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Analyzing the Impact of Climate Resilience on Container Terminal Throughput: A Continent-Wide Comparative Study

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Abstract

As the response to climate change transitions from passive adaptation to transformation and resilience, the importance of climate resilience has become increasingly evident. The port logistics industry is highly vulnerable to climate change, and the efficacy of climate resilience within the sector must be empirically validated. In this study, we aim to investigate the impact of national climate resilience on container port throughput. To achieve this, we conducted a panel regression analysis using data spanning 13 years (2010–2022) from 83 countries. The findings reveal that, overall, climate resilience positively influences container port throughput, but in Latin America, it showed a negative correlation. This suggests that the relationship between climate resilience and container port throughput varies depending on regional characteristics and factors. Further, climate resilience indicators specific to the port logistics industry should be developed. This study serves as a foundational exploration into climate resilience in the port logistics industry, providing empirical evidence of its critical role. The findings serve as a foundation for sustainable development and policy decision-making.

Keywords: climate change; climate resilience; port logistics industry; ND-GAIN; panel regression analysis

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1. Introduction

1.1. Background

In June 1992, following the adoption of the United Nations Framework Convention on Climate Change at the Rio Earth Summit in Brazil, aimed at preventing abnormal climate phenomena caused by global warming, countries worldwide made significant efforts to reduce greenhouse gas emissions. These efforts have included measuring emissions from the port logistics industry and developing eco-friendly solutions to address them effectively. The continuous growth of cross-border maritime transport has led to a significant increase in vessel traffic across various port waters [1]. The advancement of Intelligent Transportation Systems (ITS), a core infrastructure for modern port operations, has become an essential factor in maintaining the efficiency of global trade. In particular, as maritime logistics handles over 80% of the world's goods circulation, the port logistics industry holds strategic importance in international trade and global supply chains [2].

Despite this global movement, the impacts of climate change worldwide are becoming increasingly severe, posing diverse risks to the global economy and society. Phenomena such as rising temperatures, extreme weather events, and sea level rise (SLR) caused by climate change significantly impact the port logistics industry, which is inherently sensitive to climate conditions owing to its industrial nature [3–7].

The International Monetary Fund (IMF) illustrates the impact of climate change on the global port logistics industry by drawing on the drought crisis affecting the Panama Canal, which serves as a vital logistics artery connecting the Pacific and Atlantic Oceans, and currently handles approximately 5% of the global cargo volume. However, the worst drought to hit Central and South America last year caused the water levels in the Panama Canal to drop, restricting vessel passage. Consequently, the average number of vessels transiting daily decreased from 34 to 18 by February 2024. This drought crisis led to widespread logistics delays, causing significant disruptions to global supply chains [8]. The port logistics industry is a crucial hub for international trade. Therefore, fluctuations in cargo volume owing to climate change can have major impacts on the global economy. The negative ripple effects of climate change are particularly pronounced in port logistics. For instance, rising sea levels pose the risk of flooding to low-lying ports, whereas extreme weather events such as typhoons can damage port facilities. This shortens the maintenance cycle of port infrastructure and simultaneously increases costs. In Korea, which is surrounded by the sea on three sides, the average annual sea level rose by 4.27 mm between 2011 and 2020. and the maximum intensity of typhoons increased by 31% (39.4 km/h) between 1980 and 2020. This significant impact of climate change raises concerns about the damage to ports and their hinterlands, where diverse populations and industries are closely concentrated [9].

1.2. Aim of the Study

Nations worldwide are acutely aware of the need to strengthen their climate resilience, including that of their ports, in response to climate change. Therefore, they are individually adopting various strategies to enhance their preparedness for and resilience to climate change, and indicators for assessing climate resilience are being actively developed [10–12]. The Notre Dame Global Adaptation Initiative Country Index (ND-GAIN index) is a representative indicator. It comprehensively assesses a country's resilience by evaluating its vulnerability to climate change and preparedness capacity, indicating its level of climate resilience. It is currently used as a key resource within the international community to compare and improve climate change management [12].

The impact of climate change shocks on port cargo volumes must be understood because the port logistics industry plays a critical role in national logistics supply chains and global trade. Specifically, the ND-GAIN index, an indicator that indirectly reflects the climate resilience of port-related social, economic, and physical systems, can serve as a useful variable for analyzing the effect of climate resilience on port cargo volumes [13]. For instance, as extreme weather events caused by climate change become more frequent, negative impacts on port operations and cargo flows are anticipated. Countries with higher ND-GAIN index indices are expected to manage crises stemming from climate change better. Therefore, the aim of this study was to compare and estimate the relationship between a country's ND-GAIN index and its container port cargo volume by continent to analyze the impact of climate resilience on port operations. Specifically, this study utilizes panel regression analysis (PRA) to effectively control for factors that vary across countries and times and to precisely identify relationships between variables. This approach analyzes the relationship between climate resilience and port container cargo volume using country-specific panel data.

1.3. Research Gap

Various extreme weather events induced by climate change pose serious risks to ports and global logistics supply chain [14,15]. These include direct impacts such as sea level rise, typhoons, floods, and hurricanes causing significant damage to port infrastructure. Indirectly, climate change also creates substantial risks for port operations. In response to this climate change, modern society emphasizes the importance of resilience—the ability to understand change and transition and recover—rather than merely adapting [16–19]. Similarly, stakeholders in the highly climate-vulnerable shipping, port, and logistics supply chain sectors have begun prioritizing sustainable infrastructure, operational efficiency, and resilience [15]. In other words, efforts to mitigate, adapt, respond, and recover ports under climate change are becoming increasingly vital. Climate resilience, in particular, is considered a core consideration in port operational planning and policy formulation. Some studies have explored the importance of climate resilience in the port logistics industry, including the development and application of a Port Resilience Index (PRI) for climate change [20]. The relationship between climate change and the port industry has been a subject of consistent research. Previous studies have focused on the impacts of climate change on ports, the damages and losses caused by climate change, the importance of climate resilience to address these issues, and the development of climate resilience indices [4,6,14,20].

However, these studies have concentrated on micro-level analyses centered on operational disruptions and infrastructure vulnerabilities in ports caused by climate change. Macro-level, comprehensive analyses examining how national-level climate resilience impacts port performance remain scarce. Furthermore, most research has been confined to specific ports or sea areas, and no attempts have been made to analyze the relationship with port operational performance using comparable national-level indicators. Therefore, the objective of this study is to empirically analyze the impact of a nation's climate resilience, measured using the ND-GAIN index, on container port cargo volume and to understand the practical effects of climate resilience on ports. This study advances existing research by empirically clarifying the relationship between climate resilience and cargo volume, a core port indicator. It is expected to provide practical and strategic implications for adapting to and responding to climate change within the port logistics industry.

2. Literature Review

2.1. Climate Change and Climate Resilience

In June 1992, the United Nations Framework Convention on Climate Change (UNFCCC) defined climate change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods" [21]. In December 2015, the international community adopted the Paris Agreement, which established a new climate regime with the participation of all countries from 2020 onward. This agreement set a long-term global goal of limiting the increase in average global temperature to 1.5 °C, well below 2.0 °C compared with pre-industrial levels. Furthermore, the Agreement requires all countries to participate and enhance their efforts through a five-year cycle of implementation reviews [22]. Therefore, the international community has been continuously responding to climate change. Climate change is undeniably disruptive to modern processes, presenting new challenges for economic and social actors to confront [23]. Climate change has often been discussed in terms of its negative effects.

The negative impacts of climate change include changes in the physical environment or biota that significantly impair the composition, resilience, or productivity of natural and managed ecosystems, in addition to the functioning of socioeconomic systems, and human health and welfare [24]. Climate change induces alterations in global temperature and precipitation, SLR, and biodiversity loss, all of which negatively affect the environment, economy, human society, and ecosystem health [25].

In response to such negative impacts, activities that reduce and mitigate greenhouse gas emissions, while simultaneously identifying vulnerabilities and adapting to the impacts of climate change, have attracted increasing attention [26–28]. The potential to develop synergies between mitigation and adaptation has been widely recognized in the literature. For instance, some researchers argue that, in coastal areas, adaptation and mitigation policies should be considered jointly because their integration provides a stronger response to anthropogenic climate change than when each is pursued separately [29]. Others contend that focusing solely on either mitigation or adaptation is insufficient and that combining both strategies yields the most sustainable outcomes, although they caution that the two strategies do not always complement one another and may even create trade-offs [30].

Recently, the discourse has moved beyond passive mitigation and vulnerability assessment/adaptation to emphasizing transition and transformation, highlighting the concept of climate resilience [16–18]. That is, incremental adaptation alone is insufficient to cope with climate change, and transformational adaptation is increasingly considered necessary [19]. With the growing need to adapt to severe climate impacts, the focus has shifted toward transformational adaptation, which involves fundamental systemic changes. In this sense, climate resilience is not only about recovering from shocks, but also about reconfiguring social systems for the future [31].

Climate resilience, also referred to as climate robustness, adaptive capacity, or resilience to climate change, has been applied in various fields. It is commonly defined as the capacity of urban systems to respond effectively to climate risks [17]. The Intergovernmental Panel on Climate Change (IPCC) defines climate resilience as the capacity of social, economic, and environmental systems to handle hazardous events, trends, or disturbances related to the climate while maintaining their essential function, identity, and structure, as well as their capacity for adaptation, learning, and transformation [32]. Further, Climate resilience, from a long-term perspective, offers opportunities for improved decision-making and provides a framework for understanding how transitions and transformations unfold under climate change [33]. Resilience thus offers a perspective for strengthening the capacity to respond to many contemporary challenges.

Meanwhile, various research institutions have developed quantitative indicators for climate resilience and adaptability and published them as open data. Examples include the Environmental Performance Index (EPI), Germanwatch's Global Climate Risk Index (GCRI), and the ND-GAIN index. The EPI, developed by the World Economic Forum (WEF) in collaboration with Yale University and Columbia University, provides a data-driven summary of global sustainability status. It ranks 180 countries based on their performance in climate change, environmental health, and ecosystem vitality [34]. GCRI ranks countries based on human and economic losses from extreme weather events, analyzing the extent to which climate-related extreme weather impacts nations. Rankings are determined by economic and human impacts (number of deaths, casualties, injuries, and people made homeless). These indices synthesize the impacts of climate-related extreme weather events across diverse regions and time periods [35]. The ND-GAIN index, developed by the University of Notre Dame, measures each country's preparedness for climate change and its vulnerability to climate-related disruptions.

2.2. Climate Change and Resilience in the Port Logistics Industry

Severe climate change observed over the past decade has had significant impacts on ports and the shipping industry, particularly because port operations are highly vulnerable to the negative effects of climate change [6,36]. Various forms of climate change are impacting ports. For instance, hurricanes and typhoons account for approximately 32% of annual port infrastructure damage, primarily affecting the U.S. Gulf Coast and Southeast Asia. Flooding (including saltwater coastal inundation, rainfall, and river overflow) is cited as the most common natural disaster experienced annually by about 80% of ports worldwide [37]. Hurricane Ike in 2008 caused approximately $2.4 billion in damage to ports in the Texas region, while Hurricane Harvey in 2017 caused severe disruptions that halted operations at the Port of Houston for nearly a week [38]. Additionally, sea level rise continues to pose a persistent threat to port infrastructure. Sea level rise, primarily driven by thermal expansion of seawater due to climate change and glacial melting, interacts with regional ground subsidence, increasing the risk of flooding in port areas. These changes impose new technical and financial burdens on the operation and maintenance of existing ports. Globally, the estimated investment required for port adaptation to rising sea levels by 2050 ranges from $223 billion to as much as $768 billion. Furthermore, climate-related disasters are causing direct disruptions to port operations. For instance, Typhoon Haikui in 2012 caused approximately $10 million in economic losses at the Port of Shanghai, while Typhoon Lekima in 2019 resulted in about $65 million in losses at the Port of Dalian [37]. Furthermore, Typhoon Hagibis in 2019 caused widespread damage across Japan, delaying operations at Yokohama Port [39], while Cyclone Amphan in 2020 caused damage across India and Bangladesh, severely disrupting operations at Kolkata Port [40]. These cases starkly illustrate how climate change impacts not only port infrastructure but logistics operations as a whole.

As seen in the above cases, Ports are exposed not only to direct risks, such as SLR and storms that affect coastal infrastructure, including navigational aids and port facilities, but also to indirect risks that disrupt trade, shipping, and local communities [41,42]. These adverse effects present considerable challenges to port operators, making adaptation essential. Accordingly, the study in [6] systematically reviewed the literature on climate change-related issues, their impact on port operations, and adaptation strategies. The results confirmed that SLR, storm surges, and extreme winds are major meteorological factors disrupting port operations, and that climate change is increasingly undermining ports worldwide, further highlighting their vulnerability. Furthermore, in [14], the authors examined how weather conditions influence port productivity. They emphasized that the maritime transport sector is particularly sensitive to climatic factors, as ships entering ports face navigation and port operation risks due to wind, waves, rain, and fog. Their analysis specifically assessed the impact of wind speed and wave height on port productivity and demonstrated that meteorological conditions significantly influence the technical efficiency of ports.

In addition, climate change has been identified as a critical risk factor for ports and supply chains [15]. The study in [15] recognized ports as key economic actors vulnerable to future climate change on the regional, national, and international scales. With the growing awareness of climate-related risks, stakeholders in shipping, ports, and logistics supply chains, sectors that are highly susceptible to climate change, have begun to prioritize sustainable infrastructure, operational efficiency, and resilience. Their in-depth analysis in [15] the climate change risks, adaptation, and responses of ports and logistics supply chains provides important international insights. They concluded that ports worldwide have already suffered significant damage from climate-related disasters and hazards, and that such impacts are expected to intensify. Although some port authorities have begun to consider the risks to assets and operations explicitly, the actual implementation of adaptation strategies remains limited. Likewise, climate change caused by modern CO_2 emissions is one of the greatest contemporary challenges faced by humanity [20]. As critical nodes in global supply chains, ports are particularly vulnerable to the negative impacts of climate change from a logistics perspective [20]. The study in [20] aimed to assess the resilience of ports to the challenges posed by climate change and develop indicators for preventive measures to ensure long-term operational continuity. They proposed the port resilience index (PRI), a novel metric designed to evaluate the resilience of port operations while considering all stakeholders. Case applications have validated the index, showing that port infrastructure, facilities, and operating environments are highly sensitive to climate change. Additionally, regarding port resilience, some researchers have addressed port resilience to climate change and analyzed regional-level adaptation strategies, focusing on ports in the Guangdong–Hong Kong–Macao Greater Bay Area [36].

Similarly, ports—although central to global transport and trade—face significant operational disruptions and economic losses due to climate change [4]. The study in [4] analyzed historical global risk factors across 2013 ports and projected their impacts under warming scenarios. SLR has been identified as a key driver of coastal flooding, inundation, and heat stress, thereby amplifying risks. The results in [4] suggested that ports in the Pacific Islands, Caribbean, and Indian Ocean will be at extremely high risk by 2100, and those in the Mediterranean, Africa, and the Arabian Peninsula (Persian Gulf and Red Sea) are also expected to experience very high risks. In [43], the authors emphasized that ports, owing to their geographical location and central role in supply chains, are directly exposed to the impacts of climate change. They argued that port managers require appropriate tools and strategies to assess port resilience against potential threats and ensure sustainable long-term operations. Using the PRI, they evaluated the resilience of Spanish ports over a defined period and demonstrated the effectiveness of the proposed index. Their findings indicate that the PRI can serve as a valuable tool for port managers and policymakers to minimize negative climate impacts and strengthen resilience-based decision-making. Moreover, the study in [44] noted that climate change exerts multiple adverse effects on socio-environmental systems, resulting in a reduction in system vulnerability and the enhancement of resilience central to disaster planning and policymaking. Ports, often located in environmentally sensitive and high-risk areas, are particularly vulnerable to hazards such as extreme storms and sea-level rise. The authors in [44] argued that port planning and policy must reflect the vulnerabilities of human factors and diverse stakeholders depending on port functions. Through case studies, they examined the extent to which stakeholders recognize climate impacts and vulnerabilities and how such awareness is integrated into port planning and policies. Examining various climate anomalies caused by actual climate change and synthesizing findings from existing literature consistently indicates that climate change poses a serious threat to port infrastructure and operations. Rising sea levels and extreme weather events are consistently cited as causing operational disruptions and supply chain disruptions. Furthermore, the dynamics between climate change and ports vary regionally, leading to increased uncertainty.

Furthermore, the findings in [45] reported that climate change significantly threatens port infrastructure and operations, and without appropriate adaptation strategies, could cause substantial costs to the global economy and welfare. In [45], the authors also argued that the dynamics between climate change and ports vary regionally, generating uncertainty. A case study of four Australian ports revealed that, while managers perceive climate change as a major concern, responses remain fragmented and piecemeal. The study in [45] emphasized that effective adaptation requires fundamental shifts in management and planning practices rather than relying solely on physical or engineering measures. Perceptions of and responses to climate impacts vary across ports, depending on the regional context. Additionally, in [46], the authors identified ports as highly vulnerable to SLR and increasing storm intensity, potentially disrupting port operations and affecting supply chains and regional and global economies. Using a hybrid statistical–dynamic framework combining weather generators and metamodels, they probabilistically assessed the operational changes under scenarios of wave agitation and SLR at ports in northern Spain. Their results indicated that, while wave effects alone were minor, nonlinear feedback from the SLR amplified wave penetration within ports, reducing operational capacity. Their methodology offers practical applications in port design standards and climate adaptation planning. The study in [47] also highlighted ports as critical infrastructure vulnerable to climate change impacts, such as SLR and changes in wave patterns. Focusing on the Port of Barcelona, the authors in [47] employed numerical models to project wave-field variations and three levels of SLR under scenario RCP8.5. Their analysis revealed that, while wave effects alone were limited, the increase in water depth from SLR intensified wave penetration into port basins, reducing operability. Moreover, the degree of impact varied depending on the location and orientation of the berths, underscoring the need for port-specific adaptation strategies.

Examining various climate anomalies caused by actual climate change and synthesizing findings from existing literature consistently indicates that climate change poses a serious threat to port infrastructure and operations. Rising sea levels and extreme weather events are consistently identified as causing operational disruptions and supply chain disruptions. Notably, the dynamics between climate change and ports vary regionally, further increasing uncertainty. Ports are vulnerable not only in terms of physical infrastructure but also due to their extensive roles in trade, shipping, and local communities, making adaptation strategies to enhance resilience essential. In other words, the port industry must prioritize integrated and sustainable adaptation strategies that explicitly account for climate change uncertainty.

Therefore, it is only natural for port operators to build resilience against such climate change. However, discussions thus far have primarily focused on climate resilience and mitigation capabilities within the ports themselves—specifically on overcoming disruptions to port infrastructure or operations—and have examined the relationship between climate change and ports, concentrating on specific sea areas or regions. However, it is necessary to address the relationship between climate change and ports from a global and national perspective. This is because the capacity to respond to climate change cannot be fully achieved through the efforts of a single enterprise alone; it must be ensured at the regional and national levels. It is argued that the effective achievement of climate change adaptation and disaster risk management cannot be sufficiently accomplished through the efforts of a single organization or geographical unit alone. Therefore, port climate resilience cannot be achieved solely by port operators or local governments; it must be understood within comprehensive policies that integrate national response systems, institutional coordination, and civic capacity [48]. Furthermore, while research on climate change and resilience related to ports has been ongoing, there remains a limitation: no publicly available data or long-term aggregated indicators exist specifically addressing port climate vulnerability and resilience.

2.3. Climate Resilience Indicators and Country-Specific Status

As confirmed in the preceding discussion, ports are highly vulnerable to both direct and indirect impacts of climate change. Their capacity to respond to and recover from these impacts is determined not only by the durability of physical infrastructure but also by national-level policy preparedness, socioeconomic foundations, and institutional responsiveness [48]. Given this, port resilience to climate change must be understood as a complex structure where national-level climate recovery capacity can indirectly influence outcomes, extending beyond the technical characteristics of specific ports and port operators. Therefore, we aim to understand the relationship between a nation's climate change response capacity and its actual port cargo throughput. To do this, we needed to find publicly available data that could proxy national climate vulnerability and resilience. The ND-GAIN fulfills this requirement. ND-GAIN index provides a comprehensive assessment of a nation's vulnerability to climate change and its preparedness for adaptation. Its components include higher-level system variables that can impact port functionality maintenance, such as physical infrastructure, governance, economic capacity, and social systems. ND-GAIN index can serve as an indicator to quantitatively represent the level of national resilience that forms the foundational environment for port operations. Furthermore, existing researchers have found that the ND-GAIN index provides the most comprehensive and consistent coverage, performing detailed assessments for many countries. Furthermore, other scholars have noted that this index was developed through extensive consultation with academia, practitioners, and private sector users, and that its transparent methodology and usable format promote academic research [12,49–51]. Of course, ND-GAIN index is not an indicator that directly measures the micro-level physical resilience or operational efficiency of a specific port, and it has limitations in that it does not sufficiently reflect regional port characteristics. Nevertheless, as it currently provides long-term time-series data and enables the acquisition of comparable quantitative information for over 170 countries, it is judged to be the most suitable proxy for climate resilience in the design of this study's continental comparative analysis.

The ND-GAIN index assesses a nation's 'adaptation vulnerability' and 'adaptation readiness' to climate change. The ND-GAIN index, also known as the National Adaptation Capacity Index, quantitatively assesses the climate adaptation capacity of 177 countries worldwide using data that can gauge a country's adaptation vulnerability and resilience, such as water availability, food security, and education levels. Climate change 'vulnerability' refers to the degree of exposure to negative impacts of climate change, sensitivity, and adaptation capacity, whereas 'adaptation readiness' signifies a country's ability to leverage investments to transition into climate change adaptation actions [52]. The ND-GAIN index is widely used to determine the adaptation capacity (resilience) of a country based on its vulnerability to climate change. They are also utilized across diverse nations and widely employed by corporations, NGOs, governments, and decision makers as reference materials for strategic operations and decisions regarding supply chains, resource projects, and policy changes.

We examined the trends in the ND-GAIN index from 2010 to 2022 for all countries provided by ND-GAIN, categorized by the global continent encompassing all continents and by six individual continents (Africa, Asia, Europe, North America, Latin America, and Oceania), as shown in Figure 1. Countries on the Asian continent showed varying levels of distribution, whereas the ND-GAIN index for North America, Oceania, and Europe were mostly high. Conversely, the ND-GAIN index for Africa and Latin America were relatively low.

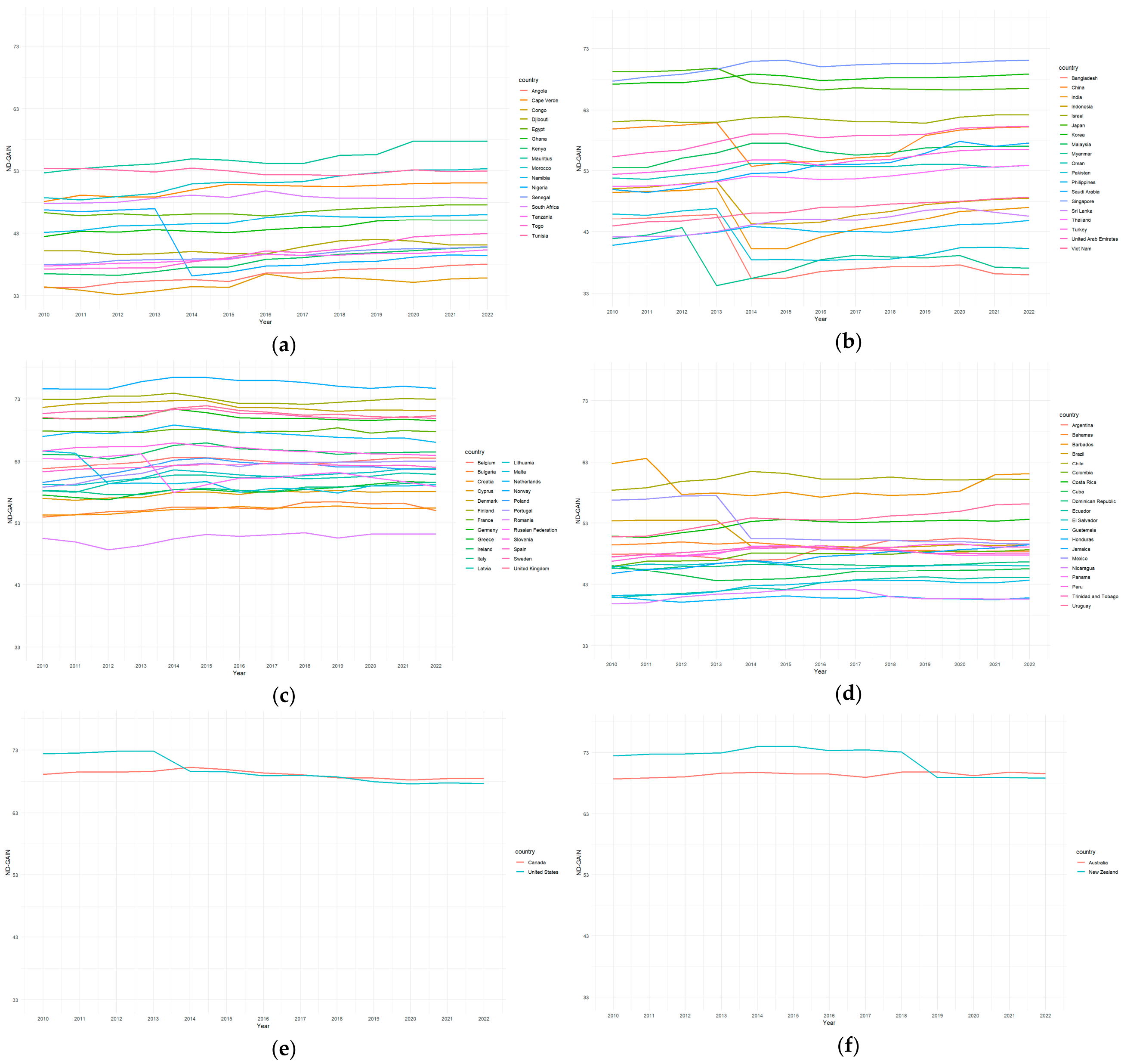


Figure 1. Trends in the ND-GAIN index by country and continent (2010–2022). (**a**) Africa ND-GAIN Time Trend; (**b**) Asia ND-GAIN Time Trend; (**c**) Europe ND-GAIN Time Trend; (**d**) North America ND-GAIN Time Trend; (**e**) Latin America ND-GAIN Time Trend; (**f**) Oceania ND-GAIN Time Trend.

3. Data and Methods

3.1. Data

In this study, we conducted an empirical analysis to examine the impact of national climate resilience on the port industry, reflecting the industry's vulnerability to climate change. We examined the relationship between the ND-GAIN index and the container port throughput of each country. In doing so, we adopt a comprehensive perspective encompassing all the countries included in the analysis and a detailed perspective dividing the analysis subjects into six continents (Africa, Asia, Europe, North America, Latin America, and Oceania). To achieve this, panel data were collected by year for 83 countries selected based on data availability. The data collection period spanned 2010, when container port cargo volumes began stabilizing after the financial crisis, to 2022, the latest year for which data on all variables were available.

However, this study aimed to analyze the impact of climate change resilience (using ND-GAIN index) on container port throughput across six continents. North America and Oceania were excluded from the panel regression analysis due to the limited availability of data, with only two countries available for each region. Nevertheless, as these two regions occupy crucial positions within the global port network, we will supplementarily examine their trends through separate descriptive statistics, time-series analysis, and additional case studies. Therefore, this study performs panel regression analysis (PRA) using time-series panel data based on a global perspective (all 84 countries) and four continental groups (Africa, Asia, Europe, Latin America).

Using country-specific year-by-year panel data, we conduct PRA, which effectively controls for factors varying by country and time and allows for the precise identification of relationships between variables, enabling the analysis of the relationship between climate resilience and container port throughput.

The variables used in the analysis were selected on the basis of previous studies. First, the ND-GAIN index was selected as a variable related to climate resilience. The dependent variable was national container port throughput. Finally, the control variables, referenced from prior studies, included the national population, real GDP, and liner shipping connectivity index (LSCI).

First, the quantitative ND-GAIN index was selected as an independent variable to proxy climate resilience. The ND-GAIN index measures a country's vulnerability to climate change and its readiness to channel financial investments (climate finance) into climate adaptation measures. Notably, open-source indicators for 182 UN countries have been published annually since 1995, making the ND-GAIN index the most suitable for collecting country-specific time-series data aligned with the objectives of this study. These indicators can be represented by values ranging from 0 to 100, with higher values indicating greater national adaptation capacity (). The formula is as follows:

$$ND - GAIN\ score = (Readiness\ score - \ Vulnerability\ score + 1) \times 50 \tag{1}$$

The vulnerability score was assessed through 45 indicators considering six life-sustaining sectors, whereas the readiness score was evaluated through 10 indicators considering three elements: economic, governance, and social readiness [52].

Next, the dependent variable, national container port throughput, was based on annual container port throughput figures provided by the UNCTAD Data Hub [53]. These data represent comprehensive throughput figures for national container port terminals and were deemed suitable for use in this study.

Finally, in addition to climate resilience, control variables expected to influence national container port throughput based on prior research were selected. These included national characteristic, national economic, and maritime network indicators. Population size was used as a proxy for national characteristic indicators [54], whereas national economic indicators were represented by each country's real GDP. The shipping network indicator was measured using the country-specific LSCI [55,56]. This reflects the discussion in existing research that excellent connectivity is essential for the further development of ports and their surrounding areas [57]. All control variables used in this study were collected as time-series data from the UNCTAD Data Hub [53].

To summarize, to enhance the data consistency of the empirical analysis in this study and ensure analytical reliability, we used data only from countries where all data from 2010 to 2022 were available. This includes a total of 83 countries, specifically excluding those with unreliable time-series data (countries with annual n/a values in the data). Furthermore, while the global perspective encompasses all six continents, individual continent-specific analyses excluded North America and Oceania due to insufficient sample sizes.

3.2. Methodology

Regression analysis examines changes in the dependent variable as independent variables, thereby identifying causal relationships between them. Panel regression analysis was utilized in this study to analyze the impact of climate resilience on container port cargo volume. The panel data used in panel regression analysis included time-series data in which cross-sectional data observed across multiple individuals are repeatedly observed over multiple time periods for the same individuals [58,59]. The advantages of analyzing such panel data can be broadly categorized into three main points.

First, it allows for the control of individual heterogeneity. Failure to do these risks distorting the results of both time-series and cross-sectional analyses. However, panel data analysis offers the advantage of controlling for both time and individual effects. Second, it provides degrees of freedom and variability, thereby enabling the adjustment of dynamics. Panel data analysis enhances the reliability of the analytical results by dividing and analyzing data in greater detail [58,59]. For instance, when using time-series or cross-sectional data alone, the limited number of observations risks reducing the degrees of freedom in the statistical analysis. Panel data analysis combines both types of data to increase the number of observations, thereby securing degrees of freedom and yielding more reliable results. Furthermore, as previously mentioned, panel data can simultaneously account for changes over time and differences between individual units, enabling the effective analysis of highly variable data. In particular, panel data offer the advantage of providing a foundation for precisely tracking adjustment processes or dynamic relationships between variables over time. Third, it can yield insights that are difficult to obtain from cross-sectional or time-series data alone. For instance, by simultaneously reflecting on the unique characteristics and temporal evolution of specific individuals, firms, or countries, it offers the advantage of analyzing long-term trends or behavioral patterns that are difficult to discern from single-point data [60,61]. That is, a panel regression analysis utilizing panel data can most efficiently extract the rich and diverse information inherent in them. Addressing unobservable omitted variables that cannot be controlled for in cross-sectional or time-series analyses is highly useful in social science research, where controlling for all variables is impossible [59]. The basic structure of the panel regression model (ordinary least squares) is as follows:

$$y_{it} = \alpha + \sum_{k=1}^{K} \beta_k X_{kit} + u_{it} \tag{2}$$

If the panel regression model is expressed as a two-way error components model based on the structure of the disturbance term (u_{it}), it is given by the following equation.

$$u_{it} = \mu_i + \lambda_t + \epsilon_{it} \tag{3}$$

where μ_i, λ_t, and ϵ_{it} denote the unobservable individual effect, unobservable time effect, and stochastic disturbance term combining the effects from cross-sectional observations and time series, respectively. In this error structure model, if each disturbance term is treated as a fixed constant, it is a fixed-effects model; if treated as a random variable, it is assumed to be a random-effects model (REM) [59]. First, the advantage of the fixed-effects model is that it distinguishes individual characteristic effects to estimate coefficients. However, creating dummy variables for this purpose reduces the degrees of freedom, potentially leading to relatively lower estimation accuracy. Additionally, the fixed-effects model cannot estimate coefficients for variables that do not vary over time within a specific individual. Next, the advantage of the random effects model is that, unlike the fixed-effects model, it carries a lower risk of reduced estimation precision. However, it has the disadvantage of requiring the assumption that individual-specific effects must be uncorrelated with the independent variables. Most prior studies utilizing panel regression analysis employed the Hausman test to determine model suitability [62]. Therefore, in this study, we conducted the Hausman test beforehand and selected the appropriate model based on its results.

3.3. Research Design

In this study, we utilized panel regression analysis to examine the impact of climate resilience on container port throughput. To this end, we conducted an analysis based on panel data covering the entire world and four individual continents (Africa, Asia, Europe, Latin America) over the 13-year period from 2010 to 2022. The research hypotheses for this are presented as Research Hypotheses (1–5). Meanwhile, due to sample size limitations, the continents of North America and Oceania were excluded from the panel regression model as they could not ensure statistical reliability. Consequently, separate research hypotheses for these regions were formulated and presented as the supplementary research question (6) below. Based on a review of prior studies, the research hypotheses for this study were as follows:

- Research Hypothesis 1: Climate resilience (ND-GAIN index) of the global continent has a significant impact on the container port throughput of that continent.
- Research Hypothesis 2: Climate resilience (ND-GAIN index) of the African continent has a significant impact on the container port throughput of that continent.
- Research Hypothesis 3: Climate resilience (ND-GAIN index) of Asia continent has a significant impact on the container port throughput of that continent.
- Research Hypothesis 4: Climate resilience (ND-GAIN index) of the European continent has a significant impact on the container port throughput of that continent.
- Research Hypothesis 5: Climate resilience (ND-GAIN index) of Latin America continent has a significant impact on the container port throughput of that continent.
- Research Question 6 (Supplementary): Could climate resilience (ND-GAIN index) in North American and Oceanian countries show a consistent correlation with container port throughput on their respective continents?

To prove the research hypotheses, we set up fixed-effects and random-effects models of the panel regression analysis as follows.

Fixed-effects model:

$$log\left(Throughput_{i,t}\right) = \beta_0 + \beta_1 \log\left(ndgain_{i,t}\right) + \beta_2 \log\left(population_{i,t}\right) + \beta_3 \log\left(gdp_{i,t}\right) + \beta_4 \log(lsci_{i,t}) + \alpha_i + \epsilon_{i,t} \quad (4)$$

where i = country, t = year, α_i = country-specific fixed effect (controlling for individual characteristics), $\epsilon_{i,t}$ = error term (residual), and $\beta_0,\ \beta_1, \beta_2,\ \beta_3, \beta_4$ = estimated coefficients.

Random-effects model:

$$log\left(Throughput_{i,t}\right) = \beta_0 + \beta_1 \log\left(ndgain_{i,t}\right) + \beta_2 \log\left(population_{i,t}\right) + \beta_3 \log\left(gdp_{i,t}\right) + \beta_4 \log(lsci_{i,t}) + u_i + \epsilon_{i,t} \quad (5)$$

where i = country, t = year, u_i = random effect representing country-specific characteristics (assumed to be an independent random variable with mean 0 and variance σ_u^2), $\epsilon_{i,t}$ = error term (residual, assumed to be an independent random variable with mean 0 and variance σ_ϵ^2), and $\beta_0,\ \beta_1, \beta_2,\ \beta_3, \beta_4$ = estimated coefficients.

Based on this model, we conducted an analysis by dividing the global continent into six continents, as previously mentioned. The sequence of analysis is as follows. First, descriptive statistics were examined to understand the basic characteristics of the variables in the sample data. Unit-root tests were performed for each variable. The Hausman test was then conducted to assess the suitability of the research model used in this study.

Subsequently, a panel regression analysis was performed to derive results based on the fixed-effects or random-effects models for the global continent and each continent.

4. Results

4.1. Descriptive Statistics and Correlation Analysis

Before examining how global and regional climate resilience affects port container cargo volume, we first examined the descriptive statistics of the analysis subjects to understand the basic characteristics of the analytical data used in this study. Descriptive statistical analysis is essential for summarizing data and understanding their characteristics, thereby setting the direction for subsequent analysis. According to [63], the authors noted that descriptive statistical analysis is crucial because it clarifies the median, variance, and normality of research data, enabling researchers to select the most appropriate statistical methods based on this information. In particular, descriptive statistics are not only useful for summarizing data, but also for understanding the overall structure of the data, and are valuable even in the stage of collecting data suitable for research questions [63].

Table 1 summarizes the descriptive statistics of the global and continental variables, including the minimum, median, maximum, and mean values of the analyzed data. All variables were log-transformed. Log transformation normalizes the data distribution and effectively reduces the impact of outliers. It is especially used to unify variables with large differences in scale.

First, by examining the ND-GAIN index, an indicator of climate resilience, Oceania showed the highest climate resilience, with an average of 4.257. This was followed by North America (4.240), Europe (4.144), Asia (3.947), Latin America (3.877), and Africa (3.773). The global average was 3.968. In terms of population size, an indicator representing a country's total population, North America had the largest average population of 11.60, followed by Asia (11.031), Africa (9.499), Oceania (9.278), Europe (9.265), and Latin America (9.093). The global average was 9.729. This result differs from the actual population figures for these continents, arising from the log transformation applied to the data, which reduces large differences and emphasizes relatively small values. Although the Asian continent includes many countries with diverse population sizes, North America comprises only two countries, both of which have large values. Considering real GDP, an indicator of a country's economic activity level, North America exhibited the highest real GDP, with an average of 15.50, followed by Asia and Oceania, at 13.09, and Europe (12.50), Latin America (11.185), and Africa (10.45). The global average was 12.01. Considering the liner shipping connectivity index, an indicator of a country's maritime network connectivity and efficiency, North America had the highest index, with an average of 5.614. This was followed by Asia (5.387), Europe (4.775), Oceania (4.766), Latin America (4.397), and Africa (4.250). The global average was 4.743. This result indicates that North America possesses high maritime network connectivity based on the density of its shipping networks and advanced port infrastructure. In particular, the United States is considered the largest consumer nation within the global logistics supply chain. In contrast, regions exhibiting low LSCI values demonstrate certain limitations in terms of global connectivity and logistics competitiveness. In terms of container port throughput volume, an indicator representing a country's total container port cargo volume, North America had the highest average, at 16.66, followed by Asia (16.07), Oceania (15.39), Europe (14.49), Latin America (14.02), and Africa (13.63). The global average was 14.65. To summarize the descriptive statistics of the variables by continent, all variables exhibited positive (+) values. As log transformation was applied during the data preprocessing stage, the standard deviations were generally low across the board.

Table 1. Descriptive Statistics for global and individual continent-specific variables.

Variable Name	Variable Definition (Unit)	Continent (Number of Countries)	Minimum	Median	Maximum	Mean	S.D.
ND-GAIN	Climate Resilience (point)	Global (83)	3.502	3.974	4.337	3.968	0.1985
		Africa (16)	3.502	3.767	4.057	3.773	0.1405
		Asia (19)	3.534	3.965	4.264	3.947	0.1854
		Europe (24)	3.886	4.137	4.337	4.144	0.0989
		North America (2)	4.214	4.236	4.288	4.240	0.0219
		Latin America (20)	3.685	3.875	4.153	3.877	0.1056
		Oceania (2)	4.229	4.244	4.304	4.257	0.0274
Population	Population (thousands)	Global (83)	5.617	9.743	14.171	9.729	1.7544
		Africa (16)	6.234	9.917	12.316	9.499	1.6981
		Asia (19)	7.922	11.168	14.171	11.031	1.5992
		Europe (24)	6.047	9.244	11.895	9.265	1.4432
		North America (2)	10.44	11.61	12.74	11.60	1.1209
		Latin America (20)	5.617	9.220	12.256	9.093	1.6403
		Oceania (2)	8.377	9.274	10.174	9.278	0.8367
GDP	Real GDP (1,000,000 USD)	Global (83)	7.29	12.26	16.87	12.01	1.8986
		Africa (16)	7.29	10.73	13.19	10.45	1.6690
		Asia (19)	10.69	12.79	16.61	13.09	1.3106
		Europe (24)	9.05	12.64	15.11	12.50	1.6075
		North America (2)	14.15	15.49	16.87	15.50	1.2611
		Latin America (20)	8.342	11.038	14.458	11.185	1.5568
		Oceania (2)	11.94	13.10	14.20	13.09	0.9889
LSCI	Liner Shipping Connectivity Index (point)	Global (83)	2.448	4.675	7.043	4.743	0.8412
		Africa (16)	2.448	4.216	5.503	4.250	0.6234
		Asia (19)	3.237	5.398	7.043	5.387	0.7771
		Europe (24)	2.959	4.708	6.069	4.775	0.8550
		North America (2)	4.951	5.620	6.277	5.614	0.5858
		Latin America (20)	2.937	4.545	5.292	4.397	0.5955
		Oceania (2)	4.428	4.795	5.069	4.766	0.2545
Throughput	Container terminal throughput (TEU)	Global (83)	10.80	14.61	19.41	14.65	1.5587
		Africa (16)	10.80	13.50	15.99	13.63	1.1641
		Asia (19)	12.72	16.07	19.41	16.07	1.2110
		Europe (24)	11.87	14.30	16.69	14.49	1.3631
		North America (2)	15.36	16.66	17.95	16.66	1.0970
		Latin America (20)	11.13	14.24	16.28	14.02	1.2757
		Oceania (2)	14.66	15.37	16.05	15.39	0.5152

Note: All variables have been log-scaled.

Figures 2 and 3 show scatter plots and correlation matrices visualizing the combinations of global continents and variables by continent. According to the global perspective scatter plot and correlation matrix (Figure 2), climate resilience (ND-GAIN index) showed a statistically significant positive (+) correlation with container port throughput. This suggests that countries with higher climate change readiness are more likely to have port operating systems functioning at a certain level of stability. Furthermore, the ND-GAIN index showed significant positive (+) correlations with GDP and LSCI, indicating that climate resilience can be directly or indirectly linked to a country's economic foundation and the quality of its maritime network services. Notably, a very strong positive (+) correlation was observed between LSCI and Throughput, confirming that LSCI is one of the key variables influencing port throughput. Next, the continental scatter plots and correlation matrix (Figure 3) revealed slight differences in variable relationships across continents. While a consistent positive (+) correlation between ND-GAIN index and throughput was observed in some continents (Asia, Europe, Latin America), the correlation was statistically insignificant in Africa and North America. Conversely, a negative (−) correlation was found in Oceania. This suggests that the impact of the ND-GAIN index on the port industry varies by continent and may differ depending on the economic context, port policies and infrastructure levels, and climate crisis severity across continents and countries.

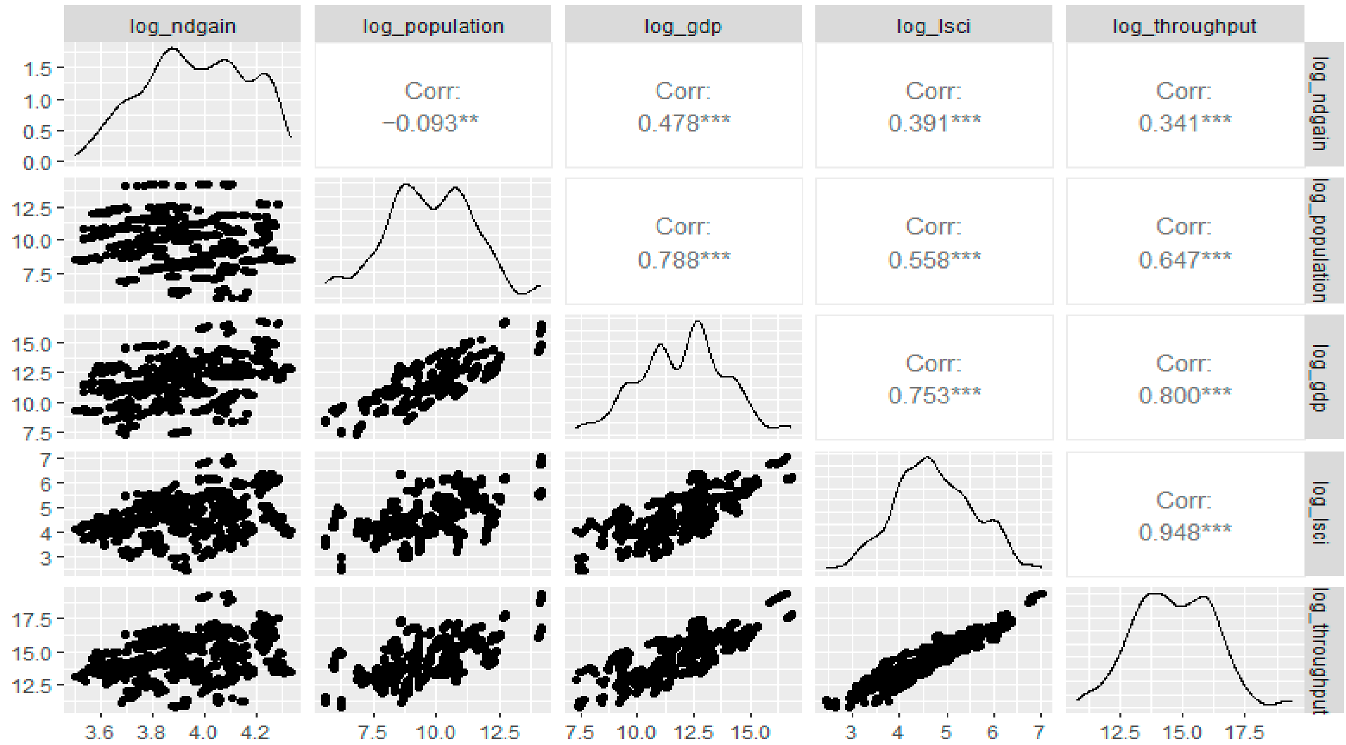
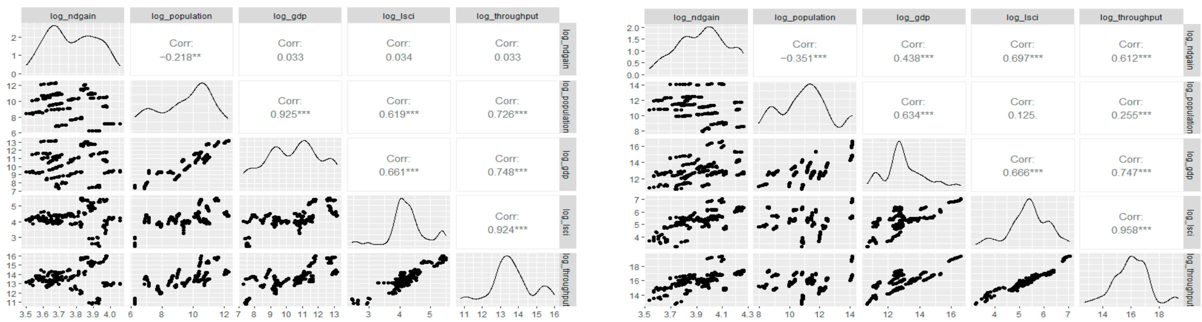


Figure 2. Scatter plot and correlation matrix of global continental variables. Note: ** and *** indicate significance levels of 5% and 1%, respectively.

4.2. Panel Unit Root Tests

We conducted an analysis using panel data that integrated time-series and cross-sectional data. Accordingly, prior to performing the panel regression analysis, a unit root test was conducted on the variables in the analysis data to verify the stationarity of the time-series data. Stationarity refers to the property in which a time-series dataset does not change its statistical characteristics, such as mean or variance, over time and lacks trends or seasonality. The reason for verifying the stationarity of such time-series data is that using variables from unstable time-series data may lead to spurious regression problems in regression analysis [64].



(**a**) (**b**)

Figure 3. *Cont.*

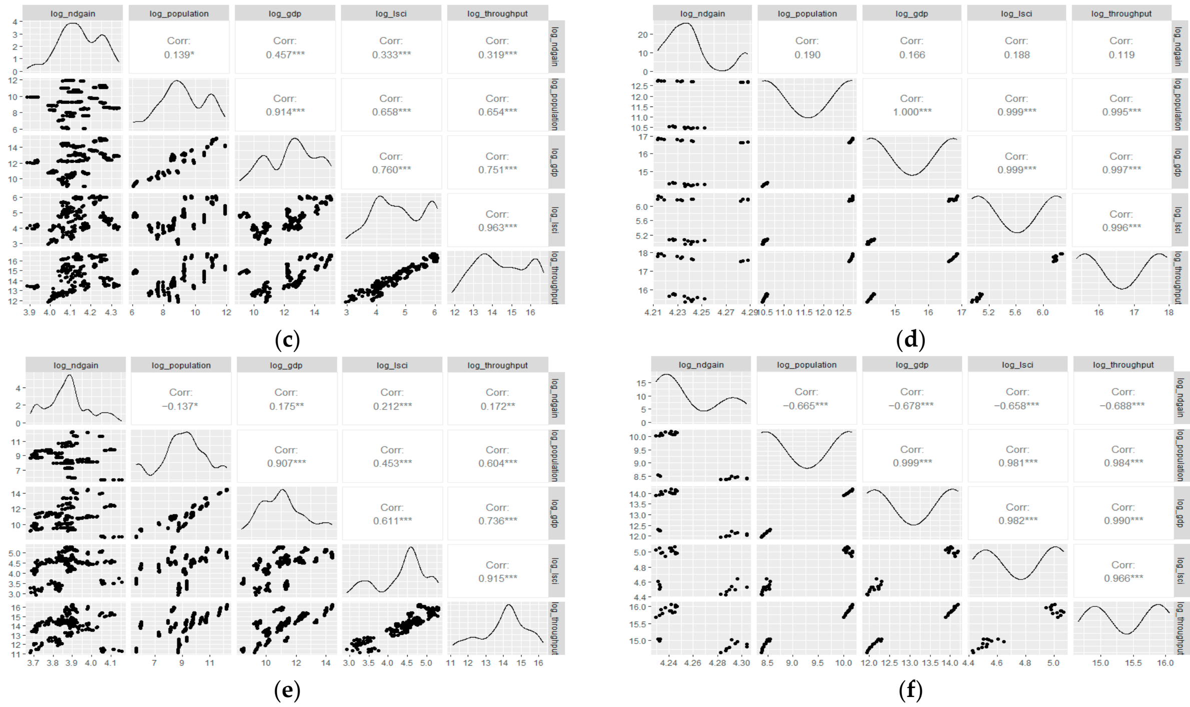


Figure 3. Scatter plot and correlation matrix of variables by continent. (**a**) Scatter Matrix: Africa; (**b**) Scatter Matrix: Asia; (**c**) Scatter Matrix: Europe; (**d**) Scatter Matrix: North America; (**e**) Scatter Matrix: Latin America; (**f**) Scatter Matrix: Oceania. Note: *, ** and *** indicate significance levels of 10%, 5% and 1%, respectively.

While several unit root tests exist, including the Dickey–Fuller (DF), Augmented Dickey–Fuller (ADF), and Phillips and Perron (PP) tests, we employed the ADF unit root test, which is the most widely used among them. The results of the unit root tests for the global continent and continent-specific variables are presented in Table 2.

Table 2. ADF unit root test results for global and regional continents.

Continent Name	Variable Name	Level Variable	1 Diff. Variable
Global	ND-GAIN	−4.7820 ***	-
	Population	−7.3629 ***	-
	GDP	−6.1997 ***	-
	LSCI	−7.2378 ***	-
	Throughput	−6.4524 ***	-
Africa	ND-GAIN	−3.4953 **	-
	Population	−3.8796 **	-
	GDP	−3.9125 **	-
	LSCI	−3.1209	−5.5664 ***
	Throughput	−3.6151 **	-
Asia	ND-GAIN	−3.5850 **	-
	Population	−3.1693 *	−5.8199 ***
	GDP	−3.2089 *	−5.9427 ***
	LSCI	−3.6869 **	-
	Throughput	−3.7206 **	-
Europe	ND-GAIN	−3.0224	−6.7713 ***
	Population	−4.0127 ***	-
	GDP	−3.5358 **	-
	LSCI	−4.4979 ***	-
	Throughput	−4.2538 ***	-
Latin America	ND-GAIN	−2.7413	−6.3329 ***
	Population	−3.9849 ***	-
	GDP	−4.2490 ***	-
	LSCI	−4.3868 ***	-
	Throughput	−4.1267 ***	-

Note: *, ** and *** indicate significance levels of 10%, 5% and 1%, respectively.

The unit root test results indicate that the following variables exhibit unstable time series: LSCI for Africa, population and GDP for Asia, ND-GAIN index for Europe, and ND-GAIN index for Latin America. This is because the null hypothesis of no unit root was not rejected at the 5% significance level. Accordingly, differencing was applied to the variables that failed to achieve a stationary state. The results indicate that, except for North American ND-GAIN index, which underwent third-order differencing, all variables rejected the null hypothesis of unit root presence at the 5% significance level after first-order differencing, confirming their stationarity. Therefore, the empirical analysis in this study utilized time series data that had been rendered stationary as variables.

4.3. Hausman Specification Test

Next, to establish an appropriate research model for this study, the Hausman test was conducted for global and individual continents. This is because the choice between a fixed effects model and a random-effects model in panel regression analysis is generally determined using the Hausman test [62]. The Hausman test assumes a p-value ≥ 0.1; if the null hypothesis is rejected, the fixed-effects model is selected, and if not rejected, the random-effects model is used [65]. Before performing the test, North America and Oceania were excluded from the analysis. This is because the random effects model requires a relatively large sample size, making stable estimation difficult for these continents, which include only two countries each. Therefore, applying a fixed effects model to North America and Oceania was considered reasonable. The results of the Hausman test for the global continent and the remaining continents (Africa, Asia, Europe, and Latin America) are shown in Table 3.

Table 3. Testing results of the Hausman research model by global continents and continents.

Continent Name	Chi-Sq. Statistic	Chi-Sq. d.f.	Prob.
Global	580.92	4	0.000 ***
Africa	149.45	4	0.000 ***
Asia	108.93	4	0.000 ***
Europe	75.72	4	0.000 ***
Latin America	42.666	4	0.000 ***

Note: *** indicate significance levels of 1%, respectively.

The Hausman test results indicated that the p-value for rejecting the null hypothesis was within the 1% significance level for all continents, including the global continent. Therefore, it is preferable to adopt a fixed-effects model, rather than a random-effects one, for the global, African, Asian, European, and Latin American continents. Accordingly, in this study, a panel regression analysis was conducted using the fixed-effects model for both the global continent and the six individual continents.

4.4. Regression Results: Global and Continental Comparisons

4.4.1. Global

Table 4 presents the results of the panel regression analysis of container port throughput across global continents. For the global continents, all variables exerted a positive (+) influence on container port throughput and were statistically significant. Examining the regression coefficients, ND-GAIN yielded a value of 0.547 at the 1% significance level, indicating that a 1% increase in the elasticity index corresponded to a 0.547% increase in container port throughput. The elasticity index increased by 1%, and the container port throughput increased by 0.547%. Population showed a coefficient of 0.200 at the 1% significance level, indicating that a 1% increase in population leads to a 0.200% increase in container port throughput. GDP was 0.850 at the 1% significance level, meaning that a

1% increase in real GDP led to a 0.850% increase in container port throughput. The LSCI was 0.699 at the 1% significance level, indicating that a 1% increase in the linear shipping connectivity index led to a 0.699% increase in container port throughput. The analysis revealed that the order of importance influencing the dependent variable, container port throughput, was GDP > LSCI > ND-GAIN > population. Research Hypothesis 1 was statistically significant, confirming that the climate resilience of global continents positively impacts container port throughput.

Table 4. Panel regression analysis results for container port throughput on global continents.

Contents	Fixed-Effects Model			
	Coefficient	**Std. Error**	***t*-Value**	***p* > [*t*]**
ND-GAIN	0.5474	0.1430	3.827	0.000 ***
Population	0.2006	0.1153	1.740	0.082 *
GDP	0.8508	0.0507	16.774	0.001 ***
LSCI	0.6992	0.0471	14.844	0.001 ***
F-test	326.398 (0.001) ***			
R^2	0.5682			

Note: * and *** indicate significance levels of 10% and 1%, respectively.

4.4.2. Continental

Panel regression analyses were conducted by continent (Africa, Asia, Europe, North America, Latin America, and Oceania). However, for North America and Oceania (auxiliary research question 6), where panel regression analysis could not be performed, we examined the preceding descriptive statistics and correlation analysis, as well as the time-series trends, as part of the auxiliary analysis.

Table 5 presents the results of the panel regression analysis of container port throughput in Africa. For Africa, similar to the global continent, all variables had a positive (+) effect on container port throughput. However, population was not statistically significant. Examining the regression coefficients, ND-GAIN index had a value of 1.574 at the 1% level of significance. This suggests that a 1% increase in the climate resilience index led to a 1.574% increase in container port throughput. Population yielded a coefficient of 0.433, indicating that a 1% increase in population led to a 0.433% increase in container port throughput; however, this was not statistically significant. GDP showed a coefficient of 0.679 at the 1% significance level, indicating that a 1% increase in real GDP led to a 0.679% increase in container port throughput. LSCI showed a coefficient of 0.696 at the 1% significance level, indicating that a 1% increase in LSCI led to a 0.696% increase in container port throughput. The analysis revealed that the order of importance of independent variables affecting the dependent variable, container port throughput, was ND-GAIN > LSCI > GDP. Research Hypothesis 2 was statistically significant, confirming that climate resilience on the African continent positively impacts container port throughput.

Table 5. Results of panel regression analysis on container port cargo volumes in Africa.

Contents	Fixed Effect Model			
	Coefficient	**Std. Error**	***t*-Value**	***p* > [*t*]**
ND-GAIN	1.5742	0.4540	3.467	0.000 ***
Population	0.4336	0.2867	1.512	0.1321
GDP	0.6795	0.1572	4.321	0.000 ***
LSCI	0.6966	0.1213	5.740	0.000 ***
F-test	45.6303 (0.000) ***			
R^2	0.4926			

Note: *** indicate significance levels of 1%, respectively.

Table 6 presents the results of the panel regression analysis of container port throughput for the Asian continent. The population variable had a negative impact on container port throughput, whereas the remaining variables had positive impacts, all of which were statistically significant. Examining the regression coefficients, ND-GAIN index was 0.207 at the 10% significance level. This indicates that a 1% increase in the climate resilience index leads to a 0.207% increase in container port throughput. Population showed a coefficient of −0.209 at the 10% significance level, indicating that a 1% increase in population led to a 0.209% decrease in container port throughput. GDP was 0.948 at the 1% significance level, indicating that a 1% increase in real GDP led to a 0.948% increase in container port throughput. LSCI was 0.600 at the 1% significance level, indicating that a 1% increase in LSCI led to a 0.600% increase in container port throughput. The analysis revealed that the order of importance of independent variables affecting the dependent variable—container port throughput—was consistent with that of the global continent: GDP > LSCI > ND-GAIN > population. Research Hypothesis 3 was statistically significant, confirming that climate resilience in Asia positively impacts container port throughput.

Table 6. Results of panel regression analysis on container port cargo volume in the Asian continent.

Contents	Fixed-Effects Model			
	Coefficient	**Std. Error**	***t*-Value**	***p* > [*t*]**
ND-GAIN	0.2079	0.1178	1.764	0.079 *
Population	−0.2098	0.1260	−1.665	0.097 *
GDP	0.9489	0.0563	16.855	0.001 ***
LSCI	0.6003	0.0635	9.447	0.001 ***
F-test	353.104 (0.001) ***			
R^2	0.8631			

Note: * and *** indicate significance levels of 10% and 1%, respectively.

Table 7 presents the results of the panel regression analysis of European container port throughput. Similarly to the Asian continent, the population variable negatively impacted container port throughput, whereas the remaining variables had a positive impact, all of which were statistically significant. Examining the regression coefficients, ND-GAIN index was 2.568 at the 1% significance level. This indicates that a 1% increase in the climate resilience index leads to a 2.568% increase in container port throughput. Population showed a value of −0.689 at the 5% significance level, meaning that a 1% increase in population led to a 0.689% decrease in container port throughput. GDP was 0.911 at the 1% significance level, indicating that a 1% increase in real GDP led to a 0.911% increase in container port throughput. LSCI was 0.833 at the 1% significance level, indicating that a 1% increase in LSCI led to a 0.833% increase in container port throughput. The analysis revealed that the order of importance of independent variables affecting the dependent variable, container port throughput, was ND-GAIN > GDP > LSCI > population. Research Hypothesis 4 was statistically significant, confirming that climate resilience in continental Europe positively impacts container port throughput.

Table 7. Results of Panel Regression Analysis on Container Port Cargo Volume in the European Continent.

Contents	Fixed-Effects Model			
	Coefficient	**Std. Error**	***t*-Value**	***p* > [*t*]**
ND-GAIN	2.5683	0.5705	4.502	0.001 ***
Population	−0.6891	0.3341	−2.063	0.040 **
GDP	0.9112	0.0860	10.586	0.001 ***
LSCI	0.8333	0.0856	9.735	0.001 ***
F-test	89.348 (0.001) ***			
R^2	0.5572			

Note: ** and *** indicate significance levels of 5% and 1%, respectively.

Table 8 presents the panel regression analysis results for container port throughput in Latin America. ND-GAIN index had a negative impact on container port throughput, whereas the remaining variables had positive impacts, all of which were statistically significant. Examining the regression coefficients, ND-GAIN index was −0.711 at the 5% significance level. This indicates that a 1% increase in the climate resilience index led to a 0.711% decrease in container port throughput. Population showed a coefficient of 1.570 at the 1% significance level, indicating that a 1% increase in population led to a 1.570% increase in container port throughput. GDP showed a coefficient of 0.635 at the 1% significance level, indicating that a 1% increase in real GDP led to a 0.635% increase in container port throughput. LSCI showed a coefficient of 0.376 at the 1% significance level, indicating that a 1% increase in LSCI led to a 0.376% increase in container port throughput. The analysis revealed that the order of importance of independent variables affecting the dependent variable, container port throughput, was population > GDP > LSCI > ND-GAIN. Research Hypothesis 6 was statistically significant, confirming that climate resilience in Latin America negatively affects container port throughput. The graph visualizing the PRA results is shown in Figure 4. The results are for the global results and four continents.

Table 8. Results of panel regression analysis on container port cargo volume in Latin America.

Contents	Fixed-Effects Model			
	Coefficient	**Std. Error**	***t*-Value**	***p* > [*t*]**
ND-GAIN	−0.7110	0.2992	−2.376	0.018 **
Population	1.5704	0.2764	5.680	0.001 ***
GDP	0.6357	0.1166	5.452	0.001 ***
LSCI	0.3767	0.0936	4.023	0.001 ***
F-test	77.491 (0.001) ***			
R^2	0.5677			

Note: ** and *** indicate significance levels of 5% and 1%, respectively.

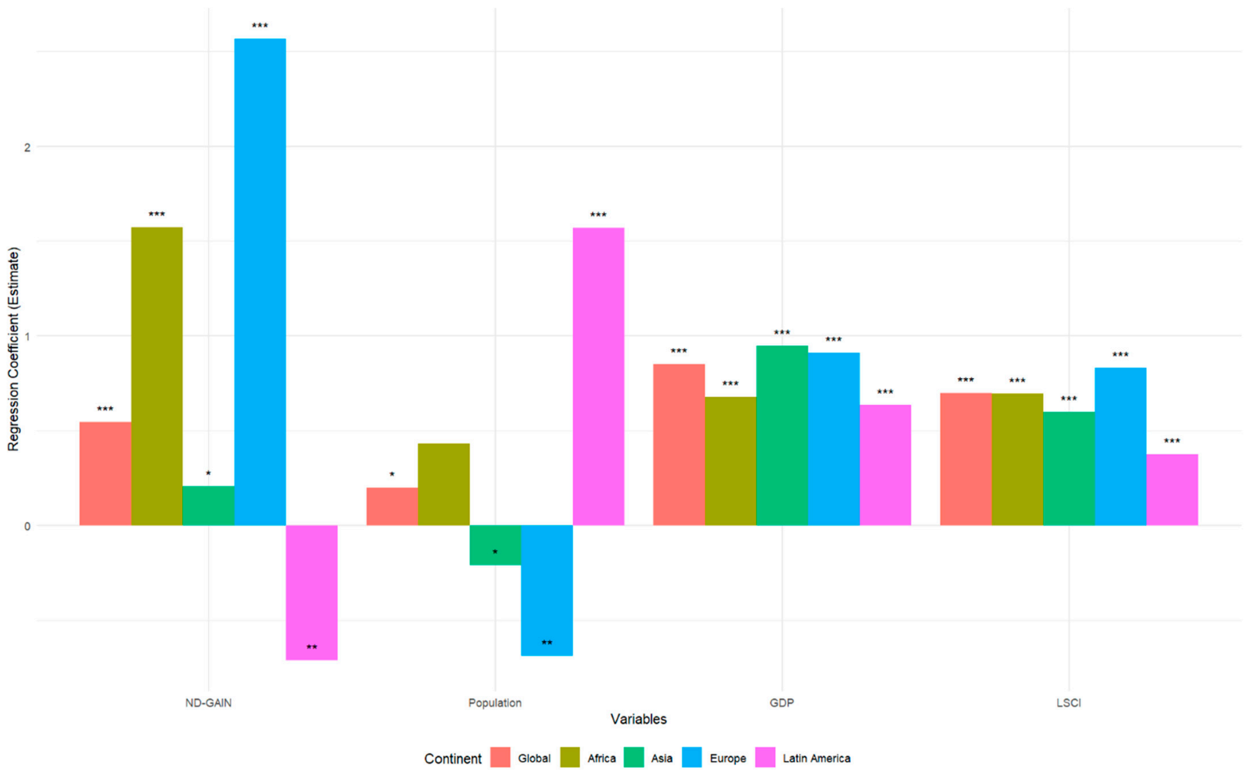
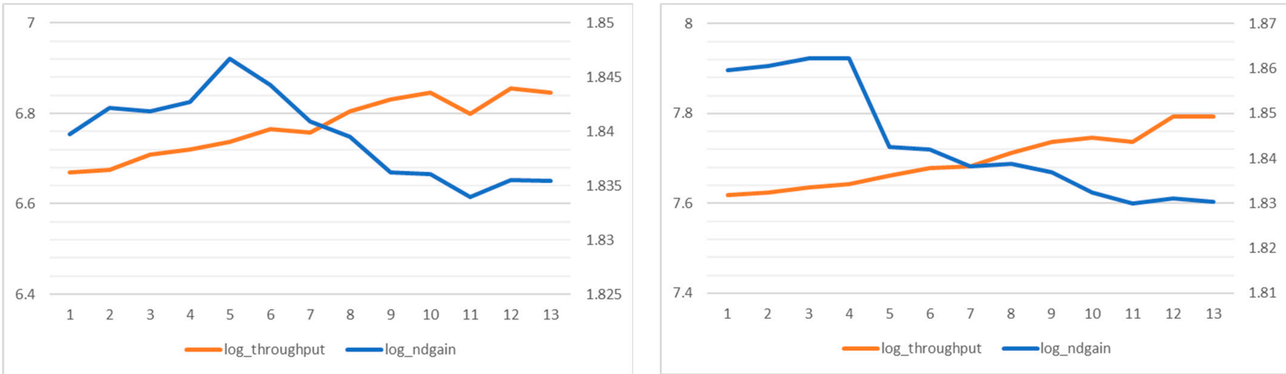


Figure 4. Summary of global and regional panel regression analysis results (regression coefficients). Note: *, **, and *** indicate significance levels of 10%, 5%, and 1%, respectively.

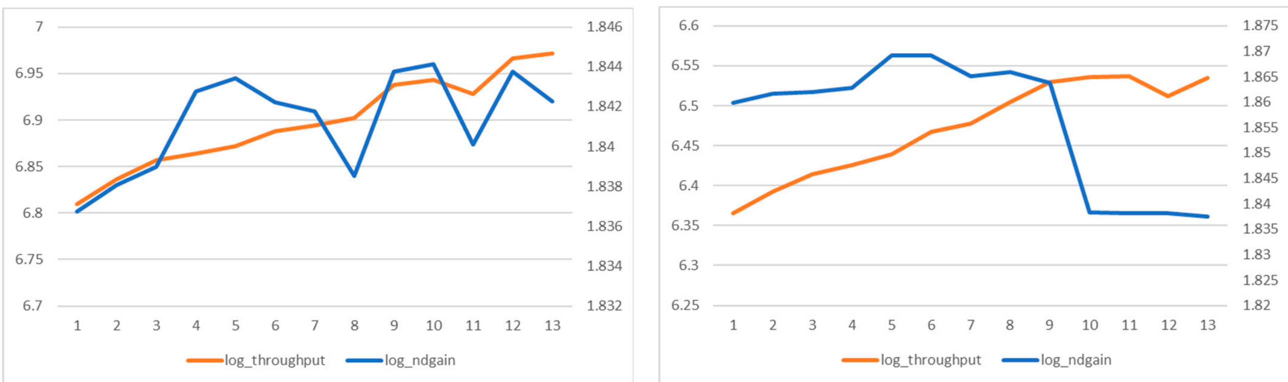
Finally, the results of the supplementary additional analysis for the North American and Oceanian continents are as follows: It was difficult to confirm a statistically significant relationship between the ND-GAIN index and port throughput for the North American continent (United States, Canada) (see Figure 3). This suggests that changes in climate resilience in this region do not directly impact port performance; rather, other factors such as economic scale (GDP) and ship connectivity (LSCI) may serve as key explanatory variables. Time-series analysis also shows that throughput continues to increase even during periods of declining ND-GAIN index, implying that port operations in North America are conducted based on relatively fixed resilience levels and stable infrastructure foundations (see Figure 5).



(**a**) (**b**)

Figure 5. Trends in Time Series Changes in Container Port Cargo Volume and ND-GAIN by North American Country. (**a**) Canada (North America); (**b**) United States (North America).

For the Oceania region (Australia, New Zealand), a statistically significant negative correlation was observed between ND-GAIN index and port throughput (log_throughput) (see Figure 6). Time-series analysis shows that New Zealand's port throughput continued to increase even after the sharp decline in ND-GAIN index in 2019, and Australia also showed no clear synchrony between the two variables. This suggests that for Oceania countries, climate resilience may have a negative impact on port throughput, or that direct causality between the two variables is low. Furthermore, a strong positive relationship exists between GDP, LSCI, and cargo volume (see Figure 3). This suggests that economic and connectivity indicators provide more direct explanatory power in these regions than climate resilience.



(**a**) (**b**)

Figure 6. Trends in Time Series Changes in Container Port Cargo Volume and ND-GAIN by Oceania Country. (**a**) Australia (Oceania); (**b**) New Zealand (Oceania).

5. Discussion

This study aims to analyze the impact of a country's climate resilience (using ND-GAIN index) on container port cargo volume using panel regression analysis. Considering the ease of variable collection, 83 countries were selected as the analysis subjects. The data collection period spans 13 years, from 2010 to 2022. Therefore, the 83 countries form the cross-sectional units, and panel data utilizing 13 years of time-series data per country was used. According to the research hypothesis, the panel data was divided into a global continental unit encompassing all continents and six continents (Africa, Asia, Europe, North America, Latin America, and Oceania). However, North America and Oceania were deemed statistically inadequate for panel regression analysis due to having only two countries each. Consequently, these continents were designated for supplementary analysis using descriptive statistics, correlation analysis, and time-series trend line analysis. Key findings are as follows:

First, the average climate resilience level (ND-GAIN index) by continent showed Oceania had the highest climate resilience, followed by North America, Europe, Asia, Latin America, and Africa. This indicates that the Oceania continent is the most proactive in responding to climate change. In particular, countries in Oceania, North America, and Europe were found to have relatively superior national-level resilience in addressing climate change.

Second, analysis focusing on all global countries revealed that climate resilience (ND-GAIN index) positively impacts container port cargo volume. This implies that national-level climate resilience can structurally influence port industry performance. Additionally, population size, real GDP, and the Linear Shipping Connectivity Index (LSCI) also exerted positive (+) effects on port cargo volume.

Third, Africa's climate resilience was found to positively influence container port throughput. Real GDP and the Linear Shipping Connectivity Index (LSCI) were also confirmed to have positive (+) effects.

Fourth, the climate resilience of the Asian continent was found to have a weak positive impact on container port throughput. Population size was found to have a negative impact, while real GDP and the Linear Shipping Connectivity Index (LSCI) were found to have positive impacts.

Fifth, climate resilience in the European continent was found to positively affect container port throughput. Population size had a negative effect, while real GDP and the LSCI had positive effects.

Sixth, Latin America's climate resilience was found to negatively impact container port throughput in the region, while population size, real GDP, and LSCI exerted positive (+) effects.

Seventh, supplementary analyses were conducted for North America and Oceania, where applying panel regression analysis proved challenging. North America (United States, Canada) showed no significant correlation between ND-GAIN index and port throughput. Furthermore, even during periods of declining climate resilience, throughput increased over time. This suggests that the assumption that climate resilience affects port cargo volume does not apply equally across all regions. It can also be inferred that in specific regions, the impact of climate resilience may be limited or inconsistent.

Based on these analytical results, the significance of this study is as follows:

Global continental climate resilience, encompassing all continents, was found to positively influence container port cargo volume. The climate resilience indicator used, ND-GAIN index, is a metric that comprehensively reflects a nation's capacity to respond to climate change. This implies that indirect factors at the national level—such as disaster response capacity against climate change impacts, infrastructure protection systems, and port network resilience—can positively contribute to port operations. In other words, while extreme weather events like sea level rise, typhoons, and floods directly impact port operations, strengthening the durability of physical assets like port berths, cranes, and hinterland roads, as well as macro-level climate resilience factors like the level of national climate policy implementation, the coordination capacity of governance systems, public goods investment, and technology innovation support policies. Therefore, climate resilience strategies to secure global port competitiveness require an approach that comprehensively considers macro-level factors—such as national climate response policies, institutional linkages, and economic resilience—rather than focusing solely on the technical and operational capabilities and response capacity of individual ports.

Next, the results of the continental panel regression analysis confirmed differences in the influence between climate resilience and port cargo throughput across continents.

Specifically, in three continents—Africa, Asia, and Europe—climate resilience (ND-GAIN) was found to positively impact container port throughput. This suggests that national-level climate change response systems within these regions are effectively contributing to the stabilization of port operations. Notably, these results align with the earlier global perspective, emphasizing that national response systems—including climate adaptation and mitigation policies, disaster management capabilities, and network resilience—play an indirect or structurally important role in port industry performance, alongside enhancing the physical durability of port infrastructure.

Conversely, in Latin America, climate resilience (ND-GAIN) was found to negatively impact container port throughput. This implies that increased climate resilience may not effectively translate into tangible port operational performance. It suggests that if national-level climate change response systems are only formally established and lack connectivity with industry, they may negatively impact port performance. In other words, even if a country enhances its climate change response capacity, if these systems lack real-world linkage and effectiveness with industry, they may instead have a negative impact. In the case of Latin America, previous studies have also highlighted their climate vulnerability. The Latin American region presents serious challenges in terms of climate change adaptation measures due to the complex impacts and interactions of climate change on its society, economy, and ecosystems, as well as the high levels of vulnerability observed in the region, primarily stemming from issues of poverty and inequality [66–68].

Furthermore, similar trends were inferred from the correlation analysis of the Oceania continent and the time-series trend line analysis of the North American continent. Existing studies also share a similar context. A study pointed out that port operators' lack of awareness, absence of policy support, and insufficient implementation technology are major factors hindering the execution of adaptation and mitigation strategies for climate change [69]. Another study also analyzed that the complex issue of climate change exists horizontally and vertically across multiple sectors and levels, and that the EU's failure to promote and coordinate an integrated strategy for climate change was a major cause limiting its strategic effectiveness [70].

Furthermore, panel regression analysis showed most control variables had a positive relationship with port cargo throughput. However, only in the analyses of the Asian and European continents was a negative relationship between population size and port cargo throughput confirmed. This aligns with the findings of [71], which used the case of Shanghai Port in China to suggest that once urban population reaches a certain saturation level, it may act as a constraint rather than a direct driver of port growth, particularly in terms of land use and infrastructure capacity. As these studies indicate, the relationship between port cargo volume and population size can be asymmetric and vary regionally. Furthermore, especially in short-term analyses, a negative relationship contrary to conventional intuition may emerge.

Therefore, synthesizing the empirical findings of this study emphasizes that the relationship between climate resilience and port throughput is not unidirectional. It can exhibit heterogeneous interaction patterns depending on national and regional capabilities, conditions, policy linkages, industrial structure, and the level and structure of port networks. Furthermore, these findings suggest that a differentiated regional approach is necessary for climate change adaptation, implying the need to establish climate resilience strategies tailored to the characteristics of each continent. Additionally, developing climate resilience indicators specific to each country's port logistics industry is essential for formulating practical measures to establish customized sustainable management strategies for each nation.

6. Conclusions

This study holds significance in that it empirically examines the relationship between climate resilience and the port logistics industry, a sector vulnerable to climate change, amid the growing global emphasis on climate resilience. This is a proactive study to allow the port logistics industry to effectively respond to climate change and pursue sustainable development. Furthermore, the significance of this study lies in its empirical demonstration that a nation's vulnerability to and preparedness for climate change, as measured by the ND-GAIN index used as a climate resilience metric, are associated with container port throughput. Furthermore, given the divergence in analytical results, it remains difficult to confidently assert that national-level climate resilience indicators have a direct and significant impact on the port industry. Nevertheless, it was necessary to examine the relationship between these factors within the port industry, which is critically vulnerable to rapidly changing climate conditions. However, future research must focus on selecting or developing climate resilience indicators that are more representative of the port industry and incorporate relevant indicators. This will enable studies examining the influence relationships between these indicators.

However, this study has several limitations. The ND-GAIN index used was evaluated from a national perspective rather than being specific to the port logistics industry, potentially limiting its applicability as a proxy for climate resilience in the industry. Therefore, future research should conduct empirical analyses using climate resilience evaluation indicators specifically tailored to the port logistics industry. This study also has a limitation in that the number of sample countries included for the North American and Oceanian continents was only two each, which is significantly fewer than the number of countries available for the other continents. This may weaken the global and continental perspectives that were the focus of this study. Nevertheless, a proactive study confirming the correlation between inter-country climate resilience indicators and port cargo volumes was necessary. Future research should address data gaps (e.g., port-specific climate resilience indices) to include the scope of all continents worldwide. Additionally, restricting the scope of the dependent variable to container port throughput was a limitation.

Nevertheless, this study holds significance in applying climate resilience to the port logistics industry for empirical analysis, unlike previous research, and in exploring the previously understudied academic research on climate change and climate resilience within the port logistics sector. Furthermore, this study is anticipated to serve as a pioneering effort to highlight the necessity of climate resilience for the sustainable development of the port logistics industry. This study is expected to provide a basis for policy decision-making by domestic and international container port operators and stakeholders.

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