



Economic and trade determinants of carbon emissions in the American region

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ABSTRACT

Balancing economic growth with sustainability has been a significant challenge over the past decades, largely due to the environmental damage caused by carbon emissions. This study investigates the relationship between energy consumption, gross domestic product (GDP), and trade openness and their impact on carbon emissions in 28 countries in the American region from 2000 to 2022. Using a multiple linear regression model for country-level analysis, the findings reveal diverse trends across the region. For instance, countries such as Antigua and Barbuda, Bolivia, Brazil, Chile, and Guatemala demonstrate a strong link between economic growth and increased carbon emissions. In contrast, developed nations such as the United States and Canada show signs of decoupling GDP growth from emissions, supporting the Environmental Kuznets Curve hypothesis, which suggests that higher income levels lead to reduced environmental degradation. The study highlights the importance of tailored, country-specific strategies to reduce emissions while promoting sustainable economic growth. A thorough understanding of the complex relationships between gross domestic product, energy consumption, trade openness, and carbon emissions will enable policymakers to devise strategies that balance ecological sustainability with socio-economic objectives.

1. Introduction

In the context of the complex relationship between economic development and environmental sustainability, it is crucial to uncover the detailed connections between energy consumption, gross domestic product (GDP), trade openness, and their collective impact on carbon emissions (Tomasz and Mateusz, 2022; Broni et al., 2020). Climate change stands as one of the most pressing global challenges of our time, making it imperative to understand its causes and effects, which have become a major focus of recent research and policy efforts (Yassine Kirat and Suardi, 2024). The concept that countries have distinct obligations regarding climate change based on their historical contributions was established by the United Nations Framework Convention on Climate Change (United Nations. Climate Action Fast Facts 2022). It suggests that countries facing major climatic issues should take significant

actions to mitigate the consequences. The Paris Agreement builds upon this notion by establishing shared objectives for minimising carbon emissions (Gyimah et al., 2023), while allowing flexibility for each country to achieve those goals based on their unique abilities and circumstances (Takeshi et al., 2020). The ultimate objective is for all nations to attain net-zero emissions in the future, thereby preventing further climate damage.

The process of economic growth and development is heavily reliant on activities involving production, transportation, and energy consumption (United States Environmental Protection Agency 2017), which, in turn, result in the emission of carbon dioxide (CO₂). Unfortunately, the environmental impact of CO₂ emissions cannot be ignored. Given that climate change is largely driven by CO₂ emissions, achieving Sustainable Development Goal (SDG) 13, which calls for “urgent action to combat climate change and its impacts”, becomes a daunting task for

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developing nations (International Energy Agency. CO2 emissions. 2019; Xiaohai Wei et al., 2024). Specifically, SDG 13 advocates urgent action to address climate change, including efforts to reduce carbon intensity and transition to renewable energy sources. All countries require significant economic progress to address poverty, provide basic needs for their populations, and compete on a global level, all of which are heavily dependent on energy production and consumption (Al-Asel, 2022). Therefore, striking a balance between economic growth and sustainability remains a challenge, making it crucial to find effective solutions to minimise the environmental impact of economic activities for the successful attainment of SDG 13 (Adeleye et al., 2021).

A study conducted in Malaysia from 1970 to 1980 has analysed the relationship between economic growth, carbon emissions, energy consumption, and population growth. The study found that per capita energy consumption and per capita gross domestic product (PGDP) have a positive impact on per capita emissions in the long run (Kazi et al., 2015). However, population growth was found to have no significant impact on carbon emissions. Studies focusing on China analysed the relationship between energy consumption, economic growth, and carbon emissions. The findings indicate that carbon emissions and energy consumption do not influence economic growth (Bingnan et al., 2022; Zeyu et al., 2023). The study's findings suggest that economic growth is not hindered by carbon emissions and energy consumption. In other words, the levels of carbon emissions and energy use do not negatively impact or restrict economic growth (Gyimah et al., 2023). Notably, few studies have concurrently examined these factors—trade openness, GDP, and energy consumption—across countries with different economic structures.

As international trade expands, more goods are transported across borders, leading to increased transportation-related carbon emissions. Policymakers in the region can develop trade policies that support sustainable economic growth by examining the relationship between trade openness and carbon emissions. Trade openness has been shown to increase carbon emissions at the 10 %–50 % quantile levels, and the impact of trade diversification on carbon emissions remains consistent (Q. Wang et al., 2024). According to a report by the Inter-American Development Bank (IDB), increasing trade openness in South America has resulted in higher carbon emissions (Aboagye and Adjei Kwakwa, 2023). Recent studies have emphasised the growing need for region-specific research on carbon emissions. These studies suggest that, despite its substantial contribution to global emissions, the American region has been underrepresented in global analyses of carbon emission drivers (Udara Wilhelm Abeydeera and Wadu Mesthrige, 2019; Jared et al., 2023). Investigating this relationship is essential to support sustainable regional economic development. Much of the existing research focuses on individual countries or regions rather than examining cross-country interactions within diverse economies. While individual factors have been studied in various contexts, there remains a significant gap in research exploring the simultaneous impact of these factors across different countries and economic structures. In particular, there is limited research on how these factors interact at different stages of economic development, making the Americas a key region for exploring these dynamics.

The primary research question of this study is: What is the relationship between energy consumption, GDP, and trade openness on carbon emissions in the American region? This question is particularly significant as it addresses key gaps in the literature and provides insights for more targeted policy interventions.

This study is motivated by the critical need to understand the dynamics driving carbon emissions, particularly in the Americas—a region that has significantly contributed to global emissions between 2000 and 2022. By identifying key determinants of carbon emissions, such as energy consumption, GDP, and trade openness, the study provides valuable insights for policymakers seeking to implement effective carbon reduction strategies and accelerate the transition towards sustainable development. This research examines how these factors have

influenced carbon emissions in 28 nations across the American continent during this period, encompassing both developed and developing economies. The urgent need to address global challenges arising from carbon emissions and their detrimental effects on environmental sustainability underpins the rationale for this study. While the relationship between economic growth, trade, and environmental degradation has been extensively explored, few studies have concurrently examined these factors across the diverse economies of the Americas. Given that this region includes nations at varying levels of economic development, it presents a unique opportunity to assess how these dynamics unfold in different contexts.

This research fills important gaps in the literature in several ways. Firstly, it provides a comprehensive analysis of the simultaneous effects of trade openness, GDP, and energy consumption as independent variables influencing carbon emissions. In contrast to previous studies, which often focus on single factors or specific groups of countries, this study examines their combined impact, offering a holistic understanding of the drivers of carbon emissions in both developed economies, such as the United States and Canada, and developing nations, such as Bolivia and Guatemala. By investigating a wide range of countries, the study illustrates the interaction between economic growth and environmental sustainability at different stages of development.

Second, by employing a robust multiple linear regression (MLR) model tailored for regional and national analysis, this study addresses a key methodological gap. This approach enables a more nuanced understanding of the interplay between economic and environmental factors within the distinct contexts of individual nations. With the dataset updated to 2022, the research ensures the inclusion of the most recent developments, providing valuable insights for stakeholders and policymakers.

The study's findings have significant implications for policy development. As nations face increasing pressure to meet global environmental targets, such as achieving carbon neutrality by 2050, it is essential to identify the primary drivers of carbon emissions. By pinpointing the key sources of emissions in countries experiencing rapid economic growth or expanding trade activity, this study equips policymakers with the necessary tools to formulate targeted, evidence-based strategies for reducing carbon footprints. Furthermore, in alignment with the broader objective of achieving sustainable development across the region, the study underscores the importance of balancing economic ambitions with sustainability goals.

The subsequent sections of the research are structured as follows: a literature review summarising previous research findings, a section on data and methodology, results and discussion, and a conclusion with policy implications.

1.1. Literature review

Climate change, primarily driven by carbon emissions, poses a severe threat to global sustainability. The significant rise in carbon emissions, predominantly resulting from human activities, has been identified as the main contributor to climate change (Rehan and Nehdi, 2005). Over the past five decades, scientists have gathered compelling evidence linking most of the observed warming to anthropogenic causes (International Panel on Climate Change, Climate Change 2001). This surge in carbon emissions disrupts natural ecosystems and weather patterns, leading to rising global temperatures, changes in ecosystems, sea-level rise, and diminished freshwater availability (United Nations. Climate Action Fast Facts 2022; National Geographic. Global Warming Effects. 2019). Understanding carbon emissions is vital as it reveals the environmental impact of human activities and provides crucial insights for policymakers to develop strategies for climate change adaptation and mitigation.

1.1.1. Energy consumption and carbon emissions

The relationship between energy consumption and carbon emissions

has been a focus of many studies. The global rise in energy consumption has significantly contributed to increasing carbon emissions, thus worsening environmental degradation. Carbon emissions not only accelerate climate change via the greenhouse effect but also hampers sustainable development. The rise in greenhouse gases (GHGs) has become a pressing issue, necessitating an understanding of the causal relationship between energy consumption and carbon emissions to formulate effective policies aimed at reducing environmental damage while promoting sustainability (Jijun and Yanjun 2020). The rapid economic growth in several countries, often accompanied by higher energy consumption, has intensified environmental concerns (Junmei et al., 2020). Consequently, the environmental challenges posed by high energy use and the resulting carbon emissions have intensified. Given that energy consumption accelerates climate change through the greenhouse effect, it is vital to understand its relationship with carbon emissions to devise sustainable environmental policies.

1.1.2. GDP and carbon emissions

The relationship between Gross Domestic Product and carbon emissions has been extensively researched, particularly in light of global efforts to combat climate change and theoretical frameworks like the Environmental Kuznets Curve suggest that economic development initially leads to higher emissions, but later decreases as countries develop cleaner technologies (Jingwen et al., 2021). Despite these efforts, the nature of this relationship remains unclear, with ongoing debates about whether economic growth inevitably leads to increased carbon emissions. International agreements such as the Kyoto Protocol have made strides in mitigating global warming, yet the link between per capita income and carbon emissions remains complex and inconclusive. This complexity underscores the need for further research and evidence-based policies to foster sustainable economic growth while mitigating carbon emission's environmental impact (Muhammad et al., 2020). Although economic growth and international trade have been linked to increased CO₂ emissions and improved energy efficiency, sustainable practices are essential to minimising environmental harm. Investments in energy efficiency and technology can reduce carbon emissions while promoting sustainable development (Q. Wang et al., 2024). Investigating GDP's impact on carbon emissions is crucial for developing strategies that balance economic growth with environmental sustainability.

1.1.3. Trade openness and carbon emissions

Trade openness has facilitated international trade but also led to increased energy consumption and, consequently, higher CO₂ emissions. Rising energy consumption and CO₂ emissions have heightened concerns about environmental consequences of trade openness, prompting a deeper understanding of this relationship (Dou et al., 2021). Studies focusing on trade openness in Asia and Africa have revealed that while international trade enhances economic growth, it also increases CO₂ emissions, particularly in energy-intensive industries. As trade flows increase, so do transportation-related emissions. Understanding the environmental impact of trade is crucial, especially in regions like South America where increasing trade openness has been correlated with higher carbon emissions (Q. Wang et al., 2024). The nexus between trade openness and CO₂ emissions has become a critical area of inquiry, emphasising the need for policy interventions that harmonise economic growth with environmental sustainability (Ahmed et al., 2017; Ansari et al., 2020). As trade openness is associated with economic growth and increased energy consumption, it plays a crucial role in determining impact of carbon emission.

The United States, the world's second-largest CO₂ emitter, has seen its carbon footprint grow alongside its economic expansion, underscoring the need to examine factors influencing carbon emissions for sustainable regional development (Rogelj et al., 2016). The Paris Agreement, a landmark international effort to address climate change, marked significant progress towards mitigating global warming

(Dimitrov, 2016). However, the United States' withdrawal from the Paris Agreement in 2017 sparked concerns, given its substantial GHG contributions (Fletcher et al., 2021). The United States of America also leads in global carbon footprints related to travel and tourism, making its involvement crucial for achieving global climate change mitigation goals (International Monetary Fund 2008). The withdrawal of the United States of America highlights the importance of international collaboration in combating climate change and the necessity for all nations to participate (Micah Fields, 2024). The active role of the United States of America is vital for realising the Paris Agreement's objectives and ensuring planetary sustainability (Manfred et al., 2018).

In South America, reliance on non-renewable energy sources contributes to high carbon emissions, making it imperative for regional authorities to understand energy consumption's impact on carbon emissions to develop sustainable energy policies (The World Bank. Latin America and Caribbean 2022). While industrialisation has exacerbated environmental degradation, advances in renewable energy are essential for reducing ecological impacts and promoting conservation (Qiang et al., 2023). Increased international trade has also led to higher transportation-related carbon emissions, highlighting the need for trade policies that support sustainable economic growth (IADB 2019). Consequently, examining the trade openness-carbon emissions relationship is critical for fostering sustainable regional development (United Nations 2018). In recent years, subnational governance has become increasingly important in addressing climate change (Graves et al., 2020). With global climate agreements faltering and a lack of comprehensive national climate policies, subnational entities have emerged as crucial players in reducing GHG emissions (Hsu et al., 2019; Rabe, 2007). States like California and regions like the Regional Greenhouse Gas Initiative (RGGI) have implemented successful emissions reduction policies (Anderton and Setzer, 2018). The growing number of states committing to net-zero emissions by 2050 underscores the importance of subnational efforts in achieving global sustainability goals (Graves et al., 2020).

Despite the broad interest in the relationship between carbon emissions, energy consumption, GDP, and trade openness, few studies have integrated all three variables in a regional context, especially in the Americas. While much of the existing literature has focused on specific countries or continents such as South Asia or Africa. The impact of these factors in the diverse economic landscape of the Americas, with its mixture of developed and developing economies, remains underexplored. This study aims to fill this critical gap by analysing the interplay between trade openness, GDP, and energy consumption on carbon emissions across 28 countries in the Americas.

1.2. Theoretical framework

This study's theoretical framework integrates the Environmental Kuznets Curve (EKC), the 3Ps Framework of Sustainability, and the Porter Hypothesis to understand how trade openness, GDP, and energy consumption affect carbon emissions in the American region. These frameworks, supported by relevant economic and environmental theories, provide a comprehensive understanding of the variables' interactions, as depicted in Fig. 1.

The EKC captures the economic-environmental relationship, suggesting an inverse "U"-shaped relationship between environmental degradation and economic growth. Initially, increased industrial activity and energy consumption lead to environmental degradation as per capita wealth rises. However, as economies grow, societies prioritise environmental quality, resulting in improved environmental conditions. The EKC's theory of eventual environmental improvement with increased affluence is reflected in this study, where "Per Capita Affluence" leads to "Initial Environmental Degradation," eventually transitioning to an "Improved Environmental Relationship" (Taiming et al., 2023; Ridwan et al., 2024).

The 3Ps framework is widely used in business to balance between

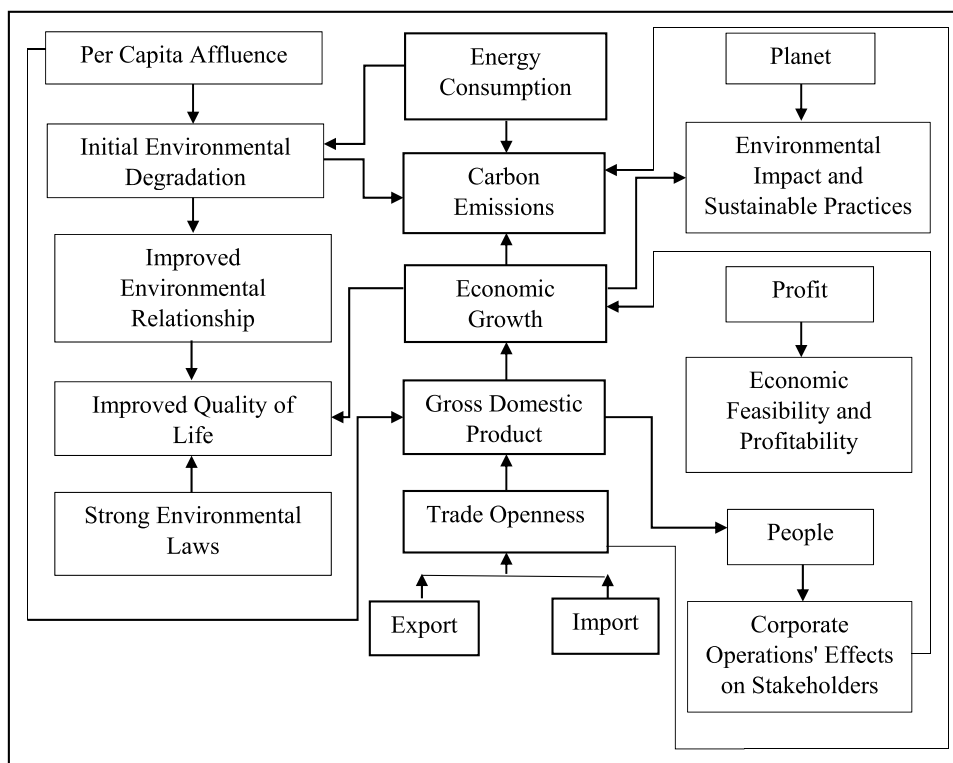


Fig. 1. Theoretical Framework. Source: Authors' illustration.

people (social factors), profit (economic factors), and the planet (environmental sustainability), which aligns with the objectives of this study in understanding how energy consumption, GDP, and trade openness interact with environmental sustainability (Adebayo et al., 2024). This framework serves as a guiding tool for discussing the implications of our findings and highlights the need for policies and practices that lower emissions and promote sustainability. Through the integration of the 3Ps with established theories including the Porter Hypothesis and the Environmental Kuznets Curve, this study offers a thorough investigation of the relationships between trade openness, GDP, energy consumption, and carbon emissions (Dharmapriya et al., 2024; Gbejewoh et al., 2021).

The Porter Hypothesis posits that strict environmental regulations can drive efficiency and innovation, enhancing economic growth and competitiveness. According to this hypothesis, strong environmental laws encourage the development and adoption of environmentally friendly technologies, leading to improved productivity and reduced carbon emissions. The framework highlights “Strong Environmental Laws” that contribute to an “Improved Quality of Life”, suggesting that such regulations can stimulate sustainable economic growth through technological advancements and cost reductions (Methmini et al., 2024; Dissanayake et al., 2023).

This theoretical framework lays the foundation for the subsequent sections on data and methodology, where data sources, variables, and analytical approaches will be detailed to explore these relationships and derive meaningful conclusions.

2. Data and methodology

The study utilised secondary data sourced from Our World in Data, with a detailed dataset carefully curated to include only relevant and accurate data. This section is divided into two parts: the first details the data sources and variables employed, while the second outlines the methodological strategy, including the data analysis techniques, research design, and statistical tools used.

2.1. Data

The analysis utilised panel data covering the period from 2000 to 2022 for 28 out of 35 countries in the American region. As shown in Table 1, the data were classified into four main categories: carbon emissions, energy consumption, GDP and trade openness. To ensure consistency and comparability across the data sets, carbon emissions were measured in metric tons per capita, energy consumption in per capita kilowatt hours, GDP in per capita terms, and trade openness as a percentage of GDP.

- Carbon emissions: This dependent variable serves as a critical indicator of environmental impact and is measured in metric tons per capita. This proxy represents the amount of carbon emissions generated by each individual in a given country over the study period..
- Energy consumption: An independent variable affecting carbon emissions through the energy mix. It is measured in per capita kilowatt hours. This reflects the amount of energy consumed by individuals in each country, with higher consumption often correlating with increased emissions due to the energy sources used.
- GDP: This independent variable represents economic activity and is measured in US dollars per capita in constant 2017. GDP per capita serves as a proxy for the overall economic output of a country and is often directly correlated with carbon emissions as economic growth may lead to increased industrial activity and energy use.

Table 1 Data sources and variables.

Variable	Measure	Source
Carbon emission	Metric Ton Per Capita	Our World in Data
Energy consumption	Per Capita Kilowatt Hours	
Gross domestic product	Per Capita	
Trade openness	Percentage of GDP	

- Trade openness: This independent variable reflects a country's involvement in international trade, measured as the percentage of GDP. It indicates the level of a country's trade relative to its overall economic activity, and can impact environmental footprints by influencing production levels, transportation, and associated emissions.

The use of consistent and standardised units of measurement ensures that the data are accurate, reliable, and allow for meaningful comparisons and analyses.

2.2. Methodology

2.2.1. Justification of the methodology

The study employed a Multiple Linear Regression (MLR) model as the primary analytical tool to investigate the relationship between carbon emissions and the independent variables—energy consumption, GDP, and trade openness—across 28 countries in the American region over a period of 22 years (2000–2022). The MLR model was chosen due to its effectiveness in modelling linear relationships between a dependent variable and multiple independent variables, making it particularly suitable for assessing how economic and environmental factors collectively influence carbon emissions.

2.2.2. Rationale for using multiple linear regression

MLR was selected because it enables the evaluation of several predictors on a single outcome variable at the same time. Several factors, including GDP, energy consumption, and trade openness, have an impact on carbon emissions in this study. A thorough examination of the combined effects of these factors is made possible by MLR's flexibility in accounting for them and any potential interactions. Compared to simple linear regression, which only permits the evaluation of the influence of a single predictor at a time and may result in omitted variable bias, this method has advantages. Furthermore, MLR models provide a clear interpretation of the coefficients, representing the expected change in the dependent variable for a one-unit change in an independent variable while holding other variables constant. This is particularly valuable for policymakers and stakeholders, who need to understand the relative importance of each factor in influencing carbon emissions.

2.2.3. Consideration of alternative methods

Alternative methods such as Vector Autoregression (Renato et al., 2020), Generalised Method of Moments (GMM), and Panel Data Fixed Effects models were considered. However, these methods were not selected for the following reasons:

- Vector Autoregression (Renato et al., 2020) : While VAR models capture dynamic relationships between multiple time series, they require large datasets and can be complex to interpret when dealing with multiple variables across several countries. VAR models may also overfit the data if not properly specified.
- Generalised Method of Moments (GMM): GMM is effective in addressing endogeneity issues in panel data, but it requires strong instruments that are often difficult to justify in cross-country analyses. The complexity and assumptions underlying GMM can also make it less transparent compared to MLR.
- Panel Data Fixed Effects Model: Although this model accounts for unobserved heterogeneity by controlling for time-invariant characteristics of the countries, it does not accommodate the examination of interaction effects as flexibly as MLR. Additionally, the focus of this study is on the aggregate effect of variables across countries rather than within-country variations over time.

2.2.4. Descriptive statistics and visualisation

Descriptive statistics were computed using STATA software to summarise the data and assess the initial relationships between the

variables. These statistics are presented in Appendix A. Additionally, maps were generated to visually represent the geographic distribution of carbon emissions and other variables across the region.

2.2.5. Multiple linear regression analysis

The MLR model was specified to examine the relationship between carbon emissions and the independent variables of energy consumption, GDP, and trade openness across the selected countries. The model is expressed as follows: Carbon Emissions in country i at time t (CE_t) is a function of Energy Consumption (EC_t), Gross Domestic Product (GDP_t), and Trade Openness (TO_t), with an error term ε_t to account for unobserved factors. Mathematically, the relationship is defined as

$$CE_t = \zeta_0 + \zeta_1 EC_t + \zeta_2 GDP_t + \zeta_3 TO_t + \varepsilon_t \quad (1)$$

where ζ_0 is the intercept and ζ_1 , ζ_2 , and ζ_3 are the coefficients representing the impact of the independent variables on carbon emissions.

2.2.6. Multicollinearity check

To ensure the robustness of the MLR model, Variance Inflation Factor (VIF) values were calculated to check for multicollinearity among the independent variables. A VIF greater than 10 would indicate potential multicollinearity, which could undermine the reliability of the regression coefficients. The results, provided in Appendix B, confirmed that multicollinearity was not a significant issue.

2.2.7. Interpretation of results

The regression coefficients were interpreted to determine the direction and significance of the relationship between carbon emissions and the independent variables. Scatter plots were created (Appendix C) to visually explore these relationships across the 28 countries. Furthermore, the MLR results for each country, along with the significance levels of the variables considered, are detailed in Appendix D.

3. Results and discussion

3.1. Descriptive analysis of energy consumption, GDP, and trade openness

This study provides significant insights into the impact of GDP, energy consumption, and trade openness on carbon emissions across nations in the American region. The Fig. 2 reveals distinct patterns and levels of influence across different continents.

The findings on the study of CO₂ emissions demonstrate a considerable diversity across the participating countries. In comparison to the significantly higher average carbon emissions of 18.46 and 21.3 metric tonnes per capita in Canada and the United States of America, less developed nations like Haiti and Nicaragua record far lower emissions, at 0.3 and 0.86 metric tonnes per capita, respectively. This implies that nations with higher incomes and levels of economic activity also tend to have higher emissions. Furthermore, significant disparities are observed in GDP per capita, with Haiti's \$3165 markedly lower than the United States of America and Canada's \$62,630 and \$49,171, respectively. This suggests that a higher economic level is linked to a decrease in environmental deterioration as per the Environmental Kuznets Curve concept.

According to the summary of descriptive statistics summary, the United States of America and Canada have the highest average energy consumption in the region. This economic disparity is also reflected in energy consumption per capita; Canada's consumption stands at 119,162 kW hours per capita, a figure that reflects its industrial activity, compared to Haiti's mere 1325-kW hours per capita.

Differences in trade openness are also evident; Panama shows a high level of trade openness at 94.5 %, indicating strong global integration, which could have implications for both environmental and economic outcomes. In contrast, Guyana, Antigua and Barbuda exhibit the highest average levels of trade openness. These findings align with the EKC

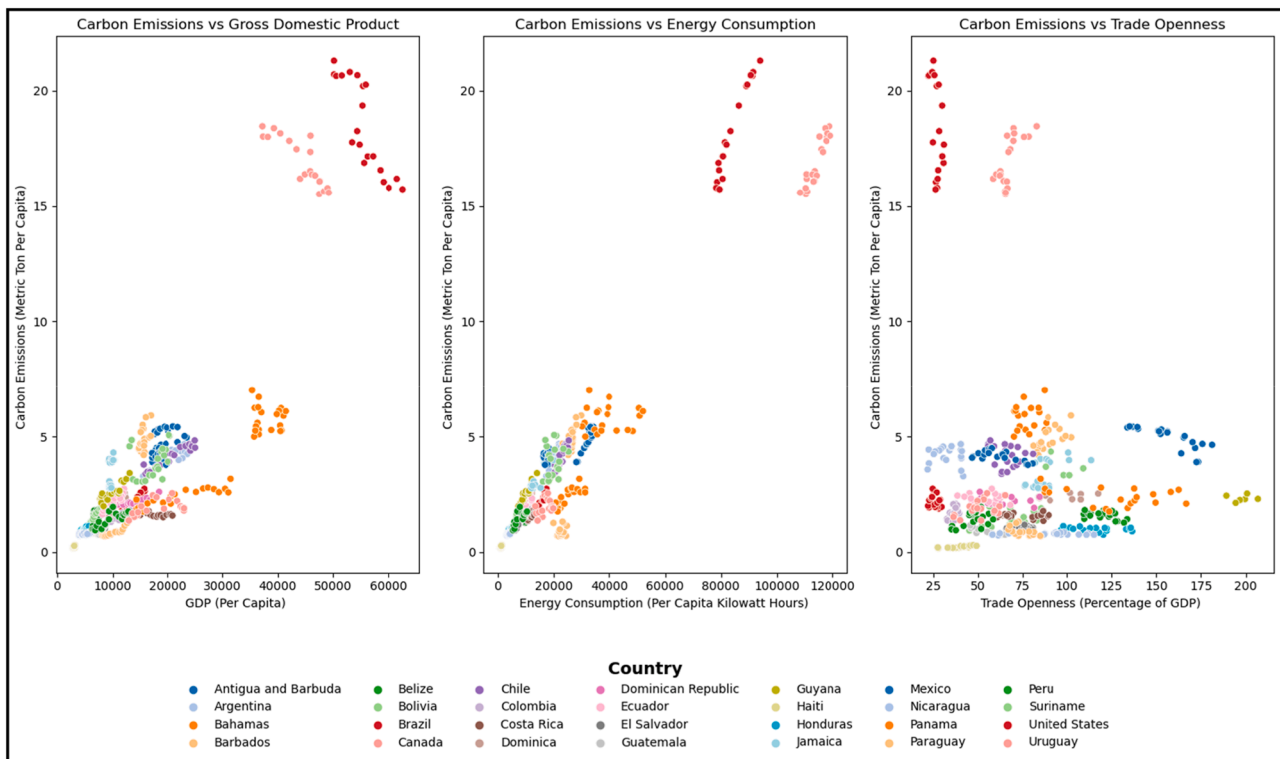


Fig. 2. Comparative Analysis of Carbon Emissions: Correlations with GDP, Energy Consumption, and Trade Openness. Source: Authors' illustrations based on Our World in Data (Our World in Data 2023) Our World in Data (Our World in Data 2023).

hypothesis, which suggests that as income levels rise, carbon emissions initially increase and later decline due to advancements in technology and environmental awareness (Adebayo et al., 2024).

3.1.1. Carbon emissions: regional variations and economic correlates

3.1.1.1. Carbon emissions across developed and developing nations. A thorough analysis of the MLR test results for several American nations, focusing on key metrics such as energy consumption, GDP per capita, and trade openness, reveals important insights. The R-squared (R^2) and adjusted R^2 values demonstrate the model's capacity to explain the variation in carbon emissions among nations. High R^2 values, such as 0.9665 and 0.9533 for the Bolivia and Canada, respectively, indicate that the model effectively captures the primary factors influencing emissions in these countries. Conversely, nations such as the Bahamas ($R^2 = 0.1543$) and Nicaragua ($R^2 = 0.1364$) display lower R^2 values, suggesting that additional variables may be necessary to fully understand their emissions patterns.

3.1.1.2. GDP and carbon emissions: economic activity and environmental impact. Countries like Argentina, Bolivia, Dominica, Honduras, Nicaragua, Panama, and Paraguay, GDP has a positive and significant impact on carbon emissions. This implies the environmental trade-offs associated with economic growth (Taiming et al., 2023). This finding observed similar trends in emerging economies were industrial expansion and reliance on fossil fuels drive emissions upward.

3.1.1.3. Energy consumption and its role in carbon emissions. On the other hand, in Canada, El Salvador, Guatemala, Jamaica, Mexico, the United States of America, and Belize, GDP has a negative and significant impact on carbon emissions, indicating that economic growth in these countries does not necessarily lead to increased carbon emissions (Lorente et al., 2023). The negative impact of economic growth on carbon emissions in these countries could be attributed to the

implementation of environmental policies and regulations aimed at reducing carbon emissions. The establishment of these policies has contributed to the decoupling of economic growth from carbon emissions (Hirai, 2022).

3.1.1.4. Trade openness and environmental outcomes. The relationship between trade openness and carbon emissions demonstrated mixed results. In some nations, such as Antigua and Barbuda and Guyana, greater trade openness correlated with higher emissions and emphasized the environmental costs of increased trade-related transportation (Pata et al., 2023). However, in other countries such as Panama and Belize, the impact was minimal, likely due to efforts to diversify trade activities and improve energy efficiency within supply chains. These findings highlight the complex interplay between trade and environmental sustainability (Fatima et al., 2020). Countries with robust trade policies promoting sustainable practices, such as environmental certification programs and reduced trade barriers for green products, may experience less adverse environmental impacts from trade openness.

3.1.2. Statistical aberrations and potential outliers

The analysis of the 28 countries in our study revealed certain statistical aberrations and potential outliers. For example, the United States of America and Canada exhibited significantly higher carbon emissions relative to their GDP per capita, which could be due to their reliance on high-carbon energy sources or specific economic factors unique to these countries. Conversely, smaller economies like Haiti reported lower emissions than expected, potentially due to underreported energy consumption data or discrepancies in trade figures.

3.2. Multivariate regression analysis: key determinants of carbon emissions

3.2.1. Model performance: R^2 values and interpretation

However, in other countries such as Argentina, Bolivia, and

Paraguay, economic growth continues to drive up carbon emissions, implying that more effective environmental regulations are necessary to ensure that GDP growth is sustainable and environmentally benign (Zhen et al., 2022). These findings underscore the importance of ongoing research into the interactions between GDP, energy consumption, trade openness, and carbon emissions, as well as the need for countries to develop successful policies that ensure sustainable economic growth.

3.2.2. Impact of GDP on carbon emissions

Energy consumption has a positive and significant impact on carbon emissions in some countries, such as Antigua and Barbuda, Brazil, Canada, Jamaica, Mexico, Nicaragua, and the United States of America, whereas it has a positive but minor impact in others, such as Barbados, Bolivia, Chile, Costa Rica, the Dominican Republic, El Salvador, Guatemala, Guyana, and Haiti. The study highlights the importance of considering other factors that may influence the relationship between energy consumption and carbon emissions.

3.2.3. Energy consumption as a predictor of carbon emissions

In certain other countries, including Belize, Dominica, Honduras, Panama, Papua New Guinea, Paraguay, and Uruguay, no substantial connections are found between energy consumption and carbon emissions. This suggests that these countries may have adopted effective strategies to promote sustainable energy use and reduce carbon emissions (Zhen et al., 2022). It also highlights the importance of developing effective policies and regulations throughout the American region to promote sustainable energy consumption and reduce carbon emissions (Takeshi et al., 2020).

3.2.4. Trade openness and environmental outcomes

The positive impact of trade openness on carbon emissions in some countries suggests that regulations supporting sustainable trade practices and environmental protections may be necessary to mitigate the adverse environmental impact of trade (Fuzhong et al., 2021). The findings also indicate that trade openness does not always result in higher carbon emissions across all countries, and other factors, such as the adoption of renewable energy sources, may play critical role in reducing carbon emissions (Fuzhong et al., 2021). Furthermore, the findings suggest that in certain countries, policies promoting sustainable trade practices and environmental regulations may be essential to mitigate the negative impact of trade on the environment.

3.3. Comparative analysis of carbon emissions and economic growth (2000–2007 vs. 2015–2022)

3.3.1. Shifts in top carbon emitters: North America vs. South America

The study's findings on the impact of economic growth, energy consumption, and trade openness on carbon emissions in the American region reveal a complex and contrasting picture. These results emphasise the need for tailored policies and strategies to encourage sustainability and mitigate carbon emissions, as well as the importance of sustainable trade practices and regulations (Alier, 2009). Overall, the study underscores the importance of continued research and the implementation of effective policies and strategies to promote sustainable economic growth, energy consumption, and trade practices in the American, thereby reducing carbon emissions. A comparison of carbon emissions between 2000–2007 and 2015–2022, is shown in Fig. 2.

3.3.2. Evolution of energy consumption patterns

In the period 2000–2007, the United States of America was the highest emitter, with 20.26 metric tonnes per capita, followed by Canada with 18.06, the Bahamas with 6, Barbados with 4.6, and Antigua and Barbuda with 4.3. However, in 2015–2022, the United States of America had reduced its carbon emissions to 15.73 metric tonnes per capita, followed by Canada with 15.58, the Bahamas with 5.7, Antigua

and Barbuda with 5.4, and Chile with 4.83. Despite the decrease, the United States of America and Canada remain among the top five emitters, indicating the need for continued efforts to reduce their carbon footprint.

In Fig. 3. A, the top five carbon emitters from 2000–2007 are all North American countries, namely the United States of America, Canada, the Bahamas, Barbados, and Antigua and Barbuda. However, Fig. 3. B shows that the top five carbon emitters from 2015–2022 include South American nations such as Chile, Argentina, Guyana, Panama, and Ecuador, in addition to Antigua and Barbuda. This suggests a shift in the distribution of carbon emissions from North America to South America.

Further analysis reveals that many South American countries have experienced an increase in carbon emissions between 2000–2007 and 2015–2022. For instance, Brazil, Colombia, and Bolivia have all seen significant increases in carbon emissions over the past decade, making them some of the highest emitters in South America. This may be attributed to rising energy consumption and subsequent carbon emissions due to growing industrialisation and economic development in these countries (Zaharia et al., 2019).

3.3.3. Regional disparities in carbon emissions and economic growth

Conversely, North American nations like the United States of America and Canada have reduced their carbon emissions over the past decade. This reduction may be linked to various laws and programmes aimed at reducing carbon emissions and promoting renewable energy (Phuc Nguyen Canh, Schinckus Christophe, and Dinh Su Thanh 2020). However, other North American countries, such as Mexico and Costa Rica, have experienced an increase in carbon emissions, indicating the need for more comprehensive measures to address climate change in these regions.

This comparison highlights the shift in the distribution of carbon emissions from North to South America. While some South American countries have experienced significant increases in carbon emissions, North American countries have shown a decrease in their carbon footprint. Nevertheless, continued efforts are needed to reduce carbon emissions across all countries in the Americas. A comparison of the top five GDP countries between 2000–2007 and 2015–2022, as shown in Fig. 4, illustrate the progress made in economic growth over the past decade.

3.4. Economic growth and environmental impact

3.4.1. Analysis of GDP growth

Fig. 4. A shows that in the period 2000–2007, the United States of America had the highest GDP per capita at \$51,609, followed by the Bahamas at \$40,563, Canada at \$39,906, Mexico at \$17,503, and Argentina at \$18,174. However, Fig. 4. B shows that in 2015–2022, the United States of America still had the highest GDP per capita at \$62,630, followed by Canada at \$49,171, the Bahamas at \$36,432, Panama at \$31,440, and Chile at \$24,967. The increase in GDP can be attributed to a range of factors, including technological advancements, increased productivity, and globalisation. For instance, technological innovations in the manufacturing and service sectors have improved productivity and efficiency, allowing goods and services to be produced at a lower cost, thereby boosting economic growth (International Monetary Fund 2008). Additionally, globalisation has enabled countries to access larger markets and benefit from economies of scale, contributing to economic expansion.

However, the increase in economic growth also has implications for the environment, particularly concerning carbon emissions. Between 2000 and 2007, and 2015 and 2022, carbon emissions increased in various nations. For instance, carbon emissions rose in Antigua & Barbuda, Chile, and Argentina during the period under consideration. The reliance on fossil fuels, industrialisation, and transportation are significant contributors to the increase in carbon emissions. Therefore, countries must strike a balance between environmental sustainability

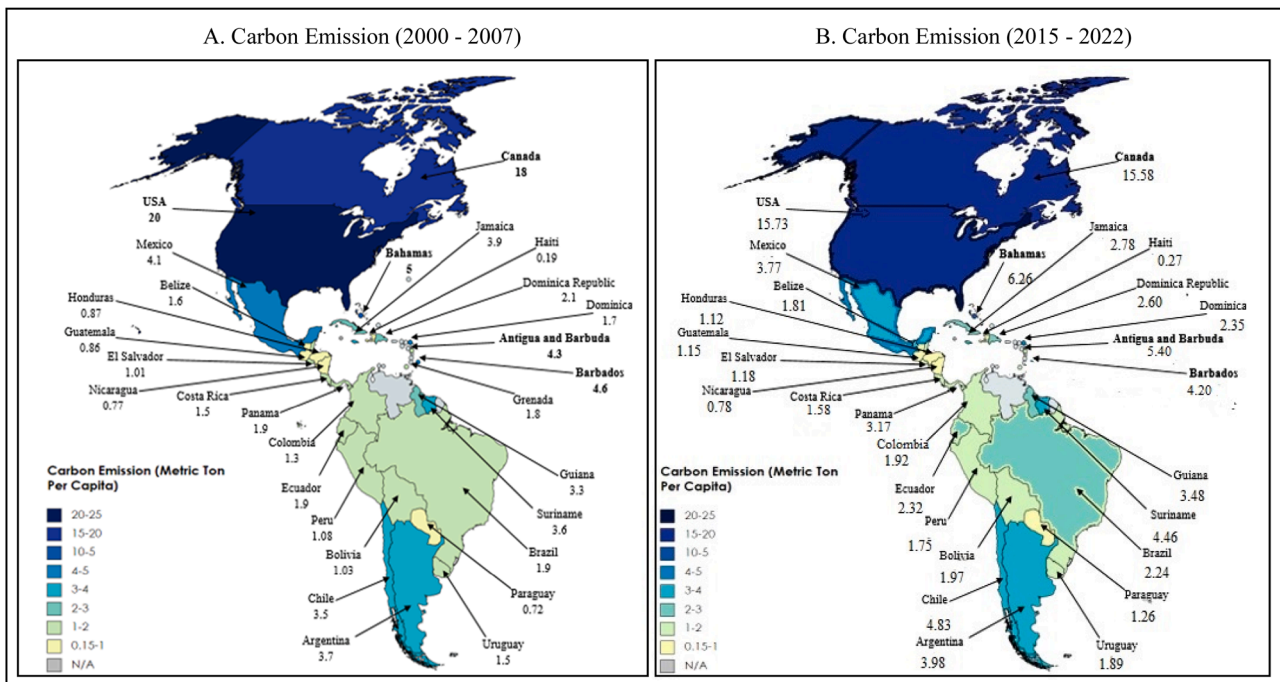


Fig. 3. Temporal Changes in Carbon Emission Across the American Region between 2000–2007 and 2015–2022. Source: Authors’ illustrations based on Our World in Data (Our World in Data 2023) Our World in Data (Our World in Data 2023). Note: Data is not available for the following countries: Grenada, Saint Lucia, and the Grenadines, Trinidad and Tobago, Saint Kitts and Nevis, Cuba, Venezuela.

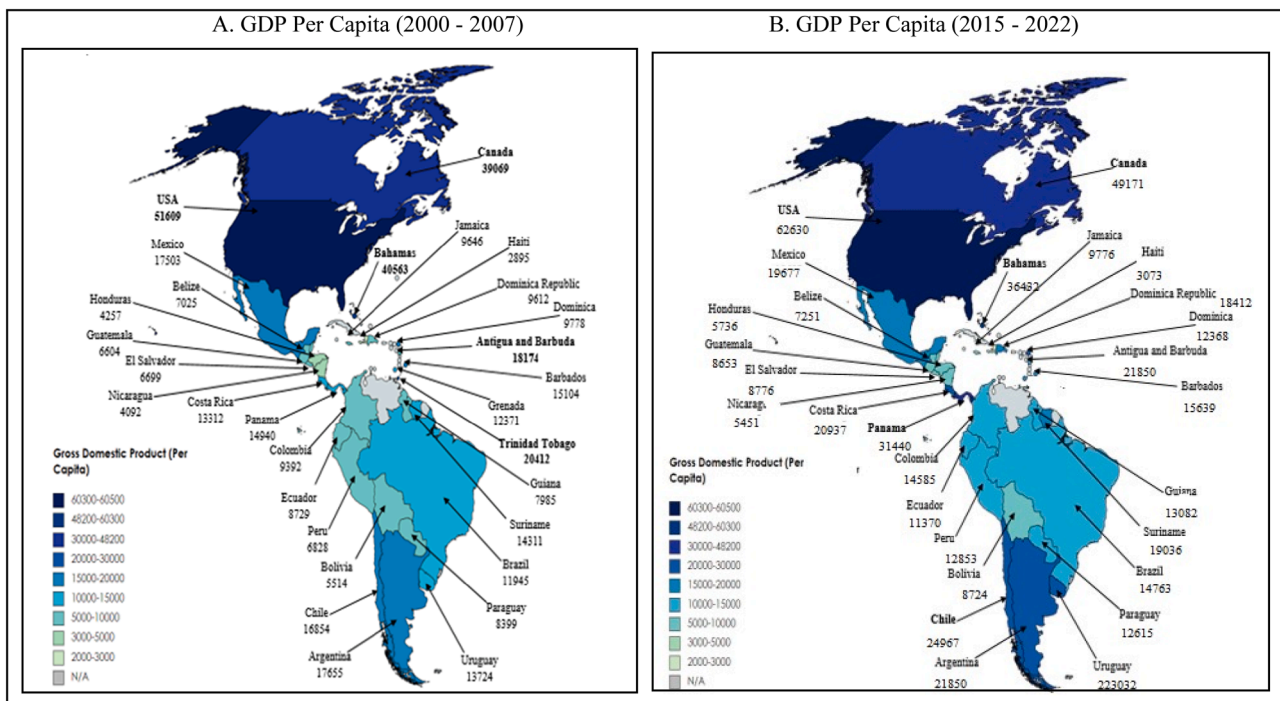


Fig. 4. Temporal Changes in GDP Per Capita Across the American Region between 2000–2007 and 2015–2022. Source: Authors’ illustrations based on Our World in Data (Our World in Data 2023) Our World in Data (Our World in Data 2023). Note: Data is not available for the following countries: Grenada, Saint Lucia, Saint and the Grenadines, Saint Kitts and Nevis, Cuba, Venezuela.

and economic prosperity. Governments should prioritise initiatives that encourage carbon emissions reduction and sustainable economic growth. For example, investing in renewable energy sources such as solar and wind power can help reduce dependence on fossil fuels (Brannstrom Christian 2023). Additionally, implementing policies that promote energy efficiency, such as fuel-efficient transportation,

energy-efficient buildings and appliances, and sustainable land use practices, can further contribute to reducing carbon emissions (Fabiana et al., 2020). This highlights the need for a balance between economic growth and environmental sustainability. While GDPs are rising globally, indicating economic progress, this development should not occur at the expense of the environment. Therefore, it is crucial for governments

and policymakers to prioritise measures that promote sustainable economic growth while reducing carbon emissions, contributing to a more sustainable future.

3.5. Energy consumption patterns

In 2000–2007, the top five energy-consuming countries were Canada, the United States of America, the Bahamas, Antigua and Barbuda, and Barbados. Among these, Canada and the United States of America had the highest energy consumption levels at 117,744 and 90,654 respectively. However, in 2015–2022, the top five energy-consuming countries had shifted to Canada, the United States of America, the Bahamas, Antigua and Barbuda, and Panama, with a noticeable decrease in energy consumption observed in the United States of America. The decrease in energy consumption, shown in Fig. 5, is consistent with the reduction in carbon emissions. This suggests that policies and initiatives aimed at reducing energy consumption and promoting energy efficiency in the United States of America may have contributed to the decrease in carbon emissions over the past decade. Similarly, Canada has also reduced its energy consumption over the past decade, which may have contributed to the decrease in carbon emissions. However, despite the decrease in energy consumption in some countries, overall global energy consumption continues to rise, which has implications for climate change and sustainable development (Pata, 2018). Diverse energy consumption patterns across the world should be noted. For instance, compared to developing countries, industrialised countries often have higher levels of energy consumption due to more developed economies, higher living standards, and more energy-intensive sectors. While developed nations typically have lower levels of energy consumption, developing nations are more vulnerable to the effects of climate change. This highlights the necessity of international cooperation and support to advance sustainable development and address the challenges posed by climate change (Inaki et al., 2016).

In conclusion, the comparison in Fig. 5. A and B highlights the top five energy-consuming countries in 2000–2007 and 2015–2022, with a notable decrease in energy consumption observed in the United States of

America. This decrease in energy consumption is consistent with the reduction in carbon emissions, indicating the need for continued efforts to promote energy efficiency and sustainable consumption patterns at the global level. It is important to recognise that energy consumption patterns vary across different regions, and a global approach is needed to address the challenges of climate change and sustainable development. The comparison of the top five trade openness countries from 2000–2007 and 2015–2022, as shown in Fig. 6, provides insights into the changing economic landscape and its impact on carbon emissions.

3.6. Trade openness and carbon emissions

3.6.1. Impact of trade openness

Fig. 6. A shows that in 2000–2007, the top five countries with the highest trade openness were Antigua and Barbuda, Panama, Honduras, and Belize. These countries had trade openness values ranging from 84 to 139. A high level of trade openness may result in increased economic activities and subsequently increased energy consumption, leading to higher carbon emissions. Fig. 6. B shows that in 2015–2022, the top five countries with the highest trade openness were Antigua and Barbuda, Belize, Dominica, Honduras, and Nicaragua, with trade openness values ranging from 95.39 to 137.00. Notably, Antigua and Barbuda and Belize were among the top five countries with the highest trade openness in both periods, indicating a sustained demand for trade despite changes in economic activities. While trade openness can lead to economic growth, it also has the potential to increase carbon emissions, which can have negative impacts on the environment (Chaoqing et al., 2017).

The relationship between trade openness and carbon emissions is complex and varies depending on factors such as economic growth, energy consumption, and industrialisation. Countries with higher trade openness may have a higher demand for energy and resources, leading to increased carbon emissions. The comparison between the top five countries in terms of trade openness from 2000–2007 and 2015–2022 can provide valuable insights into changes in economic activities and their impact on carbon emissions. The comparison between the top five carbon emissions countries and top five trade openness countries offer a

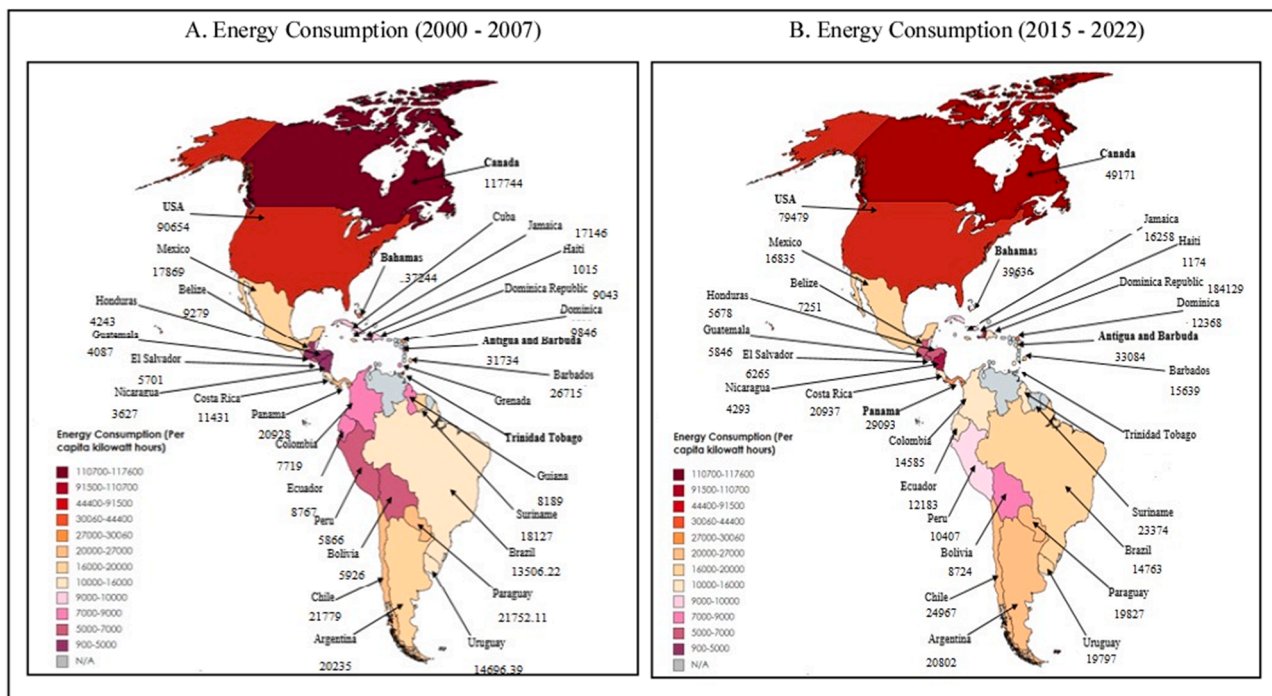


Fig. 5. Temporal Changes in Energy Consumption Across the American Region between 2000 - 2007 and 2015 - 2022. Source: Authors' illustrations based on Our World in Data (Our World in Data 2023). Note: Data is not available for the following countries: Grenada, Saint Lucia, and the Grenadines, Saint Kitts and Nevis, Cuba, Venezuela.

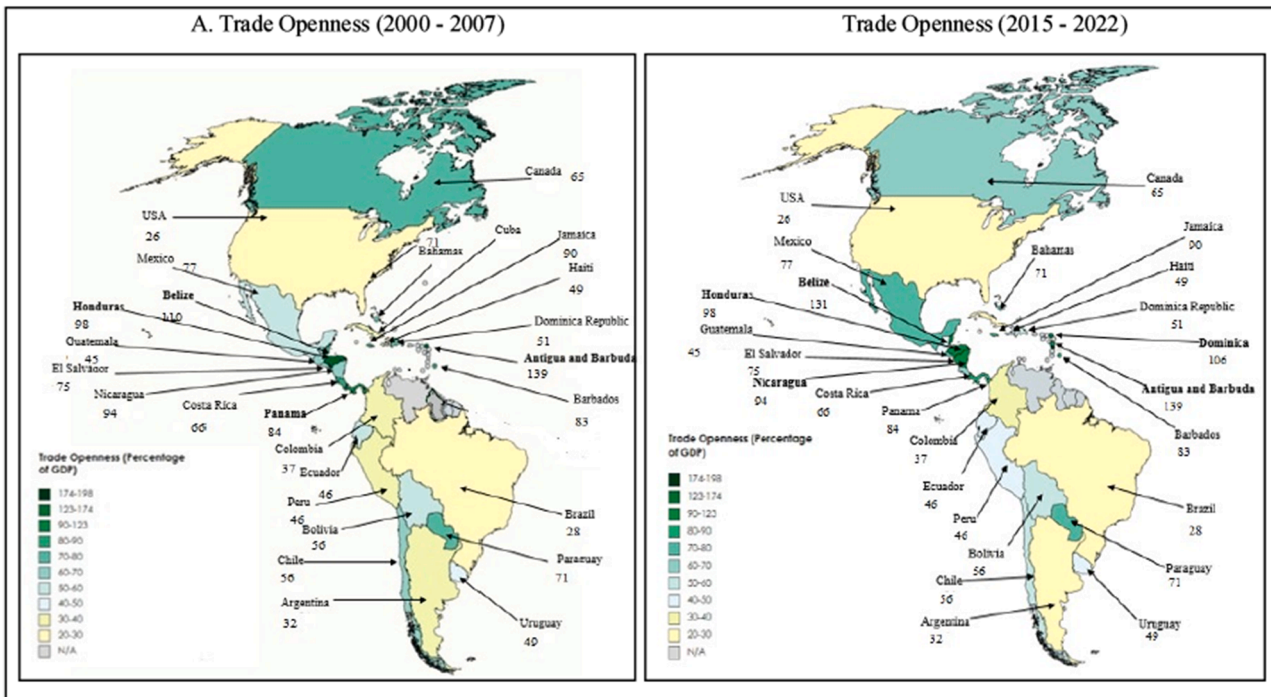


Fig. 6. Temporal Changes in Trade Openness Across the American Region between 2000 - 2007 and 2015 - 2022. Source: Authors' illustrations based on Our World in Data (Our World in Data 2023). Note: Data is not available for the following countries: Grenada, Saint Lucia, and the Grenadines, Trinidad and Tobago, Saint Kitts and Nevis, Cuba, Venezuela.

more comprehensive understanding of the relationship between economic activities and carbon emissions (Du et al., 2020). The decrease in carbon emissions in the United States of America and Canada may be attributed to various policies and initiatives aimed at reducing carbon emissions and promoting clean energy, which may have also affected their trade openness. However, increases in trade openness in some countries may have led to increased energy demand and, consequently, higher carbon emissions (Zhifu et al., 2019). It is crucial to continue monitoring and addressing the environmental impact of economic activity and to promote sustainable development practices that balance economic growth with environmental sustainability.

3.7. Correlation between economic growth, energy consumption, carbon emissions, and the role of environmental policies

According to the environmental Kuznets curve framework, developed nations like the United States of America and Canada have considerably higher average carbon emission efficiencies than developing nations when comparing industrial growth stages (Qiang et al., 2023; Li et al., 2023). Nevertheless, the negative influence of GDP on carbon emissions in these nations suggests that economic expansion is now promoting environmental improvement, possibly due to the adoption of sensible environmental laws. This is consistent with the EKC model, which posits that as societies prioritise environmental quality, environmental deterioration declines beyond a certain level of income.

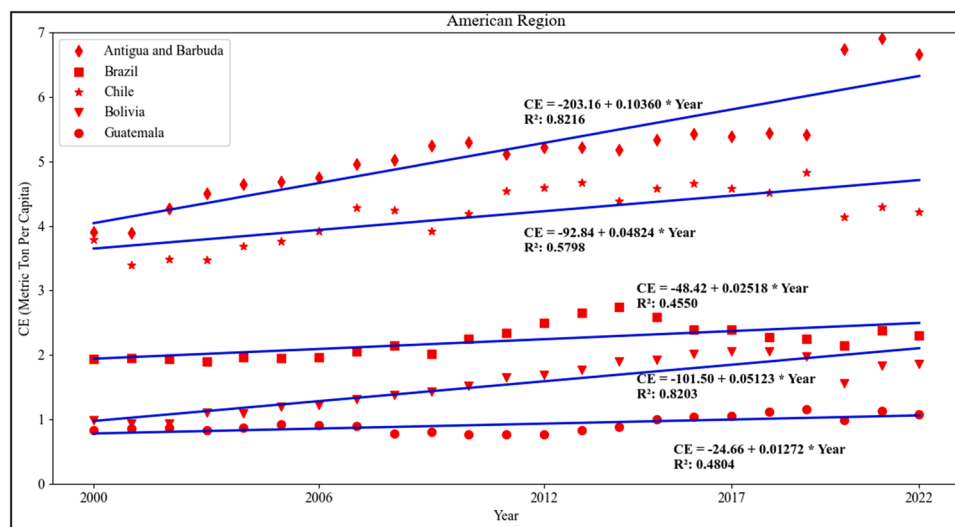


Fig. 7. Linear Fit Scatter Plot Graphs for American Region High Carbon Emitting Countries. Source: Authors' illustrations based on Our World in Data (Our World in Data 2023).

The results indicate that GDP expansion has not only raised living standards but also significantly increased carbon emissions in wealthy countries such as the United States of America and Canada. However, in many countries, the disconnect between GDP and carbon emissions suggests that economic growth is becoming more common while causing less environmental harm, likely due to improved social and environmental regulations (Methmini et al., 2024; Dissanayake et al., 2023). Fig. 7 illustrates numerous high-carbon emitting nations in the American region, demonstrating the significant relationship between the variables.

3.7.1. Positive correlation between GDP, energy consumption, and trade openness

All five countries show a positive correlation between GDP, energy consumption, and trade openness over time, reflecting economic growth and increased energy consumption and trade openness. In contrast to the other nations, Bolivia exhibits more variability, whereas Antigua and Barbuda have a positive trend. These five nations experienced significant economic growth and industrialisation over time. As a result, trade openness, GDP per capita, and energy consumption have all increased. However, as the significant association between the variables indicates, higher economic activity also leads to increased carbon emissions. This finding aligns with previous studies that have demonstrated the link between energy consumption, GDP per capita, and carbon emissions (Petar et al., 2023). While some countries showed a decrease in carbon emissions, others exhibited an increase. The variation in result underscores the complexity of the relationship between energy consumption, GDP, trade openness, and carbon emissions.

3.7.2. The role of sustainable energy practices

The significance of sustainable energy practices is highlighted by the disparate effects of energy consumption on carbon emissions in various countries. It is possible that nations like Belize, Dominica, and Panama, where energy consumption has little effect on carbon emissions, have effectively incorporated sustainable energy methods, in line with the 3Ps Framework of Sustainability (Dharmapriya et al., 2024). The negative effect of GDP on carbon emissions in the United States of America, Canada, and Mexico suggests that these nations have strong environmental policies promoting sustainable growth. This supports the Porter hypothesis by demonstrating that stringent environmental laws can achieve economic benefits without compromising environmental integrity (Bitat, 2018). According to researchers and available data, the significance levels of energy consumption, GDP per capita, trade openness, and carbon emissions are not properly addressed in previous statistical models. Only a few studies have used graphical tools to depict the influence of carbon emissions across the entire region (Pata, 2018). To achieve the target of being carbon neutral by 2050, it is essential to address the research gap concerning the impact of energy consumption, GDP per capita, and trade openness on carbon emissions for the entire American region.

3.8. Policy implication

The results of this study clearly indicate the need for policies aimed at reducing carbon emissions in the American region. The implications extend across regulatory frameworks, economic incentives, and international collaboration, highlighting the need for systemic changes.

3.8.1. Stronger carbon pricing mechanisms

Stricter environmental regulations are required to address the issue of high carbon emissions in countries like Argentina, Bolivia, and Paraguay. Governments should implement robust carbon pricing mechanisms, such as carbon taxes or cap-and-trade programmes, to provide financial incentives for businesses to lower their emissions. Additionally, a cap-and-trade system should be developed, setting initial emission caps based on current national levels and gradually tightening

these limits over time. This approach would create economic incentives for businesses to reduce their carbon footprint and invest in cleaner technologies.

3.8.2. Fostering innovation in renewable energy and energy efficiency

Promoting innovation in energy efficiency and renewable energy can be achieved by offering tax breaks and subsidies for research and development in green technology. This approach supports the Porter Hypothesis, which argues that stringent environmental regulations can drive innovation in energy efficiency and renewable energy, tax credits should be offered for investments in solar panels and energy-efficient technologies, alongside grants and low-interest loans for green technology research and development. Setting targets for renewable energy and offering financial incentives, such as grants and low-interest loans, to encourage the installation of solar, wind, and other renewable energy systems are essential. Over time, this strategy will encourage cleaner practices and technologies, leading not only to reduced carbon emissions but also to sustainable economic growth.

3.8.3. Trade policies for sustainable development

Trade policies can also contribute to reducing carbon emissions by promoting sustainable practices and minimising the environmental impact of global supply chains. Governments should work to lower trade barriers for environmentally friendly products and introduce certification programmes for goods that meet specific environmental standards.

3.8.4. Sustainable urban planning

Policy-makers should focus on promoting sustainable urban planning to reduce carbon emissions from buildings and transportation. This could involve investing in public transportation systems, supporting denser and more walkable neighbourhoods, and encouraging green building practices.

3.8.5. Regional collaboration and knowledge sharing

American region effectively requires collaboration and knowledge-sharing among countries. By pooling resources and expertise, governments can accelerate the adoption of policies, leverage best practices, and develop innovative and cost-effective methods to reduce carbon emissions through regional cooperation. Collaborative efforts could include the coordination of policy frameworks, research initiatives, and technology transfer activities.

Reducing carbon emissions in the American region necessitates a comprehensive approach that integrates policies to promote renewable energy sources, carbon pricing, sustainable trade, and sustainable urban planning. By implementing these policies, governments can reduce their carbon footprint and mitigate the adverse effects of climate change.

3.9. Limitations and future research

Despite providing valuable insights, this study has several limitations that should be considered when interpreting the findings.

3.9.1. Model limitations

Although the relationships between carbon emissions and the independent variables were analysed using a MLR model in this study, residual analysis indicated the possibility of non-linearities in the data, as indicated by the pattern in the error term. This implies that the MLR model might not fully capture all underlying dynamics, and future research should think about fine-tuning the model by adding non-linear transformations, interaction terms, or using more advanced techniques like Generalised Additive Models (GAMs) or machine learning methods to account for non-linear relationships. These refinements could provide a more accurate and robust understanding of the factors influencing carbon emissions, especially in situations with complex, non-linear interactions.

3.9.2. Data availability and representativeness

This study examines the relationships between energy consumption, GDP, trade openness, and carbon emissions using a panel dataset of 28 American nations. However, due to data limitations, certain countries were not included: Grenada, Saint Lucia, and the Grenadines, and Trinidad and Tobago lacked trade openness data; Saint Kitts and Nevis did not have carbon emissions data; and Cuba and Venezuela were missing GDP data. This limitation could impact the representativeness of the findings. Future research could incorporate these nations into the dataset once data becomes available.

3.9.3. Broader variable inclusion

This study focused on energy consumption, GDP, and trade openness. However, other factors including variables such as technological advancements, industrialisation, population growth, and urbanisation could provide a more comprehensive analysis.

3.9.4. Exploration of regional synergies

Evaluating the effectiveness of programmes aimed at reducing carbon emissions and exploring the impact of carbon taxes and clean energy legislation on GDP, trade openness, and energy consumption would also be beneficial.

Addressing these limitations and exploring the suggested research avenues will contribute to a more comprehensive understanding of the complex factors influencing carbon emissions and inform more effective policymaking.

4. Conclusion

This research set out to investigate the impact of energy consumption, GDP, and trade openness on carbon emissions across 28 countries in the American region. Through the evaluation of data from 2000 to 2022 using multiple regression analysis, maps, and scatter plots, this study has provided key insights into the factors influencing carbon emissions.

The findings underscore that in nations like Argentina, Bolivia, and Paraguay, higher rates of economic growth are frequently associated with elevated levels of carbon emissions. Conversely, in countries such as the United States of America, Mexico, and Canada, economic development does not appear to be correlated with increased carbon emissions. Energy consumption plays a significant role in driving carbon emissions in the region, with a clear association observed in high-energy-consuming nations like the United States of America, Mexico, and Brazil. The study also reveals that trade openness has a mixed impact on carbon emissions—while greater trade openness leads to higher emissions in some nations, the effect is minimal in others.

The study offers a thorough empirical analysis of the relationships between GDP, energy consumption, trade openness, and carbon emissions in the American region, providing valuable information for both regional and national policymakers. It contributes to the ongoing debate surrounding the Environmental Kuznets Curve (EKC) model by demonstrating that the relationship between energy consumption and environmental degradation is not uniform across countries but rather depends on specific national contexts and policy regimes. This study fills a significant knowledge gap by examining the simultaneous influence of GDP, energy consumption, and trade openness on carbon emissions across the American continent.

Overall, the research highlights the need for policies and programmes that promote renewable energy sources, reduce energy consumption, and increase trade while minimising carbon emissions. Understanding the relationship between these variables is crucial for effectively addressing the challenges posed by climate change. The results of the study can assist policymakers and stakeholders in developing strategies to mitigate the impact of climate change on the American region.

Supporting Information

Appendix A. Comprehensive Overview of Descriptive Statistics for The Variables of Each Country

Appendix B. Tolerance and VIF from multiple regression of Countries in the American Region

Appendix C. Linear Fit Scatter Plot Graphs for Carbon Emitting Countries in the American region

Appendix D. Evaluating MLR Test: An In-depth Analysis of Each Country in the American region

CRedit authorship contribution statement

Dithma Methmini: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Nimesha Dharmapriya:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Sandali Edirisinghe:** Visualization, Conceptualization. **Vilan Gunawardena:** Writing – original draft, Visualization, Validation, Methodology, Data curation. **Ruwan Jayathilaka:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization. **Colinie Wickramaarachchi:** Writing – original draft, Validation. **Thanuja Dharmasena:** Writing – review & editing, Writing – original draft, Validation.

Declaration of competing interest

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

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.envc.2025.101140](https://doi.org/10.1016/j.envc.2025.101140).

Data availability

Data will be made available on request.

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