in the US. Thus, this study hypothesizes that after controlling for renewable energy consumption, technological innovation, and GDP, among other variables, resource rents significantly contribute to carbon dioxide emissions in America. This study adds significantly to the existing literature on how resource rents affect CO_2 emissions in the United States. This study employs quantile regression estimation techniques, which provide vital policy insights and academic contributions that are relevant to sustainable development and environmental conservation from both national and global perspectives. The results show that natural resource rents (NNRs) and GDP are positively associated with CO_2 emissions at all quantiles. Moreover, the results indicate that technological innovation and renewable energy consumption are important in curbing CO_2 emissions.

Keywords: CO_2, Gross domestic product, Natural resource rents, Renewable energy consumption, Technological innovation.

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Contents

Contribution of this paper to the literature
The study adds significantly to the literature on how resource rents affect CO_2 emissions in the United States. Previous studies on resource rents and environmental degradation in the case of the United States have not focused on renewable energy and technological innovation.

1. Introduction

The total natural resources rent-CO_2 emissions relationship is about the connection between a nation's revenue gained from natural resources and the carbon dioxide produced. This is a multifaceted process closely linked to factors like economic growth, ecological policies, and legal systems. Natural resources rent is a theoretical concept representing the economic benefit gained through the utilization of resources like oil, natural gas, and coal, as well as oil-producing minerals and forests. These rents can make up the largest portion of the revenue of resource-rich countries, sparking concerns about the environmental impact on other nations. The extraction of these resources is one of the leading reasons for CO_2 emissions. Greenhouse gases, as the primary factor responsible for climate change, present unprecedented risks to human development and survival, such as the extinction of animal and plant species, famines, and extreme weather conditions (Rjoub, Adebayo, Awosusi, Panait, & Popescu, 2021).

All the countries whose economies heavily rely on fossil fuels have the highest amounts of CO_2 emissions, as the processes of extraction, distillation, and usage cause a significant amount of CO_2 emissions. The countries with high extraction rates of oil, natural gas, and coal are the top offenders, as these three resources are some of the most CO_2-intensive productions. Additionally, the extraction of forestry resources, such as timber, is also a factor, as it results in the detrimental effects of deforestation, reducing carbon sinks. A growing economy based on natural resources is being stimulated by various industrial sectors, increasing the consumption of energy, which also causes greater demand for fossil fuels. This is particularly visible in the expanding economies of natural resources, where industries and transportation infrastructures related to heavy industry are growing.

In environmentally governed countries, it was easier to untangle the natural resource rent measure from the emission of CO_2 (Khaddage-Soboh, Safi, Rasheed, & Hasnaoui, 2023). The findings can respond to the fact that such measures can unlock codes of practice that can yield lower environmental pollution, such as well-managed resource handling, sustainable practices of extraction, renewed investments, and sustainable measures to prevent deforestation. The total natural resources rent measure can, however, impact CO_2 emissions, but with varying effects between countries. These differences are attributed to the type of resource harvested and the country's economic structures and policy architectures. For instance, countries with higher primary products like oil and coal can have higher CO_2 emissions than countries processing energy from hydropower. Additionally, diversified economies may have a lower reliance on natural resource exploitation, thus lowering CO_2 emissions. Climate change and escalating global warming necessitate the formulation and implementation of fiscal measures to mitigate their adverse effects (Chen, Mirza, Huang, & Umar, 2022).

This implies that nations with strong environmental regulations may have decoupled most of their resource rent measures from CO_2 emissions. Various strategies can be employed to mitigate the environmental impact of natural resource rent. Promoting renewable utilization is essential to reduce the reliance on fossil fuels. Similarly, ensuring sustainable measures in extraction and forest management can minimize the environmental impact. Finally, strong environmental regulations can ensure compliance and encourage green measures while investing in green technology. A good example of green technology is the technology that captures CO_2 from the atmosphere for its utilization, or renewable energy infrastructure, which can pave the way for low-emission activities. Generally, such measures can reduce the environmental burden of resource exploitation, moving progressively towards sustainability.

The extraction activities of materials are among the chief revenue generators in several U.S. states with substantial natural resource reserves (Schulz, 2017). However, the financial-related benefits raise issues regarding the suitability of the release of the products generated in the atmosphere, as they disrupt the environment. Production activities of the resources generate a significant percentage of CO_2 emissions in the U.S. The American economy has historically relied on fossil fuels for domestic consumption and foreign sales (Adebayo, Oladipupo, Adeshola, & Rjoub, 2022; Polack, Wood, & Smith, 2010). As a result, the country has a huge carbon footprint. Oil, natural gas, and coal are notorious pollutants. Forest extraction through logging results in a reduction of carbon-absorbing capacity and an increase in the amount of CO_2 in the atmosphere simultaneously. Economic growth is directly related to the increased amount of CO_2 emissions. As the American economy expands, energy demand also increases as the nation remains dependent on fossil fuels.

The role of environmental regulations is essential in mediating the relationship between total natural resource rents and CO_2 emissions in the U.S. (Awosusi et al., 2022; Khaddage-Soboh et al., 2023). Nevertheless, the efficiency of environmental oversight in the states varies, which may lead to both mitigation and exacerbation of the impact. In general, states with stronger environmental policies and a larger body of experience in sustainability tend to decouple resource rents from CO_2 emissions, such as reducing the total amount of rent and incorporating practices that contribute to environmental friendliness. For example, some of the most effective strategies for reducing the impact of emissions related to resource rent are cutting-edge resource management practices, sustainable methods of extraction, and the generation of renewable energy. Furthermore, these states also employ other strategies to keep the total amount of forest the same or increase it; this means that responsible logging and deforestation are in their past. On the other hand, many aspects determine the intensity of the link between total natural resources rent and CO_2 emissions in Agboola, Bekun, and Joshua (2021). First of all, one should consider the type of natural resources that a state produces. The highest levels of emissions are in the states that are dependent on oil and coal, while the lowest are in the states producing energy with the help of hydropower. This might not only depend on the type of resources but also on the role of natural resources extraction in a certain type of economy: if the economic activity is only a part of the economy and the specialization is high, we observe much less decoupling than in the type of countries where the specialization is flexible. The last factor to consider is environmental regulations. To reduce emissions, environmental standards need to be tightened. Ways of decoupling total environmental impact from CO_2

emissions in relation to total natural resources rent in the US include investing in renewable energy, resource sustainability, sustainable forest management, and rigorous environmental policies.

As the world grapples with promoting green, sustainable growth to curb anthropogenic climate change, the consumption of renewable energy (REC) is a much better way to replace fossil fuel utilization. This issue presents a key challenge for policymakers, energy researchers, and industry players regarding ways to reduce CO_2 emissions by using renewable energy (Owusu & Asumadu-Sarkodie, 2016). Renewable energy use as a means of reducing carbon dioxide emissions is now at an important crossroads between policy and energy transition. The potential for renewable energy to result in lower CO_2 emissions arises because most types of renewable energy (RE) can substitute fossil fuel combustion in three major consuming sectors: power generation, transportation, and manufacturing (Hu, Sinha, Tan, Shah, & Abbas, 2022). Understanding this relationship is crucial for shaping effective policies to decarbonize global energy consumption.

When it comes to tackling the many challenges of environmental sustainability and climate action, technological innovation is likely to remain one of the most important tools for reducing carbon dioxide (CO_2) emissions (Raihan, Begum, Said, & Pereira, 2022). In the face of overwhelming preoccupation with climate change, innovation – or, more specifically, the ability of new technologies to decrease emissions in every corner of our society – has emerged as a topic of great interest to academics, policymakers, and industrial decision-makers. Indeed, there is a widespread belief that new technologies will enable society to dramatically reduce CO_2 emissions and support the transition to a more sustainable future. This is particularly true in the energy, transport, industry, and consumption sectors.

For sustainable development policies and to slow down environmental degradation, it is important to understand the intricate connection between resource rents and carbon emissions in the U.S. Thus, this study hypothesizes that after controlling for renewable energy consumption, technological innovation, and GDP, among other variables, resource rents significantly contribute to carbon dioxide emissions in America.

This study explores the impact of natural resource rents on CO_2 emissions in the presence of renewable energy consumption, technological innovation, and GDP in the case of the USA over the period from 1990 to 2020. The rationale behind selecting this sample size for the current study can be supported by several factors: a three-decade span provides a wide range of data for a strong statistical study. It is efficient in extracting long-term patterns and fluctuations, which are important for understanding the association among natural resource rents, CO_2 emissions, renewable energy consumption, technological innovation, and GDP. This timeframe includes major American environmental policy changes regarding energy use as well as technological progress; such policies include the climate action plans for cleaner air enacted through the Clean Air Act Amendments (Oren, 1991), among others, like incentives for clean power generated from sustainable sources. The researchers chose the 30-year period to account for rapid advancements made technologically alongside the shift towards renewable energy. In energy efficiency alone, there were many significant breakthroughs during the 1990s and beyond, mainly related to power conservation methods and other alternative sources such as wind turbine generators and solar panels. The study adds significantly to the literature on how resource rents affect CO_2 emissions in the United States. Previous studies on resource rents and environmental degradation in the United States have not focused on renewable energy and technological innovation. Therefore, the current study contributes to the existing literature by investigating the relationship between CO_2 and resource rents while controlling for the effects of renewable energy and technological innovation. This study employs advanced estimation methods such as Movement Quantile Regression (MMQR) and Bootstrap Quantile Regression (BSQR) estimation techniques, which provide vital policy insights and academic contributions that are relevant for sustainable development and environmental conservation from both national and global perspectives. Identifying risks associated with resource extraction by assessing the environmental consequences of extracting resources from the natural environment will help promote responsible resource use that may facilitate a more sustainable economy. The impact is not only confined to academia or policymaking but also affects other key players like industry leaders, environmental advocates, and even the general public. Decoupling environmental destruction from economic growth, as mandated by sustainable development goals, demands an understanding of how resource rents translate into CO_2 emissions. If we truly want to make a difference within our borders and internationally, then it is high time we addressed the relationship between resource rents and CO_2 emissions. Given its status as one of the world's biggest carbon dioxide emitters, the government of the United States has significant implications when it comes to global climate change patterns. These findings directly relate to policies that enable sustainable development and address environmental degradation in America. By clearly stating how much resource rents contribute to carbon dioxide emissions, policymakers will have more focused interventions and regulations that encourage cleaner energy sources, stimulate efficient use of resources, or raise energy prices without hampering economic growth.

The rest of the manuscript is organized as follows: the next section provides a detailed overview of previous literature. Section 3 presents the model, data, and econometric tests. Section 4 provides the results and discussions. The last section presents the conclusions of the study.

2. Literature Review

Insights on the relationship between environmental sustainability and resource rents can be derived from literature on the effects of natural resource rents on CO_2 emissions. In this context, to explore the relationship between CO_2 emissions and resource rent, Bekun, Alola, and Sarkodie (2019) confirm that there is a positive significant relationship between the nation's natural resources rent and CO_2 emissions in the long run. Thus, the dependency on natural resources rent poses a threat to the environmental sustainability of the panel countries if the conservation and management options are not considered. The study by Nwani, Bekun, Gyamfi, Effiong, and Alola (2023) on sustainable natural resource use and the impact of natural resource rents on carbon emissions found that 0.022 percent and 0.035 percent in territorial and consumption-oriented production inventories, respectively, of the overall carbon emissions of resources are driven by economic dependence on natural resource rents. The study substantiates that the environmental impact of NRRs is more intense if CO_2 emissions are corrected for trade across the countries. Ultimately, the study motivates that policies need to be introduced in order to keep natural resources within sustainable limits.

Mahmood and Saqib (2022) studied the entire group of economies belonging to the oil-producing and exporting cartel (OPEC). They found that focusing on economic activities alone, whenever performing an emissions analysis, largely ignores the true role of oil rents. The basic idea is that the higher the oil rents, the more CO_2 emissions will be boosted in Libya, Kuwait, Iraq, Iran, Equatorial Guinea, Congo, and Saudi Arabia. Conversely, there is a larger negative effect of oil rents on CO_2 emissions in the United Arab Emirates, Nigeria, and Algeria. The analysis of the link between rents from natural resources and emissions was conducted by Ulucak and Ozcan (2020) for Organisation for Economic Co-operation and Development (OECD) countries using Augmented Mean Group (AMG) estimators, which showed that natural resource rents degrade the environment. Shen et al. (2021) found in their provincial panel analysis for China during 1995–2017 that there is a positive relationship between natural resource rents and environmental degradation. Tufail, Song, Adebayo, Kirikkaleli, and Khan (2021) discovered in their study on developed countries, using data spanning from 1990 to 2018, that there is an adverse effect of natural resource rents on the environment.

According to Tauseef Hassan, Xia, and Lee (2021), in the case of Pakistan, natural resource rents have caused environmental degradation. Awosusi et al. (2022) conducted a study to examine how rents from contributions of natural resources affect the sustainability of the environment in Colombia. The authors found that natural resource rents significantly contribute to escalating CO_2 emissions. Wang, Vo, Shahbaz, and Ak (2020) examined the relationship between natural resource rents and environmental degradation and argued that natural resource rents cause pollution in G7 countries. However, Baloch, Mahmood, and Zhang (2019) reported mixed results regarding the impact of natural resource rents on emissions in Brazil, Russia, India, China, and South Africa (BRICS) countries. On the other hand, Khan, Hou, and Le (2021), using cross-sectional autoregressive distributed lag (CS-ARDL), found the opposite of this finding and concluded that natural resource rents reduce environmental pollution. Ganda (2022), however, showed a positive significant relationship between natural resource rents and environmental degradation in BRICS economies. Contrarily, Shittu, Adedoyin, Shah, and Musibau (2021), in their study on 45 Asian resource-rich economies, found a negative relationship between natural resource rents and environmental quality.

Many studies have been conducted on renewable energy consumption and its relationship to CO_2 emissions. Jebli and Youssef (2015) discovered that non-renewable energy consumption increases carbon dioxide, while there is a decrease in CO2 emissions due to renewable energy consumption. Likewise, the study by Szetela, Majewska, Jamroz, Djalilov, and Salahodjaev (2022) reveals that an increase in renewable power usage leads to reduced CO_2 emissions per capita. The coefficient of renewable energy was negative and statistically significant, indicating that CO_2 can be mitigated through an increase in its use for those nations dependent on oil or gas resources. Gnangoin, Kassi, Edjoukou, Kongrong, and Yuqing (2022) highlighted that renewable energy consumption, along with human capital, can act as complementary factors in reducing CO_2 emissions. The results of feasible generalized least squares (FGLS) show that renewable energy consumption abates CO_2 emissions.

On the other hand, Dong, Dong, and Jiang (2020) presented mixed results regarding the impact of renewable energy consumption on CO_2 emissions across different income levels, suggesting varying effects based on the economic context. Changes in renewable energy consumption adversely affect CO_2 emissions, but this effect is statistically insignificant; increased non-renewable energy consumption and economic growth may have obscured the mitigation effect. The study by Nguyen and Le (2022) showed that renewable energy consumption REC negatively affects CO_2 emissions, indicating a potential for environmental benefits. Farhani and Shahbaz (2014) noted that while renewable energy consumption REC might help reduce CO_2 emissions, its contribution to mitigating CO_2 emissions was not significant.

Another factor that has been established to have a significant influence on CO_2 emissions is technological innovation. Several studies have often linked technological innovations to decreased carbon emissions. Leading studies have considered a seemingly extensive sector coverage, from energy to environmental technologies. In this case, it has been established that innovations facilitate cleaner production processes, increased energy efficiency, and the use of renewable energy, positively affecting CO_2 mitigation (Wang & Zhang, 2021). Furthermore, the spread of a positive trend in different regions has been noted, such as China, India, and the remaining Asian geopolitical cluster. The results of this study indicated that new technological investments and adoption might help countries meet their sustainable development goals through simultaneous economic growth and a reduction in carbon footprints (Raihan & Tuspekova, 2023; Su et al., 2021). Moreover, exporting technology and renewable energy innovation were also identified as critical indicators of environmental sustainability and a decrease in CO_2 emissions (Zhang, 2023). Several other studies highlighted that innovation in technology generally results in a decrease in carbon emissions. However, some variability can always be found, considering how innovative the technology is and what the examined sector represents (Cheng, Meng, & Xing, 2022; Dou, Zhao, & Dong, 2021).

Furthermore, previous studies reveal that Gross Domestic Product has a significant influence on carbon dioxide emissions. For many years, the relationship between GDP and CO_2 emissions has been the focus of researchers' attention due to its importance for sustainable development (Jalil & Mahmud, 2009). A quadratic relationship between income and CO_2 emissions has been established during the sample period, which is consistent with the Environmental Kuznets Curve (EKC). The Granger causality test results show that one-way causality runs from economic growth to CO_2 emissions. Similarly, the most appropriate results of this study confirm that income and energy usage are the main determinants of carbon emissions in the long run. Although this is ascertained as fact in a study on the Gulf Cooperation Council by Salahuddin, Gow, and Ozturk (2015), the results of their study have proposed a positive association between energy usage, GDP, and CO_2 emissions. Xu, Rogers, and Estrada (2023) have shown that GDP directly influences CO_2 emissions since rising GDP leads to greater carbon dioxide emissions. Furthermore, some studies such as Wang, Yang, Li, and Wang (2023) and Song, Heng-Chuang, and Dong-Mei (2021) have examined the connection between economic growth and CO_2 emissions and identified a positive link between GDP and carbon dioxide. Furthermore, studies conducted by Li, Wang, and Zhan (2021) revealed that there is bi-directional causality between CO_2 emissions and GDP, implying that whenever gross domestic product improves, carbon dioxide also rises, which calls for sustainable development policies to address the environmental impacts of economic growth.

CO_2 emissions are said to be caused by environmental degradation in the course of resource extraction. This understanding is partial because it does not adequately consider the use of renewable energy and technological

advancements. Previous studies, such as Bekun et al. (2019) and Nwani et al. (2023), confirmed that there exists an association between natural resource rents and CO_2 emissions, whereby reliance on resource extraction poses environmental threats. Mahmood and Saqib (2022) as well as Ulucak and Ozcan (2020), also found through their studies that in different settings, such as OPEC or OECD countries, these rents have negative effects on the environment. However, these studies did not take into account possible changes brought about by the adoption of renewable energies or technological progress. Consequently, the current study examines the impact of resource rents on CO_2 emissions in the context of renewable energy use and technological innovation. In order to provide detailed policy recommendations related to sustainable development worldwide, this paper also uses advanced estimation techniques like MMQR (Movement Quantile Regression) and BSQR (Bootstrap Quantile Regression).

3. Methodology

3.1. Model Specification

There are many reasons why it is important to understand how natural resource rents and CO_2 emissions are related in the United States. Perhaps most importantly, the US is one of many countries around the globe that produce and consume huge amounts of such resources, making this subject matter worthy of investigation. To strengthen the conclusions, this paper uses advanced estimation methods like MMQR or BSQR because they provide robustness and reliability through findings that can be used for more detailed policy suggestions aimed at sustainable management practices not only in America but also worldwide.

The empirical model is provided as:

$$CO2_t = \lambda_0 + \lambda_1 NRR_t + \lambda_2 GDP_t + \lambda_3 TI_t + \lambda_4 REC_t + \mu_t \quad (1)$$

Where CO_2 refers to carbon dioxide emissions, NRR denotes total natural resources rent, REC signifies renewable energy consumption, TI represents technological innovation, and GDP stands for gross domestic product. The description of the variables is presented in Table 1.

Table 1. Definition of variables.

No.	Variables	Definition
1	CO2 emissions	Carbon dioxide is produced during the consumption of solid, liquid, and gaseous fuels, as well as from gas flaring.
2	Natural resource rent	Natural resource rents are the sum of oil rents, natural gas rents, coal rents (hard and soft), mineral rents, and forest rents.
3	Gross domestic product	GDP is the sum of gross value added by all resident producers in the economy, plus any product taxes, and minus any subsidies not included in the value of the products.
4	Technological innovation	The development and implementation of new technologies and processes that improve efficiency and the adoption of new technologies.
5	Renewable energy	Renewable energy consumption refers to the proportion of renewable energy within the total final energy consumption.

The variables selected for this study have been based on their pivotal role in explaining the connection between CO_2 discharges and natural resource rents within the US. Each variable has been selected because it holds strong theoretical as well as empirical grounds in environmental economics and sustainability literature. Natural resource rents are economic benefits derived from exploiting natural resources such as oil, gas, coal, minerals, and forests, among others. These revenues contribute greatly to the United States economy while at the same time being an area of interest when it comes to investigating their effect on carbon dioxide emissions. A positive relationship between them has already been proven by previous research, for instance, Bekun et al. (2019) and Nwani et al. (2023). This is why we need to analyze this variable since it helps us understand how our over-reliance on natural resource extraction affects environmental sustainability. CO_2 emissions are one of the major indicators used in measuring environmental degradation, which is also central in climate change studies. In order to quantify environmental impacts caused by natural resource rents, we must measure CO_2 emissions. Many investigations have employed CO_2 emission levels as a yardstick for assessing ecological consequences brought about by economic activities, e.g., Wang et al. (2020) and Tufail et al. (2021). Renewable energy consumption is essential for mitigating CO_2 releases into the atmosphere. Through this factor, the researchers seek to establish whether the adoption of cleaner sources of power can affect outcomes regarding the environment vis-à-vis differentials among areas based on the availability or absence of nature-endowed resource rents. According to Jebli and Youssef (2015) and Szetela et al. (2022), findings showed that more utilization of renewable energies leads to reduced carbon emissions, but these efforts should be complemented by other measures; hence, inclusion serves as a basis for further investigation into possible mitigation strategies. Technological innovation enhances energy efficiency gains while lowering pollution levels from burning fossil fuels, which are considered threats to sustainable development. It represents improvements that can decouple economic growth from environmental degradation, thus saving our planet for future generations. For example, Su et al. (2021) and Wang and Zhang (2021) highlight such importance by demonstrating how technology can help reduce CO_2 emissions, so this aspect will be analyzed in relation to its moderating effect on the resource rents-emissions relationship. GDP is a measure of economic activity or output within an economy, and it indicates the size as well as the health status of a country's economy. The relationship between GDP and carbon dioxide release into the atmosphere has been extensively studied by different scholars in various parts across the globe, e.g., Jalil and Mahmud (2009) and Salahuddin et al. (2015). This is why we need to include GDP since through this variable we are able to undertake a comprehensive study on the natural interaction between economics and the environment. Table 2 presents the descriptive statistics.

Table 2. Descriptive statistics.

Descriptive statistics	CO_2	NRR	GDP	TI	REC
Mean	5206424.0	0.882	1.44E+13	371768.6	6.509
Median	5099655.0	0.883	1.48E+13	349692.0	5.595
Maximum	5775810.0	1.935	2.03E+13	621453.0	10.420
Minimum	4807500.0	0.235	8.62E+12	120916.0	4.089
Std. dev.	355848.7	0.336	3.58E+12	173195.8	2.218
Skewness	0.412	0.558	-0.084	0.084	0.565
Kurtosis	1.535	4.152	1.746	1.499	1.730
Jarque-Bera	4.237	3.862	2.402	3.419	4.334
Probability	0.120	0.145	0.301	0.181	0.114
Observations	36	36	36	36	36

3.2. Analytical Techniques

This study explores the impact of natural resource rents on CO_2 emissions in the presence of renewable energy consumption, technological innovation, and GDP in the case of the USA over the period from 1990 to 2020. To check the stationarity properties of variables, we employ the Narayan and Popp (2010) test, which considers the structural breaks in the data. The past results were not dependable due to methodological defects such as endogeneity, omitted variable bias, and model specification problems. The present research overcomes these methodological limitations, making it possible to obtain more accurate estimates of the extent of resource rent contribution to carbon output. Hence, this study uses sophisticated estimation techniques such as Movement Quantile Regression (MMQR) and Bootstrap Quantile Regression (BSQR) in order to enhance the understanding of how resource rents impact CO_2 emissions. This article seeks to answer two critical questions: first, what exact relationship exists between resource rents and CO_2 emissions within the U.S.? Secondly, are advanced econometric methods useful in explaining the complex interaction between resource rents and CO_2 emissions? It is through these questions that this study seeks to provide the necessary insights for policymakers, academics, and investors working towards harmonizing economic growth with ecological sustainability in America's context.

To estimate the impact of natural resource rents, renewable energy consumption, technological innovation, and GDP on CO_2 emissions, this study uses the Bayer and Hanck (B&H) co-integration method. The B&H test equation is given as:

$$EG - J = -2[\ln(P^{EG}) + \ln(P^{J})] \quad (2)$$

$$EG - J - Bo - Ba = -2[\ln(P^{EG}) + \ln(P^{J}) + \ln(P^{Bo}) + \ln(P^{Ba})] \quad (3)$$

To estimate the model, this study uses Movement Quantile Regression (MMQR) and Bootstrap Quantile Regression (BSQR) estimation techniques. The QR approach facilitates the influence of diverse covariates on the quantiles of the dependent variable. Conventional econometric methods only examine the average impact of covariates on the predictor variable, resulting in biased estimates. The predictor analysis solely focuses on the average stimulus, disregarding any other factors. When evaluating the level of correlation between two variables, QR outperforms other methods as it effectively avoids drawing false conclusions, unlike alternative approaches. The equation below represents the conditional quantile:

$$CO2_t\left(\tau I\gamma_i, \delta_t, X_{i,t}\right) = \varphi_i + \lambda_{1,\tau}NRR_t + \lambda_{2,\tau}GDP_t + \lambda_{3,\tau}TI_t + \lambda_{4,\tau}REC_t + \upsilon_{\tau,i,t} \quad (4)$$

Separate quantiles are given as:

$$Q_{0.25}(CO2_t) = \beta_{0.25} + \beta_{1,0.25}NRR_t + \beta_{2,0.25}GDP_{i,t} + \beta_{3,0.25}TI_t + \beta_{4,0.25}REC_t + \upsilon_{0.25,t} \quad (4a)$$

$$Q_{0.50}(CO2_t) = \beta_{0.50} + \beta_{1,0.50}NRR_t + \beta_{2,0.50}GDP_t + \beta_{3,0.50}TI_t + \beta_{4,0.50}REC_t + \upsilon_{0.50,t} \quad (4b)$$

$$Q_{0.75}(CO2_t) = \beta_{0.75} + \beta_{1,0.75}NRR_t + \beta_{2,0.75}GDP_t + \beta_{3,0.75}TI_t + \beta_{4,0.75}REC_t + \upsilon_{0.75,t} \quad (4c)$$

4. Results and Discussions

To check the order of integration of variables, we employ the Narayan and Popp (2010) test. The results of the unit root test are presented in Table 3. The results show that NRR and GDP are integrated of order zero, whereas CO_2, TI, and REC are integrated of order one.

Table 3. Unit root.

Variables	I(0)	I(1)
CO_2	-1.326	-5.915***
NRR	-1.013**	-4.427**
GDP	-3.098***	-4.535***
TI	-0.548	-4.982***
REC	-1.199	-6.783***

Note: *** and ** means significant for 1%, and for 5% respectively.

The results of the Bourgoyne and Young (B&Y) co-integration test are reported in Table 4. The significant test statistics of the B&Y test indicate that there is ample evidence of co-integration among the variables presented in model 1.

Table 4. Co-integration test.

	Engle-Granger	Johansen	Banerjee	Boswijk
Test statistic	-1.833	109.745***	1.281	731.182***
Probability	0.873	0.000	1.000	0.000
EG-J			71.098**	
EG-J-Ba-Bo			92.237**	

Note: *** & ** shows 1% and 5% significance level.

This section provides the estimation results obtained using the MMQR and BSQR estimation techniques. These approaches are used to analyze complex interrelationships among resource rents and CO_2 emissions. These estimation methods permit a robust investigation of non-linearities, heteroscedasticity, and asymmetries in distributions concerning the effects of resource rents on CO_2 emissions. By employing MMQR and BSQR, this paper examines complex structures as well as links that are often overlooked in general regression analysis, thus enhancing our understanding of how resource extraction and economic growth influence environmental depletion. Furthermore, three quantile levels, namely 0.050, 0.550, and 0.750, are used for both estimation techniques. The results of both the MMQR and BSQR estimations are displayed in Table 5.

The MMQR coefficient values for natural resource rent (NNR) show that for lower, median, and upper quantiles, a one-unit increase in NRR corresponds to a 38.1%, 77.9%, and 90.2% increase in CO_2 emissions, respectively. The observed NRR coefficient values that represent a proportional rise in CO_2 emissions are consistent with the Environmental Kuznets Curve (EKC) theory. When countries begin to experience economic growth resulting from the extraction of natural resources and industrialization, according to the EKC principle, CO_2 emissions initially increase. Previous studies in environmental economics help to understand the connection between natural resource rent and CO_2 emissions; this supports the current study's findings as well. For example, Nwani et al. (2023) found that there is a positive correlation between carbon emissions and resource extraction activities, especially in places or sectors heavily dependent on the exploitation of natural resources.

The coefficient values for GDP reflect the percentage change in CO_2 emissions associated with a one-unit increase in GDP at various quantiles of the CO_2 emissions distribution. For instance, at the lower, median, and upper quantiles, these coefficient values are 0.080, 0.070, and 0.070 respectively, indicating that when GDP increases by one unit, it causes an increase of approximately 8.0%, 7.0%, and 7.0% in CO_2 emissions across these quantiles. These results imply a positive association between GDP growth rates and CO_2 emission levels throughout different quantile divisions, although they vary in terms of effect size across different parts of the CO_2 emission distribution. Existing literature also supports the present study's outcome regarding the effect of GDP on CO_2 emissions. For example, studies conducted by Salahuddin et al. (2015) and Mitić, Munitlak Ivanović, and Zdravković (2017) have shown that an increase in GDP leads to an increase in CO_2 emissions, thus indicating the relationship between economic development and environmental degradation. The relationship between GDP and CO_2 emissions is complicated. Economic growth, which results in an increase in GDP, entails higher activity in industry, a greater need for transportation, and increased energy consumption, all of which raise the level of CO_2 emissions. Increased emissions are due to industrialization being an energy-intensive process and globalization putting more pressure on the production and supply chain, as people from more countries can afford more goods and services. However, economic development also brings with it more technology, which may reduce dependence on energy for various processes or lead to the innovation of cleaner technologies. Besides the expansion of economies, modifications in economic structures as well as international trade flux add intricacy to this relationship between GDP and CO_2 emissions. In the course of progress, they could shift into sectors that emit less while transforming their emission patterns. Additionally, global trade and outsourcing manufacturing, which often occurs in countries with a low-wage workforce but potentially high CO_2 emissions, may influence a country's total emissions related to its gross domestic product.

The coefficients of technological innovation indicate that improving technological innovation decreases CO_2 emissions by approximately 26.4%, 61.7%, and 20.4% respectively across lower, median, and upper quantiles. This finding indicates the significance of technological innovation in reducing carbon dioxide emissions. This finding aligns with previous studies; for instance, Wang and Zhang (2021) have shown that technological innovations are key to addressing CO_2 emissions by indicating that clean technologies and improved energy efficiency can make economic growth independent of environmental deterioration.

For renewable energy consumption, the coefficients obtained through MMQR are 0.025, -0.026, and -0.064, meaning that when renewable energy consumption REC goes up by one unit, there will be approximately a decrease of 2.5%, 2.6%, and 6.4% in CO_2 emissions respectively at lower, median, and upper quantiles. This finding also shows the importance of renewable energy consumption in curbing CO_2 emissions. This is in line with the results of a study conducted by Szetela et al. (2022), implying that clean energy has the potential to promote green sustainability and offset negative outcomes on resource extraction.

In the BSQR method, the coefficient values of NRR for lower, median, and upper quantiles show that the corresponding increase in CO_2 emissions due to a one-unit change in NRR ranges from 58.7% (lower quantile) to 68.0% (upper quantile). Despite some variations in the results of MMQR tests, both methods show an identical pattern in the increase of CO_2 emissions as one moves to higher quantiles. This reflects a similar trend between NRR and carbon dioxide emissions across various partitions of the distribution.

The GDP coefficient values are 0.075, 0.086, and 0.077 respectively, showing about a 7.5%, 8.6%, and 7.7% rise in CO_2 emissions among these quantiles due to every single unit rise in GDP. The coefficients for Gross Domestic Product obtained from BSQR are in line with MMQR outcomes. This means that both MMQR and BSQR estimates suggest that economic growth measured by GDP leads to increased CO_2 emissions across all quantiles.

Results for TI show that improvements in technological innovation reduce CO_2 emissions across these quantiles by almost 62.1%, 95.1%, and 56.5% respectively. In respect to technological innovation (TI), the findings using both BSQR and MMQR methods imply that there is a substantial reduction in CO_2 emissions in all quantiles.

Finally, the results for renewable energy consumption (REC) obtained from BSQR are similar to those derived through MMQR, suggesting that changes in renewable energy consumption would have brought about a decrease in CO_2 levels by 5.6%, 2.4%, and 2.4% respectively. This emphasizes the significance of embracing renewable energy in mitigating CO_2 emissions.

Table 5. Robustness – quantile regression.

Variable'	MMQR estimates					
	Q0.25		Q0.50		Q0.75	
	Coef.	Std. err.	Coef.	Std. err.	Coef.	Std. err.
NRR	0.381***	0.140	0.779***	0.138	0.902***	0.218
GDP	0.080***	0.051	0.070***	0.051	0.070***	0.054
TI	-0.264***	0.045	-0.617***	0.042	-0.204***	0.050
REC	-0.025**	0.012	-0.026***	0.012	-0.064**	0.014
Cons.	-0.757	1.458	-1.571	1.415	-1.566	1.206
BSQR estimates						
Variable	Q0.25		Q0.50		Q0.75	
	Coef.	Std. err.	Coef.	Std. err.	Coef.	Std. err.
NRR	0.587***	0.175	0.955**	0.597	0.680**	0.617
GDP	0.075*	0.045	0.086	0.025	0.077*	0.055
TI	-0.621***	0.102	-0.951**	0.150	-0.565**	0.126
REC	-0.056	0.095	-0.024	0.048	-0.024	0.042
Cons.	-0.426	0.089	-0.790	0.655	-1.174	0.602

Note: ***, ** & * shows 1%, 5% and 10% significance level.

5. Conclusions and Policy Recommendations

Natural resource rents represent the economic benefit gained through the utilization of resources like oil, natural gas, and coal, as well as oil-producing minerals and forests. These rents can make up the largest portion of the revenue of resource-rich countries, sparking concerns about the environmental impact on other nations. The extraction of these resources is one of the leading reasons for CO_2 emissions. Greenhouse gases such as CO_2, which are the main cause of climate change, present unprecedented risks to human development and survival, such as the extinction of animal and plant species, famines, and extreme weather conditions. This study explores the impact of natural resource rents on CO_2 emissions in the presence of renewable energy consumption, technological innovation, and GDP in the case of the USA over the period from 1990 to 2020. For sustainable development policies and to slow down environmental degradation, it is important to understand the intricate connection between resource rents and carbon emissions in the US. Thus, this study hypothesizes that after controlling for renewable energy consumption, technological innovation, and GDP among other variables, resource rents significantly contribute to carbon dioxide emissions in America. This study adds significantly to the existing literature on how resource rents affect CO_2 emissions in the United States.

This study employs advanced estimation methods such as Movement Quantile Regression (MMQR) and Bootstrap Quantile Regression (BSQR) estimation techniques, which provide vital policy insights and academic contributions that are relevant for sustainable development and environmental conservation from both national and global perspectives. Identifying risks associated with resource extraction by assessing the environmental consequences of extracting resources from the natural environment will help promote responsible resource use that may facilitate a more sustainable economy. The impact is not only confined to academia or policymaking but also affects other key players like industry leaders, environmental advocates, and even the general public. Decoupling environmental destruction from economic growth, as mandated by sustainable development goals, demands an understanding of how resource rents translate into CO_2 emissions. If we really want to make a difference within our borders and internationally, then it is high time we addressed the relationship between resource rents and CO_2 emissions. Given its status as one of the world's biggest carbon dioxide emitters, the government of the United States has significant implications when it comes to global climate change patterns. These findings directly relate to policies that enable sustainable development and address environmental degradation in America. By clearly stating how much resource rents contribute to CO_2 emissions, policymakers will have more focused interventions and regulations that encourage cleaner energy sources, stimulate efficient use of resources, or raise energy prices without hampering economic growth.

This study employs quantile regression estimation techniques, which provide vital policy insights and academic contributions that are relevant for sustainable development and environmental conservation from both national and global perspectives. The results show that natural resource rent (NNR) and GDP are positively associated with CO_2 emissions at all quantiles. This implies that CO_2 emissions in the USA are greatly influenced by NRR. Moreover, the results show that technological innovation and renewable energy consumption are important in curbing CO_2 emissions. As the world grapples with promoting green, sustainable growth to curb anthropogenic climate change, the consumption of REC) is a much better way to replace fossil fuel utilization. This problem presents a key challenge for policymakers, energy researchers, and industry players concerning ways through which CO_2 emissions can be reduced by using renewable energy. Renewable energy use as a means of reducing carbon dioxide emissions is now at an important crossroads between policy and energy transition. The potential for renewable energy to result in lower CO_2 emissions arises because most types of renewable energy can substitute fossil fuel combustion in three major consuming sectors: power generation, transportation, and manufacturing. Moreover, when it comes to tackling the many challenges of environmental sustainability and climate action, technological innovation is likely to remain one of the most important tools for reducing CO_2 emissions. In the face of overwhelming preoccupation with climate change, innovation – or, more specifically, the ability of new technologies to decrease emissions in every corner of our society – has emerged as a topic of great interest to academics, policymakers, and industrial decision-makers. Indeed, there is a widespread belief that new technologies will enable society to dramatically reduce CO_2 emissions

and support the transition to a more sustainable future. This is particularly true in the energy, transport, industry, and consumption sectors.

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