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COULD E-COMMERCE ACTIVITIES DRIVE TO CLIMATE CHANGE MITIGATION? NOVEL EVIDENCE FROM PANEL QUANTILE REGRESSION MODEL

Nicoleta Mihaela DORAN[1], Alina Georgiana MANTA[1✉], Gabriela BADAREU[1,2], Dorel BERCEANU[1], Marius Dalian DORAN[2], Florin Liviu MANTA[3]

[1]Department of Finance, Banking and Economic Analysis, Faculty of Economics and Business Administration, University of Craiova, Craiova, Romania
[2]Doctoral School of Economics and Business Administration, Faculty of Economics and Business Administration, West University of Timisoara, Timisoara, Romania
[3]Mechatronics and Robotics Department, Faculty of Automation, Computers and Electronics, University of Craiova, Craiova, Romania

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Abstract. This study aims at shedding light on how e-commerce contributes to climate change in European Union countries. To explore this relationship, we introduced a novel index designed to measure the evolution of climate change as the dependent variable, while considering e-commerce activities as the independent variable within 2011 to 2022 period. Our investigation of the correlation between these variables employed a panel quantile regression model. The outcomes revealed a statistically significant increasing trend for higher quantiles. This finding indicates that, as we traverse the climate change index from lower to higher percentiles, the impact of e-commerce becomes more conspicuous and is statistically significant. This underscores that the influence of e-commerce on climate change intensifies as we move towards the upper percentiles of the climate change index. To address how e-commerce affects climate change, it becomes imperative to introduce and enforce the concept of environmental responsibility in the management of e-commerce activities. This could involve adopting sustainable practices, optimizing packaging materials, and encouraging eco-friendly delivery methods. Policymakers and businesses alike should consider these findings in their efforts to strike an equilibrium between the convenience of e-commerce and the need to curb its environmental impact.

Keywords: e-commerce, climate change index, quantile regression, climate risks, mitigation, quantiles.

JEL Classification: C10, C22, L81, Q54.

✉Corresponding author. E-mail: ***alina.manta@edu.ucv.ro***

1. Introduction

Today, more than ever, there is a particular concern related to climate change, and most of the states have taken measures to diminish carbon emissions through the enactment of stricter legislation or establishing emission targets (Gracceva & Zeniewski, 2014). Since 2018, as part of the Paris Agreement, the European Union has adopted the European Climate Law, raising the EU target for diminishing net greenhouse gas emissions to at least 55% by 2030 (from the current 40%) and making achieving climate neutrality by 2050 a legal obligation

(The European Parliament, 2018). Given the ongoing popularity of online purchases in recent years, a significant opportunity emerges for e-commerce platforms to contribute to addressing climate change issues (Majoral et al., 2021; Islam et al., 2023). The rapid expansion in parcel volumes, coupled with the significant proportion of returned goods introduces new challenges concerning climate change, air pollution, and traffic management (Kristensen et al., 2013; Hollaus & Schantl, 2022). As a result, there is a strong debate regarding the impact of e-commerce on climate change. Some proponents argue that, under certain circumstances, it helps reduce pollution by decreasing energy consumption and enhancing eco-friendly transportation efficiency (Grand View Research [GVR], 2021; Edwards & McKinnon, 2009; Cairns, 2005). Other researchers oppose this hypothesis, asserting that customer demand for prompt product delivery contributes to an intensification of fuel consumption, given the need for rapid transport within delivery services, thereby compromising environmental sustainability due to increased CO_2 emissions and pollution from the packaging of each product, etc. (Xie et al., 2023; Yuan et al., 2022). These debates serve as evidence that the contribution of e-commerce is significant in shaping environmental sustainability, but it cannot be solely deemed a "solution" either. Therefore, it becomes imperative to investigate how e-commerce influences climate change and the manner in which it does so.

However, in current literature, limited attention has been given to exploring the correlation between e-commerce activities and their environmental ramifications, particularly concerning climate change. To bridge this research gap, our study endeavors to examine, for the first time on a pan-European scale, the influence of e-commerce practices on climate change. Our investigation promises novel insights by offering robust empirical evidence on the complex interplay between e-commerce dynamics and climate change phenomena. By employing panel research methodologies, our primary objective is to replenish existing lacunae in the scholarly literature by conducting a thorough analysis of how e-commerce operations impact climate change. The significant contributions we bring to the specialized literature through this study materialize in the detailed exploration of the connection between these two components, incorporating the most relevant indicators to the subject, such as composite index called the Climate Change Index and e-commerce activities indicator. Additionally, the method applied in this investigation has been less utilized in studies within this area of interest, but it has the capacity to determine the sign of influence and indicate whether a change in in-fluence occurs at a certain quantile.

In the past, the products most commonly sought for online purchase were those related to travel, entertainment, or durable goods such as fashion and electronics. The online market for groceries and other consumer goods is currently undergoing a period of growth, driven by companies seeking to enhance the efficiency of their delivery logistics and reduce delivery times (van Loon et al., 2015). Eurostat data indicates that by 2022, 91% of individuals aged 16–74 in the EU will have utilized the internet, with 75% of this demographic engaging in online purchases or ordering of goods or services for personal use. This represents a significant increase from 55% in 2012 to 75% in 2022, representing a 20-percentage point rise (Eurostat, 2023). Thus, we observe a considerable increase in consumers preferring online shopping, necessitating special attention to the relationship we are investigating to identify the risks of this activity and provide solutions and directions regarding the influence of e-commerce on climate change.

The objective of this paper is to examine the influence of e-commerce on climate change in the member states of the European Union, using a newly created index. The study seeks to determine whether e-commerce activities contribute to the worsening of climate change or, under certain conditions, may have a neutral or even positive effect on the environment. In line with the aim of this paper, we have formulated a series of research questions designed to clarify and explore in more detail the relationship between e-commerce and climate change. These include:

RQ1: To what extent do e-commerce activities contribute to the worsening of climate change in the member countries of the European Union?

RQ2: Are there specific conditions under which e-commerce may have a neutral or even positive impact on the environment?

RQ3: What policies and measures can be adopted to reduce the negative impact of e-commerce on climate change?

Thus, the findings of our research may prove to be of significant value to both the specialized literature and decision-makers in the public sector involved in formulating regulations and conditions for e-commerce within the European Union. These decision-makers should pay attention to the impact that e-commerce can have on climate change in the process of formulating appropriate policies.

The primary aim of this paper is to investigate how e-commerce activities specifically contribute to climate change within European Union countries, examining the nuanced effects of these activities on climate-related metrics. The study focuses on quantifying the environmental impact of e-commerce across varying levels of climate vulnerability, seeking to provide precise insights that inform policy and business strategies for mitigating these effects. This investigation centers on analyzing the relationship between e-commerce activity and climate change metrics in EU countries, with a particular emphasis on understanding how this impact varies across different levels of climate risk. By exploring the conditions under which e-commerce activities have a statistically significant effect on climate change, the study also evaluates the role of moderating factors such as environmental regulations and green logistics infrastructure. The findings aim to inform policy and business interventions that could be tailored to specific quantiles of climate impact, thereby helping to reduce the environmental footprint of the e-commerce sector in an evidence-based manner.

In addressing the current research gap, this paper builds upon existing literature that broadly assesses the environmental impact of e-commerce, moving beyond aggregated analyses to examine how the sector's influence fluctuates across regions with varying climate vulnerabilities. Previous studies have largely focused on the general carbon footprint of e-commerce, often neglecting how this impact differs across climate risk quantiles within the EU context. This research thus contributes a more granular perspective, employing quantile regression to reveal the differential impact of e-commerce activities on climate change. By identifying the conditions and regions most affected, the study addresses a critical gap in the literature and provides a foundation for developing tailored mitigation strategies for regions with heightened environmental risk.

The structure of the research is designed to offer a clear and detailed understanding of the analyzed subject. Consequently, Section 2 offers a comprehensive review of the literature, analyzing key studies and highlighting existing gaps in current knowledge. Section 3 details the data and methodology employed, explaining the processes of data collection and the analytical methods used to obtain robust results. Section 4 is dedicated to the presentation of findings and discussions, where the results are interpreted, and their implications are examined within the context of existing literature. Finally, Section 5 includes the conclusions and recommendations, synthesizing the main discoveries and offering suggestions for future research or practical applications of the findings.

2. Literature review

The influence of information and communication technology (ICT) on the natural environment has constituted a significant and multifaceted field of investigation in recent years (Weber, 2010). Research on the nexus between e-commerce and climate change was pioneered by Room (2002), gaining more interest after the 2007 financial crisis, with the significant rise of information technology and increased digitization of economic sectors, including e-commerce. This trend led to a surge in studies on this newly emerging field. However, according to the Web of Science database, there was a shortage of studies on this relationship, with fewer than 3 publications per year until 2017. After 2018, there was an acceleration in research in this field, with 2022 having the highest number of publications on e-commerce and climate change (14 papers). This increase is attributed to the intensified use of e-commerce during the COVID-19 pandemic. Consequently, this research area is relatively young but rapidly expanding, driven by the swift development of information technology and the growing interest in the environment.

Van Loon et al. (2015) explored the carbon footprint of online and traditional retail in the UK, identifying a link between travel choices, shopping basket size, and e-fulfillment on e-commerce sustainability. Using Life Cycle Assessment (LCA), they concluded that e-commerce could reduce environmental impact by minimizing shopping trips and increasing the volume of items per order (EPA, n.d.; Marathe et al., 2019).

Guo et al. (2017) examined logistics planning for fresh food e-commerce in Shanghai, emphasizing low-carbon strategies in both distribution and return stages. Similarly, Weber (2010) assessed energy and CO_2 emissions for music album deliveries, showing that digital purchases reduce emissions by 40% to 80% compared to physical CDs, particularly if CDs are disposed of through burning, using Monte Carlo simulations.

Borggren et al. (2011) investigated the environmental impact of paper books and highlighted that online purchases and shared book usage have a lower footprint than traditional bookstore purchases. Their findings contributed significantly to understanding the interplay between e-commerce and climate change.

Heard et al. (2019) analyzed the environmental impact of meal kits versus grocery store purchases in the U.S., considering greenhouse gas emissions, water use, and land use. Their LCA revealed that meal kits produce 33% fewer emissions than traditional grocery shopping, advocating for their adoption due to reduced ingredient waste and packaging efficiency. Together, these studies provide valuable insights into the diverse environmental implications of e-commerce across sectors.

Koengkan et al. (2022) conducted the first European-level study linking e-commerce and climate change, focusing on Battery Electric Vehicles (BEVs). Using quantile regression and fixed-effects Ordinary Least Squares (OLS) on data from 29 countries (2010–2020), the study revealed that e-commerce exacerbates environmental harm through increased packaging, processor use, and cryptocurrency transactions. To mitigate these impacts, the authors recommended energy conservation policies and smaller packaging to optimize transport.

Caiyi et al. (2022) explored the connection between e-commerce and solid waste in China (2001–2017) using Dynamic Ordinary Least Squares (DOLS). Their findings demonstrated the existence of the Environmental Kuznets Curve (EKC) in most regions, except for the Yellow River area, where e-commerce consistently increased solid waste. These insights underline the need for targeted ecological regulations to support sustainable development in online commerce.

Masele (2011) emphasized the role of e-commerce and m-commerce technologies in reducing carbon emissions, especially in sustainable tourism. Conversely, Jaller and Pahwa (2020) highlighted the environmental harm caused by delivery vehicles associated with e-commerce, while Cheba et al. (2021) linked urban e-commerce activities to environmental degradation, particularly in regions with intensive market activity.

Majoral et al. (2021) examined the externalities of e-commerce deliveries and proposed environmental taxes to address these issues. Their case study in Barcelona assessed the costs and benefits of such taxes, particularly targeting the final distribution stage. Similarly, Islam et al. (2023) introduced the Sustainable E-commerce with Environmental-impact Rating (SEER) system, which reduces e-commerce's carbon footprint by promoting climate-conscious purchasing behaviors among consumers.

In China, Wang et al. (2023) and Zhang et al. (2024b) investigated e-commerce's role in reducing CO_2 emissions under the National E-Commerce Demonstration City (NEDC) policy. Both studies confirmed that policy-driven e-commerce expansion contributes to carbon reduction strategies. Wu et al. (2023) extended this analysis to assess the broader digital economy, revealing that digital technologies, including e-commerce, have a greater carbon footprint in high-emission provinces, emphasizing regional disparities in their environmental impact.

Consequently, according to these studies, the nexus between digital commerce and climate change is a controversial subject. Many researchers (Masele, 2011; GVR, 2021; Edwards & McKinnon, 2009; Cairns, 2005; van Loon et al., 2015; Weber, 2010; Borggren et al., 2011; Heard et al., 2019; Zhang et al., 2024b), support the positive contribution of e-commerce to climate change, but there are also empirical studies that deny the positive impact (Islam et al., 2023; Cheba et al., 2021; Xie et al., 2023; Caiyi et al., 2022). Additionally, we have identified that most studies are conducted at the level of a single country, lacking panel investigations, which could be more relevant regarding the impact of e-commerce on climate change.

Furthermore, recent strands in literature point to numerous approaches to mitigating the climate change impacts of e-commerce activities, given the key role that digitalization and sustainability practices can play in supporting the green transition. Thus, recent research underscores the potential of e-commerce to mitigate climate change impacts through digitalization and sustainable practices. Digital innovations, such as improved logistics and efficient supply chain management, play a pivotal role in reducing carbon footprints. For instance, Tabe-Ojong et al. (2024) and Dong et al. (2023) demonstrate how technological advancements and pilot e-commerce policies in China contribute to low-carbon development. Similarly, integrating digital economies with sustainable agriculture facilitates greener practices, as shown by Han et al. (2023), who emphasize the role of green innovation mechanisms in developed regions, and Quarshie et al. (2023), who highlight the potential of IoT technologies to support climate-smart agriculture.

Policy coordination is equally vital. Armstrong (2023) illustrates the success of multigovernmental cooperation in California's energy aggregation initiatives, while Ohta and Barrett (2023) identify challenges in implementing green energy policies in Japan. Such findings underline the importance of robust, collaborative frameworks in driving climate mitigation. On the consumer side, Islam et al. (2023) reveal that environmental impact rating systems on e-commerce platforms, such as SEER, can bridge the behavioral gap toward sustainable consumption by influencing eco-conscious choices.

Addressing social and ecological vulnerabilities, Ahmed et al. (2023) highlight the effects of climate change on nomadic Himalayan communities, stressing the need for integrated adaptation strategies. In the agricultural sector, Mandal et al. (2023) propose the use of biostimulants to enhance crop resilience to environmental stresses, a method particularly relevant in the context of rising global temperatures. Furthermore, public education and awareness are critical in addressing climate risks, as Rana et al. (2023) demonstrate in their analysis of urban adaptation strategies in informal cities.

The circular economy and efficient waste management also play a central role. Kurniawan et al. (2024) emphasize the integration of digital solutions to optimize recycling and resource use, which are important for sustainable e-commerce practices. Complementing this perspective, Mokni et al. (2024) and Heydari (2024) argue that sustainability-oriented regulations can stabilize economic uncertainties while promoting responsible consumption behavior. Similarly, investment strategies geared toward climate transition, as outlined by Xiang et al. (2024), and enhanced transparency in climate risk reporting, discussed by Khalifa et al. (2024), can encourage sustainable economic practices and attract environmentally conscious investors.

The role of the forestry and construction industries in climate change mitigation intersects with e-commerce's potential. Hurmekoski et al. (2023) demonstrate how the expansion of wood-based materials in construction and textiles reduces emissions, a principle that can also be applied to eco-friendly e-commerce packaging solutions. Similarly, Bhebhe and Ndlovu (2023) highlight the financial risks associated with climate impacts on stock performance, reinforcing the importance of e-commerce's adoption of green practices to reduce business vulnerabilities in a changing climate.

From an economic perspective, Liu et al. (2023) and Awuni et al. (2023) emphasize that aligning e-commerce operations with climate-smart principles can bolster resilience to economic and environmental risks. These strategies include adopting energy-efficient logistics and fostering collaboration within supply chains to optimize resources. Additionally, Wu et al. (2023) show that integrating sustainable energy technologies into digital commerce models has a dual benefit of reducing emissions and promoting economic stability.

Access to accurate and applicable information remains a cornerstone of effective climate action. Rainer (2025) underscores the importance of data accessibility in raising climate awareness, though Hall et al. (2024) caution that global interconnectivity can complicate information dissemination. This interplay between awareness and action is further reflected in Duncan et al. (2024), who argue that individuals with high socioeconomic status can drive the adoption of sustainable practices through their consumption behavior. Supporting this view, Asibey and Yeboah (2024) highlight the role of collective adaptation and community education in enhancing resilience to climate risks.

Thus, e-commerce's potential to mitigate climate change lies in its ability to integrate sustainable practices in logistics, packaging, and supply chains. This is reinforced by research from Zhang et al. (2024a) on carbon tax applications and Trimmel et al. (2024) on resistance to energy transition policies, both emphasizing the importance of targeted policy measures and energy-efficient solutions. Collectively, these studies demonstrate that through digital innovations and environmentally responsible strategies, e-commerce can significantly contribute to global sustainability goals.

However, we have observed that these studies have a limited scope, covering only specific aspects of e-commerce, whether it be e-commerce in the music market, the food market, or books, etc. These studies often have a restricted focus, comparing an online retail system with conventional shopping and overlooking important effects, such as consumer-associated travel. The absence of comprehensive studies in the literature that analyze the overall influence of e-commerce on climate change, as well as the limited number of studies examining this relationship at the level of European countries, has motivated us to develop a model that allows for a broad analysis of this relationship. Thus, investigating this relationship gains even more importance and interest, and a study like the one proposed by us could shed more light on the nature of this correlation.

Thus, based on this extensive literature review we can formulate the Hypotheses of the study:

H1: E-commerce activities significantly increase greenhouse gas emissions in EU member countries, especially in regions with underdeveloped logistical infrastructure and high consumer demand for rapid delivery.

H2: In countries with stringent environmental regulations and high investment in sustainable logistics, e-commerce activities have a lower or even neutral impact on emissions.

H3: Policies encouraging the use of green technologies (such as electric vehicles for deliveries) and eco-friendly packaging significantly reduce the negative impact of e-commerce on climate change.

These Hypotheses offer a structured approach to investigating the specific factors and policies that can modulate the environmental impact of e-commerce in the EU.

3. Data and methodology

3.1. Data and variables

The main goal of the study is to outline the impact of e-commerce activities on climate change in the European Union. For the assessment of climate change, we used a newly discovered composite index called the Climate Change Index (CCI), calculated based on nine indicators according to the methodology proposed by Wolf et al. (2022). This index constitutes 38% of the Environmental Performance Index, alongside Ecosystem Vitality (42%) and Environmental Health (20%). Figure 1 illustrates the structure of the Climate Change Index and the weights of the indicators.

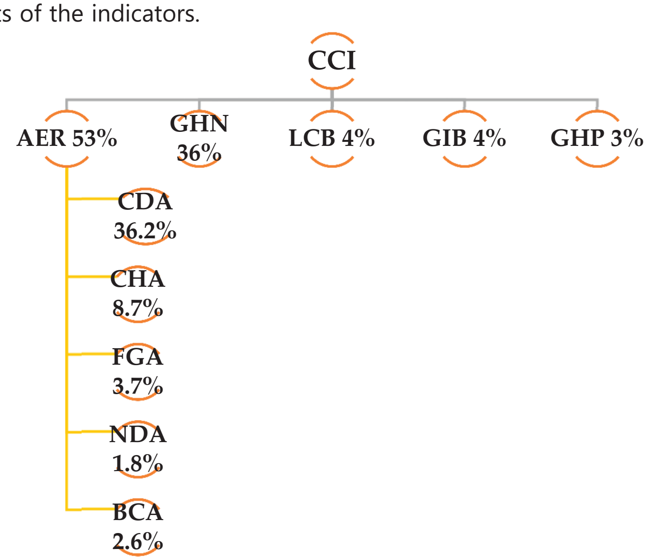

Figure 1. Climate change index (CCI) structure

The nine indicators used to determine the CCI are: Adjusted emissions growth rate for carbon dioxide (CDA), Adjusted emissions growth rate for methane (CHA), Adjusted emissions growth rate for F-gases (FGA), Adjusted emissions growth rate for nitrous oxide (NDA), Adjusted emissions growth rate for black carbon (BCA), Projected GHG Emissions in 2050 (GHN), Growth rate in carbon dioxide emissions from land cover (LCB), Greenhouse gas intensity growth rate (GIB), Greenhouse gas emissions per capita (GHP). These indicators evaluate how close states are to achieving globally determined sustainability targets related to specific environmental concerns. While the overall scores in the CCI serve to highlight sustainability leaders and identify under-performers, the detailed disaggregated data provides a more precise tool for pinpointing policy weaknesses, irregularities, and successful programs that nations can adopt from their high-achieving counterparts. The Adjusted Emission Growth Rates (AER) tracks the patterns in countries' emissions of climate pollutants, encompassing four green-house gases and black carbon contributing with 53% to the Climate Change Mitigation index.

Developed over two decades and incorporating the latest data, the CCI methodology empowers decision-makers to discern the factors driving top-notch performance. Examination of CCI data underscores the significance of financial resources, effective governance, human development, and regulatory quality in enhancing a country's sustainability. By emphasizing these linkages, the CCI actively contributes to fostering sustainable development, promoting a more environmentally secure, and just future.

To estimate the intensity of e-commerce activity, we used the Internet use indicator: e-commerce activities (ECOMACT), which expresses the percentage of individuals who have used the internet for e-commerce activities for the period 2011–2022, based on data provided by Eurostat (n.d.). E-commerce activities encompass a diverse range of actions and commercial transactions conducted through the internet. These activities can range from simple online purchases to more complex business operations. Some common elements included in e-commerce activities are: transactions involving the purchase and sale of goods and services on online platforms form the core of electronic commerce; the use of specialized electronic commerce platforms, such as Amazon, eBay, Alibaba, or local platforms, to facilitate the processes of selling and buying; the use of electronic payment systems and payment gateways to conduct transactions online (this can include credit cards, online payment services like PayPal, or other electronic methods); buying and selling products or services through mobile devices, such as smartphones or tablets; utilizing digital marketing tools to promote products or services, including online advertising, social media marketing, and other digital tactics; integrating delivery services to ensure the transportation and delivery of products to customers. This aspect is significant in the context of electronic commerce; implementing security measures to protect the personal and financial data of customers during online transactions; providing assistance and services to customers through online channels, such as live chat, email, or other forms of digital communication or using data analysis to understand customer behavior, improve the shopping experience, and streamline business operations.

Before conducting the econometric analysis to determine the nexus between e-commerce activities and climate change, it is mandatory to examine the descriptive statistics of the dataset used (Table 1). These descriptive statistics help in gaining in-sights into the distribution, central tendency, and variability of a dataset, facilitating a better understanding of the data's characteristics.

Table 1. Descriptive statistics, and normality test (source: author's own calculation)

	CCI	ECOMACT
Mean	55.0205	45.5509
Median	51.7793	45.9950
Maximum	95.3532	85.1800
Minimum	35.5621	5.7700
Std. Dev.	12.5012	19.2478
Skewness	1.4413	–0.0581
Kurtosis	4.8550	2.0089
Jarque-Bera	158.6402	12.2802
Probability	0.0000	0.0021
Observations	324	296

The Jarque-Bera test is a statistical test employed to ascertain whether the data in a given sample exhibit the requisite skewness and kurtosis to be considered representative of a normal distribution (Jarque & Bera, 1980). The degree of asymmetry in a distribution is indicated by the value of skewness, with a value of 0 representing perfect symmetry. A positive skewness indicates a distribution with a longer right tail, whereas a negative skewness suggests a longer left tail. In contrast, kurtosis pertains to the degree of "tailedness" exhibited by a given distribution. A normal distribution, for instance, is characterized by a kurtosis of 3, which is referred to as mesokurtic. A kurtosis greater than 3 indicates a distribution with "heavy tails" (leptokurtic), whereas a value less than 3 suggests "light tails" (platykurtic). The Jarque-Bera test synthesizes these measures to evaluate the null hypothesis that the data follow a normal distribution. The test statistic consists of a chi-square distribution, and when the p-value is below 0.05, the null hypothesis is rejected, outlining that the data do not conform to a normal distribution.

3.2. Estimation model

To outline the effect of e-commerce activities on the climate change index, this study adopts a modified version of the model introduced by Koenker and D'Orey (1987), employing the Barrodale and Roberts (1974) simplex algorithm. The traditional probability distribution function for a set of n observations of a random variable Y is expressed as follows:

$$F_n\left(y\right)=\sum_{k}1\left(Y_i\le y\right), \quad (1)$$

where $1\left(Y_i\le y\right)=1$, if $Y_i\le y$ is true or $1\left(Y_i\le y\right)=0$ otherwise.

The quantile corresponding to this probability distribution function is determined by:

$$Q_n\left(\tau\right)=\operatorname{argmin}_{\vartheta}\left\{\sum_{i:Y_i\ge\vartheta}\tau\left|Y_i-\vartheta\right|+\sum_{i:Y_i<\delta}\left(1-\tau\right)\left|Y_i-\vartheta\right|\right\}=\operatorname{argmin}_{\vartheta}\left\{\sum_{i}\rho_\tau\left(Y_i-\vartheta\right)\right\}, \quad (2)$$

where ρ_τ represents the check function, which assigns asymmetric weights to positive and negative values.

The quantile regression Equation extends this formulation to incorporate regressors *X* in the following manner:

$$Q\left(\tau \mid X_i, \beta\left(\tau\right)\right) = X_i'\beta\left(\tau\right), \tag{3}$$

where $\beta(\tau)$ is the vector of coefficients associated to the τ-th quantile.

Thus, the Equation for the estimator in conditional quantile regression is expressed as follows:

$$\hat{\beta}_n\left(\tau\right) = \arg\min_{\beta\left(\tau\right)} \left\{ \sum_i \rho_\tau \left(Y_i - X_i'\beta\left(\tau\right)\right) \right\}. \tag{4}$$

Evaluating the effectiveness and robustness of a quantile regression model often involves assessing its quality through goodness-of-fit measures and conducting formal tests like the quasi-likelihood ratio and Wald tests. Koenker and Machado (1999) introduced a goodness-of-fit statistic for quantile regression that is analogous to the R^2 in traditional regression analysis. They proposed two test statistics known as quantile-p tests, although Koenker (2005) later pointed out that these can also be viewed as quasi-likelihood ratio tests. Additionally, Koenker and Bassett (1982) proposed a robust heteroskedasticity test by comparing the equality of slopes across quantiles. Newey and Powell (1987) also developed a test for a less restrictive hypothesis of symmetry, specifically designed for asymmetric least squares estimators, which can be readily applied to quantile regression.

4. Results

To employ the quantile regression equation, unit root tests were conducted on the data used in the model. Four different cross-section panel unit root tests were applied: Levin, Lin, and Chu (LLC) (Levin et al., 1987), Im, Pesaran, and Shin (IPS) (Im et al., 2003), as well as Fisher-type tests using the ADF and PP approaches (Maddala & Wu, 1999; Choi, 2001). The results (Table 2) from all these tests indicate that a unit root is absent, as the LLC, IPS, and both Fisher tests reject the null hypothesis of a unit root due to p-values below 0.05.

Table 2. Unit root tests results (source: author's own calculation, 2023)

Unit root test	CCI		ECOMACT	
	t-statistic	p-value	t-statistic	p-value
LLC	–5.94940	0.0000	1.81941	0.0056
IPS	–2.81839	0.0024	5.31172	0.0014
ADF-Fisher	84.4310	0.0051	14.0909	0.0068
PP-Fisher	111.445	0.0000	31.9007	0.0028

The covariance matrix is calculated using the Huber sandwich estimator, providing robust standard errors, while individual sparsity estimates are obtained through kernel-based methods. The bandwidth, determined using the Hall and Sheather formula, yields a value of 0.14578, ensuring an accurate estimation of the distribution's density. The quantile regression analysis (Table 3) uncovers a statistically significant relationship between e-commerce activities and the climate change index. Specifically, the results show that a 1% increase in the median value of e-commerce activities leads to a 5% rise in the median value of the climate change index, underscoring the influence of digital commerce on environmental factors.

In the lower portion of the output, the goodness-of-fit measure (pseudo-R-squared), as proposed by Koenker and Machado (1999), is provided, along with an adjusted version of this statistic. Additionally, the scalar estimate of sparsity, derived from the kernel method, is included. The associated probability with the Quasi-LR statistic indicates the model's reliability and stability, confirming that the quantile regression model is a robust tool for analyzing the impact of e-commerce on climate change.

Table 3. Quantile regression estimation (source: author's own calculation, 2023)

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	49.54994	1.584490	31.27186	0.0000
ECOMACT	0.050740	0.535163	11.44299	0.0150
Pseudo R-squared	0.006528	Mean dependent var		55.26975
Adjusted R-squared	0.003149	S.D. dependent var		12.82516
S.E. of regression	13.09277	Objective		1291.539
Quantile dependent var	51.77939	Restr. objective		1300.026
Sparsity	21.17544	Quasi-LR statistic		3.206302
Prob (Quasi-LR stat)	0.073355			

Table 4 displays the outcomes for the 10 quantiles suggested in this investigation. Notably, the coefficients are found to be insignificant for the 30%, 40%, 50%, and 60% quantiles, as indicated by p-values exceeding 0.05. The findings reveal a diminishing trend for the first two quantiles, while statistically significant results indicate an increasing trend from the seventh quantile onward.

Table 4. Quantile process estimates (source: author's own calculation, 2023)

	Quantile	Coefficient	Probability
C	10%	37.99297	0.0000
	20%	44.22127	0.0000
	30%	46.65285	0.0000
	40%	48.56492	0.0000
	50%	49.54994	0.0000
	60%	50.43100	0.0000
	70%	48.04756	0.0000
	80%	47.77934	0.0000
	90%	51.70263	0.0000
ECOMACT	10%	0.105113	0.0126
	20%	0.056737	0.0430
	30%	0.037077	0.2055
	40%	0.038004	0.2129
	50%	0.050740	0.1501
	60%	0.085649	0.1055
	70%	0.256777	0.0000
	80%	0.336408	0.0000
	90%	0.468686	0.0000

Quantile regression enables researchers to explore how the association between independent variables and the dependent variable varies across different quantiles (or percentiles) of the distribution of the dependent variable. In this instance, the findings reveal that coefficients are not statistically significant for the 30% to 60% quantiles, as evidenced by p-values exceeding the commonly used threshold of 0.05 for statistical significance. Essentially, within this range, there is no statistically significant correlation between e-commerce activities and the climate change index. Conversely, for higher quantiles, a noteworthy increasing trend is observed, and this trend is statistically significant. This implies that as we progress along the climate change index, moving from lower to higher percentiles, e-commerce activities exhibit a more pronounced and statistically significant influence on the climate change index.

This outcome suggests that the impact of e-commerce activities on climate change may differ at various points. Specifically, there appears to be a more substantial impact on climate change among higher quantiles, whereas at lower quantiles, the impact is less pronounced. This finding underscores the intricacy of the relationship between e-commerce activities and the climate change index, emphasizing the importance of considering climate change risks when analyzing this connection.

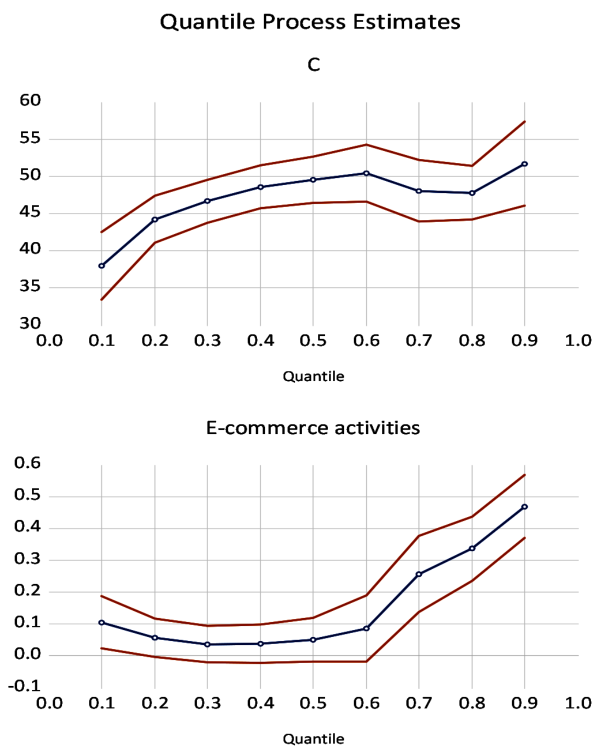

Figure 2. Graphical representation of the quantile process estimates

Based on the findings presented in Table 4 and in line with Koenker's approach (Koenker, 2005), Figure 2 illustrates a process chart for a revised form of the preceding equation. Specifically, it represents a median regression utilizing the Engel data, wherein the climate change index data is fitted to the centered e-commerce activities series and a constant term. The results for 10 quantiles, accompanied by 95% confidence intervals, are visually depicted in the figure.

Table 5 presents the results of the test for equality of slope coefficients across quantiles proposed by Koenker and Bassett (1982). The results of the Wald test indicate that the Chi-square value for the slope equality test is 24.61, indicating statistical significance. Consequently, the slope equality Hypothesis is rejected at the 5% significance level, indicating that the equality of slopes differs across quantile levels. This suggests that the influence of the independent variables on the dependent variable differs across quantiles of the dependent variable. In other words, the slope of the nexus between the independent and dependent variables is not consistent across the distribution of the dependent variable.

A comparison of the slope (non-intercept) coefficients of the estimated tau with the 10 specified taus reveals a discrepancy across quantile values, indicating that the conditional quantiles are not identical. The reference to "10 Taus" pertains to the specific quantiles that were modelled in the study. In quantile regression, the value of tau corresponds to the quantile being modelled. Therefore, this outcome suggests that the nexus between e-commerce activities and the climate change index in European Union countries is complex and varies throughout the distribution of climate change.

Table 5. Quantile slope equality test (source: author's own calculation, 2023)

Test summary	Chi-Sq. Statistic	Chi-Sq. d.f.	Prob.
Wald Test	24.61909	2	0.0000

The test for symmetric quantiles is a Newey and Powell (1987) examination of conditional symmetry. Conditional symmetry implies that the average value of two sets of coefficients for symmetric quantiles around the median will be equal to the value of the coefficients at the median. The collective p-value for the test in Table 6 is 0.00, indicating evidence of asymmetry across the quantiles.

Table 6. Symmetric quantiles test (source: author's own calculation, 2023)

Test summary		Chi-Sq. statistic	Chi-Sq. d.f.	Prob.
Wald Test		89.05510	8	0.0000
Restriction detail: b (tau) + b (1-tau) – 2*b (.5) = 0				
Quantiles	Variable	Restr. Value	Std. Error	Prob.
0.1, 0.9	C	–9.404291	3.839495	0.0143
	ECOMACT	0.472319	0.073876	0.0000
0.2, 0.8	C	–7.099273	2.577400	0.0059
	ECOMACT	0.291664	0.060404	0.0000
0.3, 0.7	C	–4.399478	2.154219	0.0411
	ECOMACT	0.192374	0.053412	0.0003
0.4, 0.6	C	–0.103963	1.502437	0.9448
	ECOMACT	0.022172	0.036039	0.5384

In quantile regression analysis, a specific test is employed to ascertain whether the impact of independent variables on the dependent variable is symmetrical around the median. This test is predicated on the assumption that if the relationship is symmetrical, the average effect at two quantiles equidistant from the median should be consistent with the effect observed at the median. In this case, the test yielded a p-value of 0.00, which is below the typical significance threshold of 0.05. A p-value lower than 0.05 typically signifies the rejection of the null hypothesis, which, in this context, implies that the symmetry of the effect around the median is not substantiated. This outcome indicates an asymmetry in the nexus between the independent variables (such as e-commerce measures) and the dependent variable (climate change index), suggesting that the impact varies across the distribution and differs above and below the median.

These results highlight the complexity of the nexus between e-commerce activities and the climate change index in European Union countries. They point to potential negative environmental consequences, such as increased packaging waste if not managed sustainably, the environmental impact of data centers depending on their energy sources, and higher emissions and traffic congestion associated with last-mile delivery if not efficiently optimized. Additionally, the frequent returns and rapid product turnover linked with e-commerce can further contribute to emissions and packaging-related environmental issues.

5. Discussions

The study reveals a nuanced relationship between e-commerce activities and the climate change index, highlighting significant variability across quantiles. These findings underscore the need for differentiated analyses and policies that address regional climate vulnerabilities. For high-impact regions, targeted interventions such as emissions caps, incentives for sustainable packaging, and green logistics requirements could mitigate e-commerce's environmental effects. Conversely, areas with lower climate risks may require less stringent measures, focusing instead on voluntary sustainability practices.

The asymmetrical relationship between e-commerce and climate change emphasizes the importance of context-sensitive strategies to manage its environmental footprint. This nuanced perspective calls for granular, quantile-specific analyses to better understand and address the varying impacts of the digital economy on climate change.

Moreover, the findings of our study are consistent with the results obtained by Islam et al. (2023), Cheba et al. (2021), Xie et al. (2023) who reported a negative impact on carbon emissions at medium and higher quantiles, as well as by Caiyi et al. (2022), who argue for a negative impact of e-commerce in terms of substantial waste. These results seem to contradict the conclusions drawn in other studies (Cairns, 2005; van Loon et al., 2015; Weber, 2010; Heard et al., 2019; Zhang et al., 2024b) where the authors emphasized the positive contribution of e-commerce to the environment. This positive contribution was highlighted in situations such as replacing direct travels of buyers for a specific item with joint deliveries to multiple consumers (Cairns, 2005) or when the substitution of digital downloads for physical products, such as music CDs, represents a significant shift in the distribution of cultural goods (Weber, 2010).

Also, the results of this research can be explained by the fact that an increase in online orders may lead to an increase in the quantity of packaging used, becoming more alarming in the case of single or low-item orders, where these packages become environmentally hazardous if not properly recycled. According to Fichter (2002), packaging materials used for product realization and delivery in logistic networks represent one of the critical points in waste generation in e-commerce.

Nevertheless, the environmental impact of e-commerce can vary depending on the chosen delivery method (to the customer's address or to collection lockers) and the non-collection of the parcel by the customer. This issue has also been identified by Srivastava (2007), arguing that many individual packages are shipped directly to customers, further increasing pollution, with many situations where they are returned to merchants due to the refusal to pick up the order. Additionally, there is a consumer trend to purchase different products from various online platforms, requiring independent distribution, according to the arguments presented by Carling et al. (2015).

Equally, we cannot overlook the energy consumption associated with e-commerce, which is considerable and has direct effects on the environment. Previous research, exemplified by the works of Dost and Maier (2018), as well as Pålsson et al. (2017), highlighted the favorable influence of e-commerce on energy consumption. According to these authors, the expansion of e-commerce affects multiple devices involved in storage, packaging, and distribution processes, and these devices exhibit a significant level of energy consumption due to reduced energy efficiency. Another aspect emphasized by these researchers is related to the use of low-energy-efficient vehicles in distribution and delivery operations.

The findings of our study closely align with recent literature on the environmental impact of e-commerce and the role of sustainable practices. The observed positive correlation between high e-commerce activity and increased greenhouse gas emissions in regions with underdeveloped logistics reflects Dong's et al. (2023) findings on the substantial environmental footprint driven by logistics and rapid delivery demands.

Our results also confirm that stringent environmental policies and investments in sustainable logistics reduce emissions, consistent with Islam et al. (2023), who highlight the effectiveness of green infrastructure and regulatory measures in lowering per-transaction emissions. Similarly, Liu et al. (2023) emphasize that adopting green technologies, such as electric vehicles and recyclable packaging, significantly reduces e-commerce's carbon footprint, supporting our study's evidence of emissions reductions through such practices. Aligned with Han et al. (2023), our study demonstrates that investments in optimized logistics and sustainable infrastructure improve environmental outcomes in e-commerce. Additionally, Armstrong (2023) highlights the role of policy measures in encouraging eco-friendly technologies, corroborating our findings that policies promoting green practices effectively reduce e-commerce's environmental impact.

Together, these consistent findings reinforce the growing body of literature that underscores the critical role of regulatory frameworks, green technologies, and optimized logistics in managing and mitigating the environmental impact of e-commerce. This convergence of results suggests that our study not only corroborates prior research but also contributes valuable empirical support to the understanding of how sustainable practices can reshape the environmental profile of the digital economy.

6. Conclusions

In accordance with the results obtained, it was inferred that the impact of the e-commerce on the climate change index exhibits variations depending on the quantiles of the dependent variable, the influence being more pronounced at higher quantiles, while at lower quantiles, the effect is less significant. However, the application of econometric models allowed us to address the first research question (RQ1) and conclude that, based on the analyzed sample, e-commerce appears to have a negative impact on the environment. This negative effect can be justified by several factors, including increased packaging waste, carbon emissions from deliveries, and frequent returns of products.

To mitigate the negative repercussions of e-commerce on climate change, it is imperative to implement the concept of environmental responsibility in managing e-commerce activities.

To address RQ2, we consider previous studies and acknowledge that, although our results indicate negative effects, we cannot deny that e-commerce could reduce these effects if eco-friendly delivery vehicles are encouraged, packaging is properly recycled, supply chains are optimized, and sustainable products are promoted. Thus, these observations suggest new directions and opportunities for research, as well as recommendations for policymakers. In this regard, we provide answer to RQ3 and we recommend that governments pay special attention to promoting and monitoring how e-commerce operators handle the recycling of single-use plastic products and cardboard packaging. It is also essential to monitor the sources of energy used (renewable or traditional) and the types of fuels used in vehicles for product deliveries, among other relevant aspects.

Similarly, the adoption of policies for consumers in the e-commerce sector is necessary. In this context, we propose the revision of legislation and adjustments to e-commerce conditions, such as imposing additional fees for orders not picked up by consumers, encouraging the placement of multiple items in a single order, thereby discouraging the ordering of separate products from the same supplier in short time intervals, and other measures.

Additionally, fostering consumer awareness and education regarding sustainable consumption practices is of outmost importance. Implementing initiatives such as incentivizing the purchase of eco-friendly products, providing transparent information about the environmental impact of products, and promoting the reuse and recycling of packaging materials can empower consumers to make more environmentally conscious choices when engaging in e-commerce transactions. By encouraging a shift towards more sustainable consumption habits among consumers, alongside regulatory measures targeting e-commerce operators, a more holistic approach to mitigating the adverse effects of e-commerce on climate change may be achieved.

Also, the findings from the study provide empirical support for all three hypotheses:

- H1 is confirmed, as the study shows that increased e-commerce activity correlates with higher emissions, especially in regions with underdeveloped logistics infrastructure and high demand for quick delivery.
- H2 is validated by evidence that stringent environmental regulations and investments in sustainable logistics moderate the emissions impact of e-commerce, leading to a neutral or lower effect on climate change in those regions.
- H3 is supported by the results showing that the adoption of green technologies and eco-friendly logistics practices (such as electric vehicles and sustainable packaging) reduces the negative environmental impact of e-commerce.

These validations underscore the critical role of both regulatory frameworks and technology adoption in managing the environmental footprint of e-commerce across different regions of the EU. The findings suggest that, while e-commerce presents challenges for climate change, these can be managed effectively through targeted policies and sustainable practices.

The findings of our study reveal a layered and asymmetric relationship between e-commerce activities and the climate change index, with variations in impact intensity across different quantiles. Specifically, the results demonstrate that within the 30% to 60% quantiles, the coefficients are not statistically significant, suggesting a lack of meaningful correlation between e-commerce activities and climate change metrics in these mid-range quantiles. This absence of statistical significance implies that, at moderate levels of climate impact, e-commerce activities may not exert a discernible influence on the climate change index. This lack of impact could be due to moderating factors or regional characteristics –such as established logistics infrastructure or regulatory practices – that mitigate e-commerce's environmental effects in areas with moderate climate pressures.

Conversely, as we examine higher quantiles, a statistically significant positive trend emerges, where e-commerce activities show a marked and increasing impact on the climate change index. This trend suggests that in regions experiencing heightened climate stress, the environmental footprint of e-commerce activities is more substantial. This effect may arise from several interlinked factors, including increased energy consumption for expedited delivery, higher waste generation from packaging, and expanded logistical operations to meet consumer demand. Therefore, in areas with elevated climate risk, e-commerce appears to contribute more substantially to the worsening of environmental pressures.

This study significantly enriches *academic literature* on e-commerce's environmental impact by employing a quantitative panel regression model to analyze the relationship between online purchasing behaviors and climate indicators in EU countries. This methodological approach provides a replicable framework for examining similar dynamics in other economic sectors or regions. Additionally, it offers empirical evidence on how the growth of the e-commerce sector directly influences environmental outcomes, such as carbon emissions and energy consumption, advancing research on the digital economy and sustainability.

From a *managerial perspective*, the study highlights opportunities for e-commerce companies to reduce their carbon footprints and enhance sustainability by optimizing logistics and adopting green practices, such as route optimization, recyclable packaging, and partnerships with renewable energy suppliers. These measures not only improve operational efficiency but also attract environmentally conscious consumers, strengthening corporate social responsibility. By leveraging data and technology, companies can further optimize distribution and minimize waste, aligning profitability with environmental stewardship.

The findings also carry *practical implications for policymakers and businesses*. The environmental impact of e-commerce varies across regions, intensifying in high-climate-impact areas and requiring targeted interventions. Policymakers should implement region-specific strategies, such as stricter emissions standards, carbon caps on delivery fleets, and incentives for sustainable practices like recyclable packaging and green logistics. Flexible regulatory frameworks, including carbon pricing mechanisms and tax rebates, can address varying regional climate vulnerabilities while encouraging voluntary sustainability measures in lower-impact areas.

For e-commerce companies, region-specific sustainability practices are essential to aligning with regulatory trends and reducing environmental harm. In high-impact regions, companies can prioritize sustainable logistics, such as electric delivery fleets and decentralized warehousing, to minimize emissions. Consumer-facing initiatives like carbon-neutral shipping and environmentally friendly packaging further support these efforts. Moreover, publicly committing to sustainability and transparently reporting carbon metrics can provide a competitive edge, particularly in regions where environmental concerns are paramount.

Broader Implications and Future Directions. The findings of our study suggest that e-commerce companies and policymakers alike must consider regional climate risks and associated environmental pressures in both regulatory and operational strategies. This study also emphasizes the importance of a granular approach in analyzing e-commerce's environmental footprint. Recognizing that e-commerce's climate impact varies across quantiles, future research could explore additional regional factors, such as infrastructure quality or consumer behavior, that might influence the extent of e-commerce's environmental effects.

Thus, the study underscores the importance of tailored, adaptive policies and corporate sustainability practices in addressing the differential impact of e-commerce on climate change across regions. By aligning operational strategies with regional climate needs and regulatory requirements, e-commerce can evolve into a sector that not only meets consumer demand but also contributes to a sustainable future.

The study has several *limitations* that should be acknowledged. First, its focus on European Union member countries limits the applicability of the findings to other regions with different regulatory frameworks, logistical capabilities, or consumer behaviors. The temporal scope is also a limitation, as the environmental impact of e-commerce may evolve with advancements in technology, shifts in consumer preferences, and stricter regulations. Additionally, while quantile regression provides insight into the variability of impact across climate change levels, it may not fully capture non-linear or complex interactions, nor does it identify underlying causal mechanisms.

Furthermore, the intersection of e-commerce and climate change demands ongoing attention and debate. While the recommendations outlined provide a starting point for mitigating the negative environmental influence of e-commerce, it is essential to recognize that this is a complex and multifaceted issue that requires continuous exploration and adaptation of strategies. As the e-commerce industry continues to grow and evolve, policymakers, businesses, and consumers must remain engaged in discussions and actions aimed at fostering sustainability and minimizing environmental harm. This subject deserves ongoing scrutiny and debate to ensure that efforts to address the environmental consequences of e-commerce remain effective and relevant in an ever-changing landscape.

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Disclosure statement

The authors declare no conflict of interest.

References

Ahmed, S., Iqbal, Z., & Antahal, P. C. (2023). Impact of climate change on nomadic herders' livelihoods: Evidence from Bakarwal community in the Western Himalayas in India. *Environmental Development*, *48*, Article 100930. https://doi.org/10.1016/j.envdev.2023.100930

Armstrong, J. H. (2023). Formal local government coordination to mitigate climate change. *Urban Climate*, *51*, Article 101636. https://doi.org/10.1016/j.uclim.2023.101636

Asibey, M. O., & Yeboah, V. (2024). Investigating climate change adaptation strategies among informal residents in Kumasi through the lenses of the social action and control theories. *International Journal of Disaster Risk Reduction*, *114*, Article 104963. https://doi.org/10.1016/j.ijdrr.2024.104963

Awuni, S., Adarkwah, F., Ofori, B. D., Purwestri, R. C., Huertas-Bernal, D. C., & Hajek, M. (2023). Managing the challenges of climate change mitigation and adaptation strategies in Ghana. *Heliyon*, *9*(5), Article e15491. https://doi.org/10.1016/j.heliyon.2023.e15491

Barrodale, I., & Roberts, F. D. K. (1974). Solution of an overdetermined system of equations in the norm. *Communications of the ACM*, *17*(6), 319–320. https://doi.org/10.1145/355616.361024

Bhebhe, S., & Ndlovu, G. (2023). Natural disasters, climate change risk and the performance of financial stocks: Evidence from the Johannesburg stock exchange. *Reference Module in Social Sciences*. https://doi.org/10.1016/B978-0-44-313776-1.00157-4

Borggren, C., Moberg, Å., & Finnveden, G. (2011). Books from an environmental perspective – Part 1: Environmental impacts of paper books sold in traditional and internet bookshops. *The International Journal of Life Cycle Assessment*, *16*, 138–147. https://doi.org/10.1007/s11367-011-0254-1

Cairns, S. (2005). Delivering supermarket shopping: More or less traffic? *Transport Reviews*, *25*(1), 51–84. https://doi.org/10.1080/0144164042000218391

Caiyi, L., Xiaoyong, L., & Zhenyu, L. (2022). The nexus between e-commerce growth and solid-waste emissions in China: Open the pathway of green development of e-commerce. *Frontiers in Environmental Science*, *10*, Article 963264. https://doi.org/10.3389/fenvs.2022.963264

Carling, K., Han, M., Håkansson, J., Meng, X., & Rudholm, N. (2015). Measuring transport related CO_2 emissions induced by online and brick-and-mortar retailing. *Transportation Research Part D: Transport and Environment*, *40*, 28–42. https://doi.org/10.1016/j.trd.2015.07.010

Cheba, K., Kiba-Janiak, M., Baraniecka, A., & Kołakowski, T. (2021). Impact of external factors on e-commerce market in cities and its implications on environment. *Sustainable Cities and Society*, *72*, Article 103032. https://doi.org/10.1016/j.scs.2021.103032

Choi, I. (2001). Unit root tests for panel data. *Journal of International Money and Finance*, *20*(2), 249–272. https://doi.org/10.1016/S0261-5606(00)00048-6

Dong, K., Yang, S., & Wang, J. (2023). How digital economy leads to low-carbon development in China? The case of e-commerce city pilot reform. *Journal of Cleaner Production*, *391*, Article 136177. https://doi.org/10.1016/j.jclepro.2023.136177

Dost, F., & Maier, E. (2018). E-commerce effects on energy consumption: A multi-year ecosystem-level assessment. *Journal of Industrial Ecology*, *22*(4), 799–812. https://doi.org/10.1111/jiec.12639

Duncan, S., Hjelmskog, A., & Papies, E. K. (2024). No agency and responsibility for the privileged? Perceptions of climate action among high socioeconomic status citizens in the United Kingdom. *Energy Research & Social Science*, *115*, Article 103604. https://doi.org/10.1016/j.erss.2024.103604

Edwards, J., & McKinnon, A. C. (2009). Shopping trip or home delivery: Which has the smaller carbon footprint? *Logistics and Transport Focus*, *11*(7), 20–24.

EPA. (n.d.). *Life Cycle Assessment*. Retrieved December 12, 2023, from https://web.archive.org/web/20120306122239/http://www.epa.gov/nrmrl/std/lca/lca.html

Eurostat. (n.d.). *E-commerce statistics*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=E-commerce_statistics

Eurostat. (2023). *E-commerce continues to grow in the EU*. Retrieved December 11, 2023, from https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20230228-2#:~:text=In%202022%2C%2091%25%20of%20people%20aged%2016%20to,2022%2C%20an%20increase%20of%2020%20percentage%20points%20%28pp%29

Fichter, K. (2002). E-commerce: Sorting out the environmental consequences. *Journal of Industrial Ecology*, *6*(2), 25–41. https://doi.org/10.1162/108819802763471762

Gracceva, F., & Zeniewski, P. (2014). A systemic approach to assessing energy security in a low-carbon EU energy system. *Applied Energy*, *123*, 335–348. https://doi.org/10.1016/j.apenergy.2013.12.018

Grand View Research. (2021). *Online grocery market size, share & trends analysis report by product type (Fresh produce, breakfast & dairy, snacks & beverages, staples & cooking essentials), by region, and segment forecasts, 2022–2030*. https://www.grandviewresearch.com/industry-analysis/online-grocery-market

Guo, J., Wang, X., Fan, S., & Gen, M. (2017). Forward and reverse logistics network and route planning under the environment of low-carbon emissions: A case study of Shanghai fresh food e-commerce enterprises. *Computers & Industrial Engineering*, *106*, 351–360. https://doi.org/10.1016/j.cie.2017.02.002

Hall, G., Culhane, T., & Roberts, J. T. (2024). Climate coalitions and anti-coalitions: Lobbying across state legislatures in the United States. *Energy Research & Social Science*, *113*, Article 103562. https://doi.org/10.1016/j.erss.2024.103562

Han, A., Liu, P., Wang, B., & Zhu, A. (2023). E-commerce development and its contribution to agricultural non-point source pollution control: Evidence from 283 cities in China. *Journal of Environmental Management*, *344*, Article 118613. https://doi.org/10.1016/j.jenvman.2023.118613

Heard, B. R., Bandekar, M., Vassar, B., & Miller, S. A. (2019). Comparison of life cycle environmental impacts from meal kits and grocery store meals. *Resources, Conservation and Recycling*, *147*, 189–200. https://doi.org/10.1016/j.resconrec.2019.04.008

Heydari, M. (2024). Cultivating sustainable global food supply chains: A multifaceted approach to mitigating food loss and waste for climate resilience. *Journal of Cleaner Production*, *442*, Article 141037. https://doi.org/10.1016/j.jclepro.2024.141037

Hollaus, M., & Schantl, J. (2022, January 14–17). Incentivizing consumers towards a more sustainable online shopping behavior: A study on nudging strategies in B2C E-Commerce. *In Proceedings of the 2022 13th International Conference on E-Education, E-Business, E-Management, and E-Learning* (pp. 372–376). Tokyo, Japan. ACM Digital Library. https://doi.org/10.1145/3514262.3514268

Hurmekoski, E., Kunttu, J., Heinonen, T., Pukkala, T., & Peltola, H. (2023). Does expanding wood use in construction and textile markets contribute to climate change mitigation? *Renewable and Sustainable Energy Reviews*, *174*, Article 113152. https://doi.org/10.1016/j.rser.2023.113152

Im, K. S., Pesaran, M. H., & Shin, Y. (2003). Testing for unit roots in heterogeneous panels. *Journal of Econometrics*, *115*, 53–74. https://doi.org/10.1016/S0304-4076(03)00092-7

Islam, M. S., Proma, A. M., Wohn, C., Berger, K., Uong, S., Kumar, V., Korfmacher, K. S., & Hoque, E. (2023). SEER: Sustainable e-commerce with environmental-impact rating. *Cleaner Environmental Systems*, *8*, Article 100104. https://doi.org/10.1016/j.cesys.2022.100104

Jaller, M., & Pahwa, A. (2020). Evaluating the environmental impacts of online shopping: A behavioral and transportation approach. *Transportation Research Part D: Transport and Environment*, *80*, Article 102223. https://doi.org/10.1016/j.trd.2020.102223

Jarque, C. M. & Bera, A. K. (1980). Efficient tests for normality, homoscedasticity and serial independence of regression residuals. *Economics Letters*, *6*(3), 255–259. https://doi.org/10.1016/0165-1765(80)90024-5

Khalifa, M., Ullah, S., & Abdelfattah, T. (2024). Mapping the influence: Institutional blockholder coordination and climate change risk disclosure. *Journal of Environmental Management*, *370*, Article 122788. https://doi.org/10.1016/j.jenvman.2024.122788

Koengkan, M., Fuinhas, J. A., Belucio, M., Alavijeh, N. K., Salehnia, N., Machado, D., Silva, V., & Dehdar, F. (2022). The impact of battery-electric vehicles on energy consumption: A macroeconomic evidence from 29 European countries. *World Electric Vehicle Journal*, *13*(2), Article 36. https://doi.org/10.3390/wevj13020036

Koenker, R. (2005). *Quantile regression*. Cambridge University Press. https://doi.org/10.1017/CBO9780511754098

Koenker, R., & Bassett, G. (1982). Robust tests for heteroskedasticity based on regression quantiles. *Econometrica*, *50*(1), 43–62. https://doi.org/10.2307/1912528

Koenker, R. W., & D'Orey, V. (1987). Algorithm AS 229: Computing regression Quantiles. *Applied Statistics*, *36*(3), 383–393. https://doi.org/10.2307/2347802

Koenker, R., & Machado, J. A. F. (1999). Goodness of fit and related inference processes for quantile regression. *Journal of the American Statistical Association*, *94*(448), 1296–1310. https://doi.org/10.1080/01621459.1999.10473882

Kristensen, K., Borum, N., Christensen, L. G., Jepsen, H. W., Lam, J., Brooks, A. L., & Brooks, E. P. (2013). Towards a next generation universally accessible online shopping-for-apparel system. In M. Kurosu (Ed.), *Lecture notes in computer science: Vol. 8006. Human computer interaction: Users and cotexts of use* (pp. 418–4270). Springer. https://doi.org/10.1007/978-3-642-39265-8_47

Kurniawan, T. A., Meidiana, C., Goh, H. H., Zhang, D., Othman, M. H. D., Aziz, F., Anouzla, A., Sarangi, P. K., Pasaribu, B., & Ali, I. (2024). Unlocking synergies between waste management and climate change mitigation to accelerate decarbonization through circular-economy digitalization in Indonesia. *Sustainable Production and Consumption*, *46*, 522–542. https://doi.org/10.1016/j.spc.2024.03.011

Levin, A., Lin, C.-F. & Chu, C.-S. J. (2002). Unit root tests in panel data: Asymptotic and finite-sample properties. *Journal of Econometrics*, *108*, 1–24. https://doi.org/10.1016/S0304-4076(01)00098-7

Liu, Q., Shen, B., & Wen, X. (2023). Role of climate-smart agriculture in fighting against climate change in competitive supply chains. *International Journal of Production Economics*, *264*, Article 108978. https://doi.org/10.1016/j.ijpe.2023.108978

Maddala, G. S., & Shaowen, W. (1999). A comparative study of unit root tests with panel data and a new simple test. *Oxford Bulletin of Economics and Statistics*, *61*(S1), 631–652. https://doi.org/10.1111/1468-0084.0610s1631

Majoral, G., Gasparín, F., & Saurí, S. (2021). Application of a tax to e-commerce deliveries in Barcelona. *Transportation Research Record*, *2675*(10), 642–655. https://doi.org/10.1177/03611981211012412

Mandal, S., Anand, U., López-Bucio, J., Radha, Kumar, M., Lal, M. K., Tiwari, R. K., & Dey, A. (2023). Biostimulants and environmental stress mitigation in crops: A novel and emerging approach for agricultural sustainability under climate change. *Environmental Research*, *233*, Article 116357. https://doi.org/10.1016/j.envres.2023.116357

Marathe, K.V., Chavan, K. R., & Nakhate, P. (2019). Life Cycle Assessment (LCA) of PET bottles. In S. Thomas, K. Kanny, M. G. Thomas, A. Rane, & V. K. Abitha (Eds.), *Recycling of polyethylene teraphthalate bottles* (pp. 149–168). William Andrew Publishing. https://doi.org/10.1016/B978-0-12-811361-5.00008-0

Masele, J. J. (2011). Towards sustainable tourism: Utilizing e-commerce applications for minimizing impacts of climate change. In P. Golinska, M. Fertsch, & J. Marx-Gómez (Eds.), *Information technologies in environmental engineering: New trends and challenges* (Vol. 3, pp. 445–459). Springer. https://doi.org/10.1007/978-3-642-19536-5_35

Mokni, K., Zaier, L. H., Youssef, M., & Jabeur, S. B. (2024). Quantile connectedness between the climate policy and economic uncertainty: Evidence from the G7 countries. *Journal of Environmental Management*, *351*, Article 119826. https://doi.org/10.1016/j.jenvman.2023.119826

Newey, W. K., & Powell, J. L. (1987). Asymmetric least squares estimation. *Econometrica*, *55*(4), 819–847. https://doi.org/10.2307/1911031

Ohta, H., & Barrett, B. F. D. (2023). Politics of climate change and energy policy in Japan: Is green transformation likely? *Earth System Governance*, *17*, Article 100187. https://doi.org/10.1016/j.esg.2023.100187

Pålsson, H., Pettersson, F., & Hiselius, L. W. (2017). Energy consumption in e-commerce versus conventional trade chan-nels-Insights into packaging, the last mile, unsold products, and product returns. *Journal of Cleaner Production*, *164*, 765–778. https://doi.org/10.1016/j.jclepro.2017.06.242

Quarshie, P. T., Abdulai, A.-R., Duncan, E., Kc, K. B., Roth, R., Sneyd, A., & Fraser, E. D. G. (2023). Myth or reality? The digitalization of Climate-Smart Agriculture (DCSA) practices in smallholding agriculture in the Bono East Region of Ghana. *Climate Risk Management*, *42*, Article 100553. https://doi.org/10.1016/j.crm.2023.100553

Rainer, L. (2025). Climate change and information sciences. In D. Baker & L. Ellis (Eds.), *Encyclopedia of libraries, librarianship, and information science* (Vol. 4, pp. 56–67). Academic Press. https://doi.org/10.1016/B978-0-323-95689-5.00135-8

Rana, I. A., Arshad, H. S. H., Jamshed, A., Khalid, Z., Younas, Z. I., Bhatti, S. S., & Ahmad, J. (2023). The impact of psychological distance to climate change and urban informality on adaptation planning. *Urban Climate*, *49*, Article 101460. https://doi.org/10.1016/j.uclim.2023.101460

Romm, J. (2002). The internet and the new energy economy. *Resources, Conservation and Recycling*, *36*(3), 197–210. https://doi.org/10.1016/S0921-3449(02)00084-8

Srivastava, S. K. (2007). Green supply-chain management: A state-of-the-art literature review. *International Journal of Management Reviews*, *9*(1), 53–80. https://doi.org/10.1111/j.1468-2370.2007.00202.x

Tabe-Ojong, M. P. J., Salama, Y., Abay, K. A., Abdelaziz, F., Zaccari, C., Akramkhanov, A., Menza, G., & Anarbekov, O. (2024). Harnessing digital innovations for climate action and market access: Opportunities and constraints in the CWANA region. *Global Food Security*, *41*, Article 100763. https://doi.org/10.1016/j.gfs.2024.100763

The European Parliament. (2018). *Reducing CO_2 emissions: EU objective and policy*. Retrieved December 13, 2023, from https://www.europarl.europa.eu/news/ro/headlines/society/20180305STO99003/reducerea-emisiilor-de-co2-obiective-si-politici-ue

Trimmel, K. E., Kriechbaum, M., Lazou, R., & Brudermann, T. (2024). Between distributive and procedural justice claims: Reframing patterns of discursive resistance against climate action. *Energy Research & Social Science*, *109*, Article 103424. https://doi.org/10.1016/j.erss.2024.103424

van Loon, P., Deketele, L., Dewaele, J., McKinnon, A., & Rutherford, C. (2015). A comparative analysis of carbon emissions from online retailing of fast moving consumer goods. *Journal of Cleaner Production*, *106*, 478–486. https://doi.org/10.1016/j.jclepro.2014.06.060

Weber, E. U. (2010). What shapes perceptions of climate change? *WIREs Climate Change*, *1*(3), 332–342. https://doi.org/10.1002/wcc.41

Wang, H., Li, Y., Lin, W., & Wei, W. (2023). How does digital technology promote carbon emission reduction? Empirical evidence based on e-commerce pilot city policy in China. *Journal of Environmental Management*, *325*, Article 116524. https://doi.org/10.1016/j.jenvman.2022.116524

Wolf, M. J., Emerson, J. W., Esty, D. C., de Sherbinin, A., & Wendling, Z. A. (2022). *Environmental Performance Index* (Technical appendix). Yale Center for Environmental Law & Policy. https://epi.yale.edu/downloads/epi2022technicalappendixv02.pdf

Wu, W., Xu, Z., Zenchenko, S., & Strielkowski, W. (2023). Does sustainable digital economy have implications for climate change? Novel evidence in the context of sustainable energy technologies. *Sustainable Energy Technologies and Assessments*, *60*, Article 103524. https://doi.org/10.1016/j.seta.2023.103524

Xiang, D., Ghaemi Asl, M., Nasr Isfahani, M., & Vasa, L. (2024). Would really long-only climate-transition strategies in commodities bring lower market risk for sustainable markets in the long run? *Economic Analysis and Policy*, *82*, 1271–1295. https://doi.org/10.1016/j.eap.2024.05.012

Xie, H., Chang, S., Wang Y., & Afzal, A. (2023). The impact of e-commerce on environmental sustainability targets in selected European countries. *Economic Research – Ekonomska Istraživanja*, *36*(1), 230–242. https://doi.org/10.1080/1331677X.2022.2117718

Yuan, X., Su, C.-W., Umar, M., Shao, X., & Lobonţ, O.-R. (2022). The race to zero emissions: Can renewable energy be the path to carbon neutrality? *Journal of Environmental Management*, *308*, Article 114648. https://doi.org/10.1016/j.jenvman.2022.114648

Zhang, J., Chen, L., Xie, Y., Yang, P., Li, Z., Guo, H., Zhang, Y., & Liu, L. (2024a). Climate change mitigation in energy-dependent regions – A carbon tax-based cross-system bi-layer model with equilibrium-optimization superposition effects. *Resources, Conservation and Recycling*, *200*, Article 107315. https://doi.org/10.1016/j.resconrec.2023.107315

Zhang, R., Liu, H., Xie, K., Xiao, W., & Bai, C. (2024b). Toward a low carbon path: Do E-commerce reduce CO_2 emissions? Evidence from China. *Journal of Environmental Management*, *351*, Article 119805. https://doi.org/10.1016/j.jenvman.2023.119805