



Is economic fitness helpful in achieving environmental sustainability in BRICS economies? A risk exposure perspective

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ABSTRACT

A country's ability to create complex goods and diversify its lines of products is essential for addressing all types of vulnerabilities. Quantifying a country's vulnerability to extreme climatic events, such as droughts, superstorms, and other natural disasters, and its capacity for successful adaption, is an essential global need that has been ignored. This study examines the role of economic fitness (EF) in addressing climate change risk exposure in BRICS countries in the context of the environmental Kuznets curve using panel data from 1995 to 2015. Panel threshold methodology is employed to ascertain the nonlinear relationship between EF and climate change risk exposure (i.e., Notre Dame Global Adaptation Initiative Country Index (ND-GAIN)). In addition, empirical associations were estimated using panel-corrected standard errors, Driscoll-Kraay standard errors, and feasible generalized least squares estimation techniques. These findings demonstrated an inverted N-shaped link between EF and ND-GAIN. Moreover, even after controlling for significant ND-GAIN influencing variables such as gross domestic product per capita, financial development, and urbanization, our robustness checks revealed significant and consistent findings.

1. Introduction

In recent decades, environmental degradation and climate change have emerged as the world's most difficult and controversial problems, and there is a growing global consensus that these serious issues must be addressed immediately (Khan et al., 2022). Environmental sustainability is now seriously threatened by rising temperatures. Reducing greenhouse gas (GHG) emissions, which are the primary causes of environmental degradation (ED), was the goal of the 1997 Kyoto Protocol. The main cause of this is countries' aspirations to build their economies (Ul-Haq et al., 2023; Younis et al., 2021). Climate change affects not only the environment and ecology, but also every aspect of global society and the economy (Ikram et al., 2021).

The actual effects of climate change, such as droughts, heat waves, floods, landslides, and storms, occur more frequently (Beck and Mahony, 2018; Kling et al., 2021), and are already being experienced by most economies of the world (Kling et al., 2021). Signifi-

cant economic implications are associated with this dramatic increase in climate change-related disasters. The direct impact of severe natural disasters on the economy is well established (Botzen et al., 2019; Cavallo et al., 2013; Felbermayr and Gröschl, 2014). Previous studies have examined different factors that have a significant impact on ED, including foreign direct investment (FDI) (Ahmad et al., 2021a; Balsalobre-Lorente et al., 2021), urbanization (Ahmad et al., 2021b), financial development (FD) (Umar et al., 2020), globalization (Baloch et al., 2021), innovation (Khan et al., 2020), industry structure (Khan et al., 2019), gross domestic product (GDP) and renewable energy (REN) (Destek et al., 2024; Kartal et al., 2023), and information and communications technology (ICT) (Usman et al., 2021).

As a result of rising ecological pollution, many developed and developing countries have begun to pay attention to environmental protection measures, and the international community has taken significant actions and implemented significant environmental protection measures to reduce environmental pollution (Shahzad et al., 2020).

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Awareness of ED is growing in contemporary societies consequent to global ecological degradation. The industrialization process, national and military expenditures have caused greater environmental degradation (Destek et al., 2024; Pata et al., 2023), with environmental awareness being promoted by regional and international organizations (Çınar et al., 2022). The United Nations Framework Convention on Climate Change represents a major step forward in global cooperation to combat climate change and the damage it causes and the COP26 agreement has been crucial for fostering global understanding and diplomatic relations regarding climate-related issues (Deep et al., 2022).

Environmentally friendly products and services are being promoted by both international and local organizations to reduce the negative effects of industrialization. Additionally, decision-makers have increasingly adopted environmental laws to promote the creation of sustainable and climate-neutral products and control the sale of products harmful to the environment. Environmental commodities have been defined and categorized by the World Trade Organization (WTO), Organization for Economic Cooperation and Development (OECD), and Asia-Pacific Economic Cooperation (APEC). The OECD and the European Union Statistics Office (Eurostat) refer to items used to measure, stop, or lessen air pollution as “environmental goods”. This wide range of products makes it possible to produce ecologically friendly goods (Can et al., 2021; Can et al., 2022).

Economic fitness (EF) plays an important role in environmental degradation reduction, by producing energy-efficient products that reduce energy demand (Çınar et al., 2022; İskenderoğlu and Akdağ, 2018). EF assesses a country's ability to produce sophisticated products that are internationally competitive and its level of diversification. This situation varies depending on the productive capacity (economic efficiency) of the countries and their respective stages in the structural transformation process. Generally, developed countries have a high productive capacity and are advanced in structural transformation. Conversely, developing countries typically have relatively low productive capacities and the process of structural transformation is ongoing (Oluc et al., 2023; Oluc et al., 2024). Economically efficient countries can diversify their product baskets, produce more complex items, have more predictable long-term growth, and obtain a competitive edge over rival nations (Tacchella et al., 2012; World-Bank, 2021).

The impact of EF on environmental degradation depends on a country's diversification policies. Product diversification can be improved through intensive margin enhancement of existing products or extensive margins by introducing diverse items (Dou et al., 2023; Shi et al., 2023). If a country continues to produce new products alongside the existing products of polluting industries, it will enhance diversification, causing EF to rise while deteriorating the environment (Hu et al., 2020). Conversely, if a country continues to produce new products and reduces or stops the production of products from polluting industries, it will increase diversification, causing the EF to rise while mitigating environmental deterioration. This is particularly evident in countries that manufacture green products for domestic consumption and exports (Can et al., 2022). This type of EF can improve the environment. Thus, the EF affects the environment through product diversification (PD) (Can et al., 2020; Ul-Haq et al., 2023). As developing countries experience population expansion, energy consumption will increase to fulfill the energy demand of their population and boost economic activities via PD, thereby accelerating carbon footprints that are harmful to humanity and the planet (Can et al., 2020; Ul-Haq et al., 2024; Ullah et al., 2024). It is predicted that by 2040, emerging countries will consume nearly 90% more energy than developed countries (Energy Information Administration(EIA), 2013; IEA, 2013).

BRICS countries produce approximately half of the world's glasshouse gas emissions, and have suffered the costly effects of these large emissions. Rapid growth in the BRICS region has the potential

to produce significant benefits such as low unemployment and rising per capita income. Consequently, it is impossible to ignore the simultaneous and recent changes in the BRICS economies. To maintain the rate of rapid economic expansion, BRICS countries must generate significant amounts of energy using fossil fuels. Thus, these emissions are expected to significantly impact global warming (Rahman et al., 2021). Owing to their economic activities, BRICS countries consume more than 40% of the world's energy and emit significant amounts of glasshouse gases (Adebayo et al., 2022). BRICS countries account for 41% of the world's population and are the main contributors to environmental deterioration. Therefore, the topic of ED in BRICS nations has been the subject of numerous studies within the environmental Kuznets curve (EKC) framework.

Various outcome-based measures (such as CO₂, SO₂, CH₄, and PM_{2.5}) have been used as ED proxies in previous studies. Several studies have used these outcome indicators as proxies for ED within the context of the EKC hypothesis (Ali et al., 2017; Allard et al., 2018; Balsalobre-Lorente et al., 2023; Farooq et al., 2023; Hye et al., 2023; Khan et al., 2020; Leitão et al., 2021; Ogundari et al., 2017; Sarkodie and Ozturk, 2020; Shahzad et al., 2023; Tedino, 2017). To the best of our knowledge, no study has explored the overall risk exposure to climate change (Notre Dame Global Adaptation Index) in the context of the EKC, at least regarding BRICS countries. In this study, we employed the Notre Dame Global Adaptation Initiative Country Index (ND-GAIN) Index, which is a comprehensive measure of the overall risk of exposure to climate change. The ND-GAIN Index summarizes a country's vulnerability to climate change and other global issues, and its capacity to enhance resilience. The annually updated ND-GAIN Country Index evaluates a nation's susceptibility to extreme climatic events such as droughts, superstorms, and other natural disasters, and its capacity to successfully adopt adaptation measures (Kling et al., 2021).

The ND-GAIN quantifies two parameters: vulnerability and readiness. It divides readiness measures into economic, governance, and social components and vulnerability measures into exposure, sensitivity, and adaptive capabilities. ND-GAIN scholars have assessed the elements common to successful climate change adaptation, such as developed economies, access to clean drinking water, agricultural capacity, and political stability (Kling et al., 2021). All countries encountered difficulties in adapting, albeit to varying degrees. Some countries are more vulnerable to the negative consequences of climate change owing to their geographical location or socioeconomic status. Moreover, some nations are better equipped to implement adaptation measures by influencing public- and private-sector resources, such as government action, community knowledge, and the capacity to support private-sector solutions (Chen et al., 2015).

Therefore, quantifying climate change risk in the BRICS nations is crucial for development and sustainable growth. To achieve this goal, we conducted this study to evaluate the climate change risk exposure of BRICS within the EKC framework. This study examines how EF affects CO₂ emissions (i.e., an outcome-based indicator of ED) for BRICS countries in relation to the environmental Kuznets curve (EKC) and is the only study that focuses on EF. No studies have used the ND-GAIN Index, which evaluates overall risk exposure to climate change, regarding BRICS economies. Our research fills an important void, particularly for BRICS nations.

This study makes numerous contributions to the literature on the EKC hypothesis. First, it study examines the relationship between economic fitness and climate change risk exposure in the BRICS economies. Second, we use a more comprehensive measure of climate change risk exposure (i.e., the ND-GAIN index) than the commonly used outcome-based measures (such as CO₂, SO₂, CH₄, and PM_{2.5}) as proxies for ED in previous studies. The ND-GAIN index measures a country's overall risk of exposure to climate change and other global issues and its capacity to build resilience. It aims to assist businesses and the public sector in correctly prioritizing investments to address

impending severe global challenges more effectively. Third, we use EF to assess a country's ability to produce sophisticated internationally competitive products. Fourth, based on the availability of data, this study employs the threshold technique, the feasible generalized least squares (FGLS), the panel-corrected standard errors (PCSE), and the Driscoll-Kraay standard errors (DKSE), on BRICS panel data from 1995 to 2015. This study contributes to the literature on economic fitness and climate change risks.

The remainder of this article is organized as follows. In Section 2, we discuss the literature review. In Section 3, the panel threshold, FE, and FGLS models are presented, along with a discussion of the data and methodology. Section 4 presents the findings and discussion, and Section 5 concludes the study and provides recommendations for policymaking.

2. Literature review

The economies of the BRICS countries, where industrial production has accelerated over the past few decades, are among the fastest-growing economies in the world. Furthermore, these countries are dedicated to addressing problems related to biodiversity, global climate change, and environmental management (Pradhan et al., 2022). Numerous extant studies have examined the effects of various ED factors on the EKC in BRICS countries (Adebayo et al., 2022).

Mehrara and Rezaei (2013) examined the association between trade liberalization, CO₂ emissions, and economic growth (EG) in BRICS countries between 1960 and 1996. Using unit root and Kao panel co-integration tests, they discovered evidence of the EKC with an inflection point at the US \$5 269.4 level of per capita income using unit root and Kao panel co-integration tests. They concluded that the BRICS nations would have to give up their rapid economic development to reduce emissions. By analyzing the EKC utilizing short- and long-run income elasticities, Bakirtas et al. (2014) showed that CO₂ emissions and income for BRICS countries are statistically strongly associated. Balsalobre-Lorente et al. (2023) used panel data for BRICS countries from 1995 to 2020 to analyze the relationship between CO₂ emissions per capita, the economic complexity index, renewable energy, and inward foreign direct investment. The empirical findings validate the existence of the environmental Kuznets curve. The EKC was also valid in BRICS nations from 1990 to 2015 (Leitão et al., 2021).

After excluding Russia from their sample, Ahmed et al. (2016) assessed the connection between energy consumption, trade, and GHG emissions for BRICS countries from 1970 to 2013. In contrast to previous studies, they demonstrate that trade liberalization leads to a long-term reduction in CO₂ emissions. According to their findings, an EKC exists among these countries. Using data from 1980 to 2013, Sinha and Sen (2016) evaluated the applicability of the EKC to BRICS countries. The authors discovered an EKC connection between EG and air pollution in Brazil and India, but not in Russia or China. Tedino (2017) found the EKC in South Africa, China, and India, but not in Brazil and Russia. Using EG, finance, transportation, and energy to analyze the EKC, Nassani et al. (2017) discovered a U-shaped relationship. Kostakis et al. (2023) examined the relationship between economic growth, globalization, population density, energy consumption, trade openness, and CO₂ emissions using the EKC framework from 1994 to 2014.

Tacchella et al. (2012) developed an Economic Fitness Index (EF) to assess the production potential and economic complexity of various nations. Using this index to examine, for the first time, the connection between nations' low-carbon and eco-friendly production potential and ED in 122 nations, they found that nations with a higher Green Complexity Index (GCI) experienced less ecological degradation. Can and Gozgor (2017) found a negative association between

CO₂ emissions and economic complexity in developed countries, and Doğan et al. (2019) and Yilanci and Pata (2020) discovered a positive relationship between CO₂ emissions and economic complexity in developing countries.

Çınar et al. (2022) investigated the relationship between EF, environmental complexity, and ED at the state level in the United States and showed that while exporting more complex green products has negligible effects on local and global pollutant levels, such as carbon dioxide, EF had a significant negative impact on emission levels, suggesting that sophisticated production in the United States greatly improves environmental quality, thus reducing countries' vulnerabilities to extreme climatic events. Similarly, we examined how EF influenced CO₂ emissions in the BRICS region between 1995 and 2015. Researchers discovered that the connection between EF and CO₂ emissions has an inverted N-shaped association using Feasible Generalized Least Squares (FGLS) and panel-corrected standard error (PCSE) methods.

In summary, no study has used the ND-GAIN index, which evaluates the overall risk of exposure to climate change with the overall EF, at least in BRICS countries. To achieve this goal, we conducted this study to evaluate the climate change risk exposure of BRICS within the EKC framework. Therefore, it is crucial to quantify climate change risk in the BRICS nations for development and sustainable growth.

3. Method and data

3.1. Method

In our analysis, panel data for the BRICS nations from 1995 to 2015^① were used. Following Wang and Wang (2021), this empirical work applies the threshold method to analyze the relationship between EF and ND-GAIN in the BRICS countries. We then used the panel FGLS approach, as described by Ul-Haq et al. (2023) and Visas et al. (2023), to verify the validity of the threshold results by examining whether the connection between ND-GAIN and EF was an N-shaped or inverted N-shaped EKC. First, we checked whether the relationship between ND-GAIN and EF could be estimated using a 3-degree polynomial. This is the definition of the model.

$$GAIN_{it} = a_0 + a_1 EF_{it} + a_2 EF_{it}^2 + a_3 EF_{it}^3 + e_{it} \quad (1)$$

Where, $GAIN_{it}$ is a country's vulnerability to climate change at time t , and EF_{it} is economic fitness of country i at time t . and e_{it} is the residual term. Risk exposure to climate change will initially reduce as EF rises ($a_1 < 0$), then climb after reaching a minimum point (i.e., $a_2 > 0$), suggesting a positive relationship between risk exposure and EF . Then, the $GAIN$ indicator will exhibit a declining trend as EF rises further ($a_3 < 0$) if the country's product diversification is improved through the intensive margin. This is the inverse (i.e., an N-shaped EKC) if a country's product diversification improves through an extensive margin. Because the FGLS technique addresses the problems of first-order autocorrelation and heteroscedasticity, it is a better estimation technique than panel-corrected standard errors and fixed-effect strategies (Beck and Katz, 1995; Davidson and MacKinnon, 1993; Maddala and Lahiri, 2006). We introduced the following cubic panel specifications, including controls, to display the inverted N-shaped hypothesis linking EF and $GAIN$.

$$GAIN_{it} = a_0 + a_1 EF_{it} + a_2 EF_{it}^2 + a_3 EF_{it}^3 + a_4 EG_{it} + a_5 FD_{it} + a_6 Urban_{it} + e_{it} \quad (2)$$

Where, i symbolizes the country (BRICS), t is time, and e_{it} is noise. Details of the variables used in this model are presented in Table 1. The various signs associated with the EF parameter will have an impact on the curvature of the EKC (Çınar et al., 2022; Ul-Haq et al., 2023).

①The selection of data timespan is due to availability of our main variable (i.e., EF). Which is one of study's limitation as well.

Table 1
Definition of Variables

Variables	Code	Explanation	Sources	Existing studies
Dependent variable				
Global Adaptation Index	<i>GAIN</i>	ND-GAIN index summarizes a country's vulnerability to climate change and other global challenges in combination with its readiness to improve resilience.	ND-GAIN (2022)	Chen et al., 2015; Kling et al., 2021
Independent variables				
Economic Fitness Index	<i>EF</i>	A country's ability to produce complex goods on a globally competitive basis is measured by its EF index.	World Bank (2021)	Çınar et al., 2022; İskenderoğlu et al., 2018; Ul-Haq et al., 2023
Other control variables				
Economic Growth	<i>EG</i>	Log of GDP per capita (constant 2015 US \$) as a proxy for economic growth.	World Bank (2021)	Hye et al., 2023; Umair et al., 2023; Yi et al., 2023
Urbanization	<i>Urban</i>	Share of urban population	World Bank (2021)	Visas et al., 2023
Financial development	<i>FD</i>	Financial development index	IMF (2022)	Al-Malki et al., 2022
	q_{it}	Threshold parameter		
Gamma	γ	Threshold critical value		

We established a hypothesis regarding parameter directions based on the empirical literature and the country's diversification strategy. In accordance with the theory of the inverted N-shaped EKC if a country's product diversification is improved through intensive margin, according to our hypothesis, *EF* has a negative influence on *GAIN*, indicating that emissions are increasing in the early stages. EF^2 has a positive influence, indicating that emissions are decreasing, whereas EF^3 has a negative influence, showing that emissions rise again with *EF*. This is reversed (i.e., an N-shaped EKC) if the country's product diversification is improved through extensive margins. Although we predicted that GDP-PC (*EG*) would increase *GAIN*, we also predicted that it would decrease *GAIN*; therefore, *EG* would display a mixed sign. Urbanization (*Urban*) would decrease *GAIN*, as predicted. Finally, we predicted that *FD* would exert conflicting effects on *GAIN* expression.

3.2. Threshold model

The threshold effect occurs when the evolution of an accompanying variable is altered by its predictor variable once it attains a specific value. This is the result of the first variable reaching its threshold value (Huang et al., 2018; Sun and Cai, 2020; Wang and Wang, 2020). To depict the threshold effect successfully, threshold models that explain the curvilinear link between the two quantities should be applied.

3.2.1. Single threshold effect

Threshold regression models lack a methodical technique for selecting sample separation points, resulting in complicated regression procedures and ambiguous results. Hansen (1999) proposed a panel threshold model with separate influences as a solution to problems with conventional threshold analysis methods. The results of the threshold model are easy to comprehend because it precisely determines the critical threshold and evaluates its significance. The challenging regression procedure and ambiguous outcomes of the traditional threshold regression model are caused by the unsystematic choice of sample separation points in the model. Hansen (1999) first presented a panel threshold model with distinct influences to address the drawbacks of traditional threshold analysis techniques. The ability of the threshold model to detect the critical threshold and assess its significance renders its findings intuitive.

For a single threshold variable, the threshold regression model is as follows.

$$y_{it} = \mu + \beta_0 Z_{it} + \beta_1 X_{it}(q_{it} < \gamma) + \beta_2 X_{it}(q_{it} > \gamma) + u_i + e_{it} \quad (3)$$

The threshold variable is q_{it} , the threshold parameter is γ , the outcome variable is y_{it} , the control variable is Z_{it} , the predictor variable is X_{it} , and these variables divide the equation into two regimes with coefficients β_1 and β_2 . The subscripts i and t are the entity and year indices, respectively; and the parameter u_i indicates the individual effect while e_{it} is the disturbance.

3.2.2. Model parameter estimation

For the parameter estimation, the threshold model was run using several different threshold-setting levels. A traditional linear model is generated by including the computed threshold in the threshold specification (Wang and Zhang, 2020; Su and An, 2018). The OLS method is then used to compute the sum of squared residual ($s_1(\gamma)$) for each linear model. The value of the threshold variable is a constant obtained by minimizing the $s_1(\gamma)$ of the overall model.

The OLS estimation is then used to estimate the accompanying coefficient β as follows.

$$\hat{\beta}(\gamma) = (X^*(\gamma)' X^*(\gamma))^{-1} X^*(\gamma)' Y^* \quad (4)$$

X^* and Y^* in the above equation are obtained by applying the FE transformation to the explanatory and outcome variables. The vector residual is denoted by the expression: $\hat{e}^*(\gamma) = Y^* - X^*(\gamma) \hat{\beta}(\gamma)$ and the corresponding SSR is computed using Equation (5) below.

$$s_1(\gamma) = \hat{e}^*(\gamma)' \hat{e}^*(\gamma) \quad (5)$$

The ideal threshold $\hat{\gamma}$ is the one for which $s_1(\gamma)$ in Equation (5) is minimizes. Additionally, the parameter $\hat{\beta} = \hat{\beta}(\hat{\gamma})$ is found using Equation (6) below.

$$\hat{\gamma}(\gamma) = \arg \min_{\gamma} s_1(\gamma) \quad (6)$$

3.2.3. The threshold test

In the threshold estimation approach, two tests are conducted to establish the threshold effect. The first determines whether there is a threshold effect and the second checks whether the estimated threshold is significant.

The absence of a threshold effect serves as the null hypothesis of the first test, denoted by $H_0: \beta_1 = \beta_2$, while the alternative hypothesis is $H_1: \beta_1 \neq \beta_2$. The OLS estimation allows for the computation of the expected coefficients, residuals, and SSR. The likelihood ratio was computed using the following formula for the null hypothesis.

$$F_1 = \frac{s_0 - s_1(\hat{\gamma})}{\hat{\sigma}^2} \quad (7)$$

However, this statistic does not satisfy the standard χ^2 distribution since the threshold value ($\dot{\gamma}$) in Equation (7) is unknown. To address this issue, Hansen (1999) utilized the bootstrap method to reproduce the distribution, estimated the actual likelihood value, and established whether a threshold effect is present.

The null hypothesis for the second test is $H_0: \dot{\gamma} = \gamma_0$, while the alternative hypothesis is $H_1: \dot{\gamma} \neq \gamma_0$, with the likelihood ratio statistic as follows.

$$LR_1(\gamma) = \frac{s_1(\gamma) - s_1(\dot{\gamma})}{\hat{\sigma}^2} \quad (8)$$

In Equation (8), $s_1(\dot{\gamma})$ is the estimated SSR for different threshold settings and $s_1(\gamma)$ is the actual SSR as determined by the threshold model. $\hat{\sigma}^2$ represents the possible SSR multiplied by the opposite of the degrees of freedom. It should be emphasized that the likelihood ratio statistics were derived using nonstandard statistical methods. The reference value is used to determine whether the initial hypothesis is not maintained, is given by: $\exp\left(-\frac{d(\alpha)}{2}\right) = 1 - \sqrt{1 - \alpha}$. When $LR_1(\gamma) < d(\alpha)$, H_0 is not rejected.

We then tested Hypothesis H_1 , which states that EF has a threshold effect on a country's climate risk exposure ($GAIN$). Based on the number of thresholds, the coefficient of EF assumes multiple values:

$$\theta_1 = \begin{cases} \theta_{11} & \text{if } q_{it} < \gamma \\ \theta_{12} & \text{if } q_{it} \geq \gamma \end{cases} \quad (9)$$

Or

$$\theta_1 = \begin{cases} \theta_{11} & \text{if } q_{it} < \gamma \\ \theta_{12} & \text{if } \gamma \leq q_{it} < \gamma_1 \\ \theta_{13} & \text{if } q_{it} \geq \gamma_2 \end{cases} \quad (10)$$

Thus, for single and double thresholds, we have the following two equations.

$$GAIN_{it} = \theta_0 + \theta_{11}EF_{it}I(q_{it} < \gamma) + \theta_{12}EF_{it}I(q_{it} \geq \gamma) + \theta_2EG_{it} + \theta_3FD_{it} + \theta_4Urban_{it} + u_i + e_{it} \quad (11)$$

$$GAIN_{it} = \theta_0 + \theta_{11}EF_{it}I(q_{it} < \gamma) + \theta_{12}EF_{it}I(\gamma \leq q_{it} < \gamma_1) + \theta_{13}EF_{it}I(q_{it} \geq \gamma_2) + \theta_2EG_{it} + \theta_3FD_{it} + \theta_4Urban_{it} + u_i + e_{it} \quad (12)$$

3.3. Data and variables definition

Our study, which covers the period 1995–2015,^② is an empirical investigation of the link between EF , our core variable, and $GAIN$. In the words of ND-GAIN (2022), the “ND-GAIN index summarizes a country's vulnerability to climate change and other global challenges in combination with its readiness to improve resilience.” Higher scores (i.e., higher values of the ND-GAIN index) were considered better. The $GAIN$ data were collected from ND-GAIN (2022). We use economic expansion, urbanization, and financial development as additional explanatory variables. We obtained data on EF , EG , and $Urban$ from the World Bank (2021) and FD from the IMF (2022). Table 1 provides the definitions of all variables and Table 2 presents the descriptive statistics for each variable.

4. Results and discussion

This study examined how EF affects $GAIN$ in the BRICS countries. The average BRICS logarithm of EF was 2.65%, with minimum and maximum values of 0.57 and 10.68%, respectively, as shown in Table 2. The highest risk of exposure to climate change was 63.24%, with an average of 49.46%. The low standard deviations of these two vari-

ables and the control variables suggest reduced dispersion and no outliers.

Table 2

Summary statistics

Variables	Observations	Mean	St. De	Mini	Maxi
<i>GAIN</i>	105	49.464 9	5.634 3	38.883 1	63.249
<i>EF</i>	105	2.650 0	2.186 7	0.573 2	10.687 8
<i>EG</i>	105	27.755 3	0.976 3	25.986 9	30.034 5
<i>FD</i>	105	0.470 2	0.084 6	0.280 8	0.633 2
<i>Urban</i>	100	24.549 3	9.413 6	11.66	40.92

We now test for multicollinearity before continuing with the econometric estimation. When multicollinearity exists, the p-values are unstable, and the values of the coefficients are influenced by other variables in the model. The variance inflation factor (VIF) test presented in Table 3 indicates no multicollinearity in the variables.

Table 3

VIF test on multicollinearity

Variables	VIF	1/VIF
<i>EF</i>	2.88	0.347 7
<i>EG</i>	2.44	0.409 0
<i>Urban</i>	1.69	0.591 4
<i>FD</i>	1.38	0.724 2
<i>Mean VIF</i>	2.10	

The mean variance inflation factor (VIF) value 2.10, indicates a low multicollinearity.

4.1. Hausman test and FE estimation

The P -value for the Hausman test is less than 5%, with a χ^2 value of 73.86. Consequently, an FE model is used in this study. Table 4 presents the FE regression estimates.

Table 4

Regression results of the FE

Variables	Coefficients	<i>t</i> -Statistics
<i>EF</i>	−0.235	(0.399)
<i>EG</i>	11.937***	(1.469)
<i>FD</i>	8.294*	(4.707)
<i>Urban</i>	−0.859***	(0.250)
<i>Hausman</i>	73.86***	

Notes: The t -values are presented in parentheses; * $P < 0.01$ and *** $P < 0.1$ indicate significant levels of 1% and 10%, respectively.

According to Table 4, the coefficient of EF in relation to $GAIN$ is negative, indicating that EF increases the BRICS economies' vulnerability to climate change instead of reducing it. Regarding the control variables, the coefficient of urbanization is negative and significant at the 1% level, whereas those of EG and financial development are both positive. The results of the FE regression indicated that EF and urbanization significantly increased vulnerability to climate change, whereas economic growth and financial development significantly decreased vulnerability.

②We choose this period due to availability of data. This is one of our limitations.

4.2. Threshold effect test

4.2.1. Panel threshold model test

This test assesses the degree and existence of the threshold effect. *EF* is the regime variable in this study, *GAIN* is the dependent variable, and several control variables as listed in Equation (8) are used. To detect the threshold effect, 300 bootstrap samples were run. We conducted a triple-threshold test because the single and double thresholds were significant; however, the results were insignificant, as shown in Table 5. The threshold test results led to the conclusion that there were two thresholds, suggesting a nonlinear link between *EF* and *GAIN*.

Table 5
Bootstrapping results

Threshold	Single	Double	Triple
<i>F</i> -Stats	18.65**	14.26***	5.07
Probability	0.040	0.006	0.513
Significance levels			
1%	23.064	11.529	18.368
5%	17.869	8.814	12.252
10%	14.126	7.789	9.532
Bootstrap	300	300	300

Notes: ** $P < 0.05$, *** $P < 0.01$

The *F*-statistic for the single-threshold effect, 18.65, exceeds the critical value of 17.869 at a significance level of 5%, indicating the existence of a single-threshold effect. The *F*-statistic for the double-threshold effect was greater than that of the 1% critical value, which was 11.529. This suggests the existence of two thresholds. The *F*-statistic for the triple threshold was less than 10% of the critical value, indicating the absence of the triple threshold does not exist. Therefore, the *EF* had a double-threshold effect on the *GAIN* during the study period.

The calculated thresholds and associated 95% confidence intervals (CIs) are listed in Table 6. The single threshold value was 5.913 with CIs of 5.360 8 and 6.103 3. The double threshold value was 1.362 7 with CIs of 1.295 2 and 1.367 6. Thus, the relationship between *EF* and *GAIN* is nonlinear, as suggested by the double-threshold effect.

Table 6
Threshold value and confidence intervals (CIs)

Threshold value	95% CIs	
	Lower bound	Upper bound
5.913 4	5.360 8	6.103 3
1.362 7	1.295 2	1.367 6

4.2.2. Results of threshold analysis

Table 7 presents the regression results for the double-threshold model. The impact of *EF* on *GAIN* changes over the three intervals as its coefficient changes but remains negative. For $q_i < 1.362\ 7$, the coefficient of *EF* is -1.014 and statistically significant at the 1% level. The coefficient of *EF* changes to -1.989 and is significant at the 1% level when $1.362\ 7 \leq q_i < 5.913\ 4$, indicating that *EF* in these countries reduces *GAIN* further (means increasing vulnerability). When $q_i \geq 5.913\ 4$, the coefficient of *EF* again changes to -3.983 , and is significant, indicating that while *EF* increases countries' exposure to climate change risk, the effect is more pronounced at higher thresholds. The overall monotonically decreasing relationship between *EF* and *GAIN* in BRICS countries over the course of the study period suggests that the negative effects of *EF* on *GAIN* may become more pronounced. This asso-

ciation is illustrated in Figure 1. Compared with the control factors, urbanization in BRICS had a negative and significant effect on *GAIN*. Increasing urbanization by 1% increased the prospect of exposure to climate change by 0.8%, and this effect was significant at the 1% level. When *EG* and *FD* increased by 1%, *GAIN* levels increased by 11.63% and 10.4%, respectively. The coefficients of *EG* and *FD* were significant at the 1% level.

Table 7
Threshold model estimates

Variables	Coefficients	<i>t</i> -Statistics
<i>EG</i>	11.633***	(9.01)
<i>FD</i>	10.480**	(2.45)
<i>Urban</i>	-0.884***	(-4.00)
<i>EF</i> ($q_i < 1.362\ 7$)	-1.014***	(-2.69)
<i>EF</i> ($1.362\ 7 \leq q_i < 5.913\ 4$)	-1.989***	(-3.99)
<i>EF</i> ($q_i \geq 5.913\ 4$)	-3.983***	(-4.96)

Notes: ** $P < 0.05$, *** $P < 0.01$

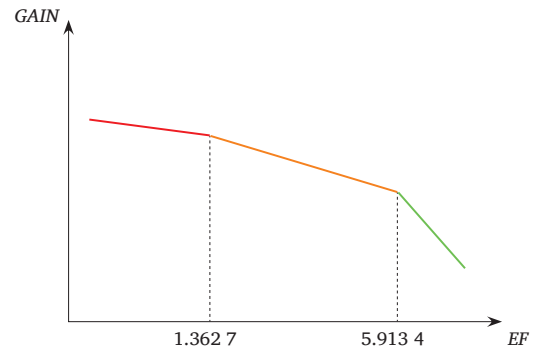


Figure 1. Economic fitness and *GAIN*

4.3. Robustness checks

To validate the threshold results, we employed the FGLS, PCSE, and DKSE methods to check whether the relationship between *EF* and *GAIN* was truly an inverted N-shape. In each column, *GAIN* is the dependent variable.

EF is inversely related to *GAIN* in the short run in both columns of the FGLS, as shown by Table 8 with negative and statistically significant coefficient of *EF*. The positive sign of the coefficient of EF^2 . EF^3 had a significantly negative coefficient, indicating an inverse relationship with *GAIN*. In the second column of our primary risk-exposure model, we include important control variables. These variables did not influence the effect of *EF* on the trend of *GAIN* in the BRICS countries. The *EG* coefficient is statistically significant and positive. Ahmed et al. (2019) demonstrated that as economic development increases, the risk of exposure to climate change decreases. The relationship between *Urban* and *GAIN* was negative and statistically significant. *Urban* increases the risk of exposure. The FGLS results revealed an inverted N-shaped relationship between *EF* and *GAIN*. The PCSE technique also revealed an inverted N-shaped link between *EF* and *GAIN* in BRICS.

In addition, we used the DKSE technique to check for additional robustness, and the estimates are presented in the last two columns of Table 8. The results demonstrate that our core variable (*EF*) had the same effect on *GAIN*. According to this study, *EF* and *GAIN* in the BRICS countries had a significant inverted N-shaped association. As indicated by the inverted N-shaped connection, *GAIN* decreased, increased, and then decreased. Besides, both FGLS and PCSE produced

Table 8
Robustness checks (FGLS, PCSE, DKSE)

Variables	FGLS		PCSE		DKSE	
<i>EF</i>	−13.467*** (1.200)	−15.755*** (1.333)	−15.783*** (1.383)	−15.369*** (0.445)	−15.783*** (1.217)	−15.369*** (1.391)
<i>(EF)²</i>	2.917*** (0.278)	2.952*** (0.348)	3.407*** (0.315)	2.827*** (0.361)	3.408*** (0.278)	2.827*** (0.360)
<i>(EF)³</i>	−0.164*** (0.017)	−0.161*** (0.025)	−0.193*** (0.019)	−0.152*** (0.026)	−0.193*** (0.018)	−0.152*** (0.027)
<i>EG</i>		3.860*** (0.409)		3.975*** (0.413)		3.975*** (0.553)
<i>FD</i>		5.407 (3.631)		7.094* (3.722)		7.094 (4.867)
<i>Urban</i>		−0.213*** (0.033)		−0.210*** (0.033)		−0.210*** (0.049)
<i>Const</i>	62.454*** (1.238)	−36.260*** (11.148)	64.939*** (1.508)	−40.590*** (11.289)	64.939*** (1.659)	−40.590*** (16.105)

Notes: *GAIN* was the dependent variable in all models. ** $P < 0.05$, *** $P < 0.01$.

results and conclusions based on identical hypotheses. Furthermore, our major findings hold even after considering crucial factors such as economic growth, financial development, and urbanization. The empirical findings indicate that BRICS countries use a product diversification strategy through intensive margins as a major policy, suggesting that they continue to produce new products alongside existing products from polluting industries, which increases diversification and boosts *EF* while deteriorating the environment (Hu et al., 2020). BRICS economies should focus on diversification through extensive margins, where countries produce new products and reduce or stop the production of products by polluting industries, thereby enhancing diversification and increasing *EF*. This is particularly evident in countries that manufacture green products for domestic consumption and export (Can et al., 2022; Dong et al., 2023). A product diversification strategy through extensive margins will help the BRICS economies mitigate vulnerability and increase their resilience to climate change risk.

5. Conclusion and policy implication

Countries are undertaking significant efforts to tackle the global warming problem that the world is currently facing. In previous studies, researchers have employed numerous outcome-based indicators (such as CO_2 , SO_2 , CH_4 , and $\text{PM}_{2.5}$, etc.). The *GAIN* was used as a comprehensive indicator because it reflects the entire risk exposure to climate change. Using BRICS panel data from 1995 to 2015, we evaluate the effect of a country's *EF* on its risk exposure to climate change in the context of the EKC. Threshold, FGLS, PCSE, and DKSE econometric approaches were used to empirically evaluate the association between *GAIN* and *EF*.

Our research shows that *EF* and *GAIN* have an inverted N-shaped association in BRICS. The FGLS, FE, and threshold panel models demonstrate that *EF* increases *GAIN*. Climate change in a nation is significantly influenced by economic development, urbanization, and financial development. Urban and *EF* have increased the BRICS economies' exposure to climate change risk. *GAIN* is positively related to economic growth and financial development in BRICS countries.

BRICS economies should focus on diversification through extensive margins, where a country continues to produce new products and reduces or stops the production of products of polluting industries, as this will enhance diversification and increase *EF* while improving the environment. A product diversification strategy through extensive margins will help the BRICS economies mitigate vulnerability and increase their resilience to climate change risk. One of the main limitations of this study is the lack of data, which may have an impact on

the results and could be overcome in the future by using a longer time span. In this study, we used an overall measure of risk exposure, which can be divided into sub-risks in future research.

Disclosure statement

No potential conflict of interest was reported by the authors.

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