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Can Forests Endure the Energy Race and Ecological Pressures? A VAR Analysis of MINT Countries

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ABSTRACT

This study investigates forest resilience in the face of intensifying energy competition and ecological pressures in MINT countries (Mexico, Indonesia, Nigeria, and Turkey) from 1990 to 2024. Energy competition is represented by renewable and non-renewable energy consumption, while ecological pressures are assessed through environmental degradation, green economic growth, and population density. Using a Vector Autoregression (VAR) approach, all variables are treated as endogenous to capture dynamic feedback relationships. Stationarity tests confirm that most variables are first-difference stationary without long-run cointegration. Granger causality analysis reveals bidirectional relationships between forest area (FA) and non-renewable energy consumption, and between environmental degradation and population density. Unidirectional causality is also found from renewable energy consumption, environmental degradation, and green economic growth to FA; from environmental degradation to renewable energy consumption; and from FA and non-renewable energy consumption to population density. Impulse response and variance decomposition results suggest that non-renewable energy consumption and ecological, such as environmental degradation and population density have a negative impact on FA, whereas renewable energy consumption and green economic growth contribute positively. The findings highlight the urgent need to integrate energy, environmental, and development policies to support forest sustainability amid growing global energy demands and ecological stress.

Keywords: Ecological Pressure, Energy Consumption, Forest Area, Green Economy Growth, MINT Countries, VAR
JEL Classifications: Q23; Q43; Q56

1. INTRODUCTION

Global environmental crises, such as deforestation, are increasingly taking center stage in 21st-century sustainable development discourse, as they are no longer seen as geographically limited issues (Biely and Chakori, 2025; Garrett et al., 2021; Ucal and Xydis, 2020). On the contrary, these problems have become transboundary and interconnected, requiring systemic approaches that involve multiple actors and policy levels, both national and global (Schilling-Vacaflor and Gustafsson, 2024; Sotirov et al., 2020). Among the many indicators reflecting the imbalance between economic and ecological sustainability, the decline in forest area (FA) stands out as one of the most alarming (Lu et al., 2020; Toledo et al., 2022). According to a report by the Food and Agriculture Organization (FAO and UNEP, 2020), the world has lost more than 420 million hectares (ha) of FA since 1990, an astonishing figure that reflects the rapid conversion of FA into agricultural land, infrastructure, and industrial zones. Ironically, most of this loss has occurred in tropical countries, which are home to the planet's richest biodiversity and play a crucial role in climate change mitigation (Muluneh, 2021).

FA is not only of ecological value but also plays a strategic role in the global life support system, such us a regulator of global temperature and humidity, a natural filter for groundwater, and a natural barrier against erosion and hydrometeorological disasters

(Feng et al., 2024). The loss of FA not only reduces habitat for flora and fauna but also directly undermines environmental carrying capacity and disrupts the stability of regional and global climates (Kumar et al., 2022; Lu and Jiang, 2023). Furthermore, communities that rely on FA for food, medicine, and livelihoods are among the most affected by uncontrolled deforestation (Madalcho et al., 2020; Wajim, 2020). Nevertheless, the existence of FA is now under increasing pressure, particularly due to the complex interaction between two major forces: the energy race and ecological stress.

The ongoing energy race reflects the global dynamics of meeting ever-increasing energy demands, ironically, often at direct odds with the sustainability of FA. The drive to accelerate economic activity and ensure national energy security has pushed the expansion of large-scale energy projects (Belaïd et al., 2023; Zohuri, 2023). Unfortunately, such expansion frequently occurs through the conversion of FA, which are often viewed as resources to be mobilized for supporting economic activities (Wassie, 2020). Furthermore, on a global scale, energy demand is projected to continue rising significantly, primarily driven by economic expansion and rapid industrialization in developing countries (Aimon et al., 2021; Kurniadi et al., 2021). The pressure to meet this demand is immense, as energy is a fundamental prerequisite for economic activity.

However, the reality is that most countries still heavily rely on non-renewable energy consumption (NREC), which not only has a high carbon footprint but also leaves long-term ecological impacts such as water pollution, soil degradation, and the loss of FA habitats (Aimon et al., 2022; Kurniadi et al., 2024). This dependency further exacerbates pressure on FA, both directly through land clearing and indirectly through the acceleration of climate change (Li et al., 2022; Psistaki et al., 2024). The expansion of fossil fuel infrastructure, such as mining, drilling, and pipeline construction, frequently encroaches upon FA (Usman and Makhdum, 2021; Yu et al., 2023). Moreover, the cumulative emissions from NREC intensify global warming, disrupting FA and reducing their regenerative capacity (Iyiola et al., 2023).

Meanwhile, although renewable energy consumption (REC) is often hailed as a transformative solution for environmental protection, its contribution to reducing pressure on FA remains far from optimal (Akpanke et al., 2023; Hakim et al., 2025). A range of structural and technical challenges still hinders the development of REC, including limitations in energy storage technology, high upfront investment costs, and unequal infrastructure distribution between developed and underdeveloped regions (Ponce et al., 2021; Raihan et al., 2023). Moreover, in some cases, projects intended to support REC, such as the construction of large dams or bioenergy plantations, can also create ecological consequences of their own if not planned with a sustainable approach (Koondhar et al., 2021).

On the other hand, ecological pressure is a term used to describe the intensity and complexity of disturbances to ecological systems, stemming from human activities as well as natural changes that are exacerbated by anthropogenic actions. In general, ecological pressure can be understood as the accumulation of environmental burdens that disrupt ecological balance, reduce the ability of natural systems to provide ecosystem services, and weaken ecosystem resilience to climate change and natural disasters (Kyere-Boateng and Marek, 2021). In the context of this study, ecological pressure is conceptualized as a complex construct comprising three main components: environmental degradation (ED), imbalances in green economic growth (GEG), and population density (POP), also contributes significantly to FA. In many cases, ED not only accelerates the degradation of FA through deforestation, soil erosion, and biodiversity loss, but also hinders natural regeneration processes and weakens the ecological resilience of FA to the impacts of climate change, such as prolonged droughts, flooding, and the increasing frequency of FA fires (Haseeb et al., 2021; Madalcho et al., 2020). Ongoing ED further heightens the vulnerability of FA to external disturbances and disrupts its role as a long-term carbon sink (Caravaggio, 2020).

Furthermore, although GEG offers new hope through economic development that emphasizes energy efficiency, the transition to REC, and community engagement in inclusive development, its implementation still faces major challenges in many countries, especially developing ones (Houssam et al., 2023; Tawiah et al., 2021). Limited access to green technologies, a lack of fiscal incentives, weak institutional capacity, and conflicts of interest in natural resource governance remain key obstacles to achieving effective protection of FA (Fang et al., 2022). As a result, a gap persists between the rhetoric of sustainable development and on-the-ground practices, further intensifying pressure on FA and calling into question the commitment of nations to the global environmental agenda (Mustafa et al., 2022; Zhang et al., 2022).

Meanwhile, the steadily growing POP has become a driving factor behind the spatial pressure on FA (Daskalova et al., 2020; Fischbein and Corley, 2022). Rising demand for land for housing, agriculture, and public infrastructure intensifies as POP increases, prompting the conversion of FA into productive or built-up land (Bologna and Aquino, 2020). This phenomenon is particularly evident in regions with high urbanization rates and weak spatial-planning systems, where settlement and agricultural expansion proceed without regard for ecological carrying capacity (Rehman et al., 2021). If not managed wisely, this pressure will continue to erode FA, increase emissions from land-use change, and weaken the role of FA in maintaining climate stability (Nikula et al., 2021).

In this context, Mexico, Indonesia, Nigeria, and Turkey (MINT) serve as relevant cases for further analysis, as they are currently facing a dual challenge: on one hand, ensuring energy security to support development, and on the other, maintaining ecological resilience, especially the sustainability of FA (Agbede et al., 2021; Eren and Alper, 2021). Furthermore, the issue of FA in MINT countries cannot be separated from each country's ability to balance increasing energy demands, economic ambitions, and the increasingly limited ecological carrying capacity (Zhang et al., 2021). All four nations are at a crossroads between economic ambition and the urgent need to protect natural resources, particularly FA (Lipiäinen and Vakkilainen, 2021).

Indonesia and Nigeria, for example, are two countries with vast tropical FA that are rich in biodiversity (Imarhiagbe et al., 2020; Nurhidayah and Alam, 2020). However, both are also among the countries with the highest deforestation rates in the world (Global Forest Watch, 2023). In Indonesia, deforestation is largely driven by the conversion of FA into oil palm plantations, coal mining operations, and the development of energy infrastructure and hydropower plants, all of which require large-scale FA clearing (Santoro et al., 2023). Nigeria faces similar issues, where oil and gas exploitation, illegal logging, and agricultural land expansion are the main drivers of FA loss (Fasona et al., 2022). This situation is further exacerbated by weak environmental law enforcement, land conflicts, and economic dependency on extractive industries (Grantham et al., 2021; Kyere-Boateng and Marek, 2021).

Meanwhile, Mexico and Turkey are facing ecological pressures stemming from accelerated infrastructure development and energy intensification as part of their industrialization and urbanization strategies (Alcocer and Escobar, 2024; Sadri, 2020). In Mexico, the expansion of major cities and the construction of transportation networks and energy projects have led to habitat fragmentation and increased pressure on protected areas (Caro-Borrero et al., 2021). In addition, metal mining activities and the development of hydropower and geothermal plants are often located within FA and ecologically sensitive mountain regions (Luna-Vega et al., 2022). On the other hand, Turkey is experiencing environmental pressure due to large-scale infrastructure projects, such as dams and power plants, as well as energy policies that remain heavily reliant on fossil fuels. These projects have sparked social conflicts and contributed to the decline of FA (Yılmaz, 2023).

However, despite the urgency of this issue, academic studies that specifically explore the dynamic relationship of FA in relation to the race between REC and NREC, as well as ecological pressures including ED, GEG, POP simultaneously and over time in MINT countries remain highly limited. Most previous studies have focused only on one-way linear and sectoral relationships, thus failing to capture the complex interdependencies among variables that are, in reality, mutually influential (Bhuiyan et al., 2022; Jie et al., 2023; Raihan and Tuspekova, 2022; Usman et al., 2022). A more detailed explanation of the limitations of prior literature and the strategic positioning of this study in addressing research gaps will be elaborated in the literature review section. Therefore, this study aims to fill that gap by adopting a VAR approach, which enables the analysis of bidirectional relationships and both short- and long-term dynamics among these variables simultaneously. This study is expected to provide significant empirical contributions to the literature on environmental and development studies and to serve as a foundation for formulating more integrative policy in developing countries.

2. LITERATURE REVIEW

Amid the complex interactions between FA sustainability, the energy race, and ecological pressures, a comprehensive understanding of the dynamic relationships among these variables is crucial. Unfortunately, most previous studies tend to oversimplify reality by assuming that one variable consistently influences another without considering the possibility of feedback effects. For instance, many earlier studies have focused solely on the direct and linear impacts of REC and NREC on ED. For example, Karimi et al. (2025) found that an increase in NREC significantly worsened ED in Indonesia, while REC appeared to have no significant effect. Similarly, the relationship between economic activity and deforestation is often portrayed linearly, assuming that economic activity always leads to increased deforestation (Caravaggio, 2022). However, Benedek and Fertő (2020) argued that in some cases, economic activity may actually increase demand for environmental protection, depending on the economic structure, public awareness, and government policies. This suggests that the relationship between economic activity and deforestation is not always linear or one-directional. This phenomenon is clearly evident, for example, in the study by Izuchukwu et al. (2025) in the Amazon and Southeast Asia, where rural economic activity accelerated deforestation due to rising demand for agricultural and residential land, despite macroeconomic indicators showing rising income levels.

On the other hand, the connection between environmental conditions and energy behavior is also often overlooked. In Sub-Saharan Africa, ED has led to a scarcity of firewood, pushing poor households to shift toward NREC, which further exacerbates the local ecological crisis (Njenga et al., 2023). A similar phenomenon occurs in rural areas of Indonesia, where reliance on traditional forms of REC is heavily influenced by the availability of FA, meaning that changes in FA directly affect household energy use patterns (Nugroho et al., 2022). When studies examine only one direction of the relationship, such as from energy to the environment, without considering the reverse direction, their findings become partial and fail to represent the real, interconnected dynamics at play.

The limitations of linear approaches are also evident in ecological literature that directly links POP with increased pressure on FA. Several classical studies assume that POP tends to drive deforestation due to rising land demands. For instance, Gatarić et al. (2022) argued that POP is a major factor intensifying pressure on natural resources, including FA. In this context, growing POP is seen as directly contributing to the conversion of FA into built-up areas. Another study by Febriyanti et al. (2022) also found a positive correlation between POP in tropical regions and increasing deforestation, particularly in developing countries that heavily depend on FA for biomass energy and subsistence agriculture. However, empirical evidence from regions such as Kerala (South India) shows that highly POP areas do not always experience faster rates of deforestation (Mathur and Bhattacharya, 2024). Factors such as successful education initiatives, land ownership structures, and strong local governance have proven effective in curbing FA degradation (Haji et al., 2020). This suggests that the relationship between POP and FA is strongly mediated by its interaction with other variables, such as development orientation and energy transition.

Furthermore, in many econometric models used in forestry studies across tropical countries, FA is often treated passively as a dependent variable, while variables such as POP, REC, NREC, and economic activity are assumed to be independent and unaffected by any feedback. For instance, Kumar et al. (2022) framed deforestation as the outcome of a combination of POP and agricultural expansion, without evaluating how the loss of FA itself might impact economic activity, energy resilience, or ecological stability. A similar pattern can be found in the study by Borda-Niño et al. (2020), which extensively reviewed how economic factors drive land-use change in tropical regions, but did not explore the potential bidirectional relationships between FA change and its driving variables. However, empirical evidence suggests that FA is not only influenced by external factors but can also affect them in return. For example, the loss of FA may disrupt local energy resilience (particularly in areas dependent on biomass), influence POP migration patterns, and even affect economic productivity through changes in local ecosystems and climate (Feng et al., 2024).

Moreover, the strategic dimension of GEG has rarely been the central focus in previous studies, despite its significant potential as a bridge between development goals and environmental conservation. In fact, the transition toward GEG could be key to strengthening FA resilience amid escalating ecological pressures and the intensifying global energy race. To date, most research has focused on conventional economic approaches to explain the dynamics between the environment and energy. This is reflected in various empirical studies showing that economies driven by conventional models tend to increase dependence on NREC, ultimately worsening ED (Djellouli et al., 2022). For instance, Musibau et al. (2021) found that increases in gross domestic product (GDP) in high-emission countries are significantly correlated with greater NREC use and heightened environmental pressures, unless offset by investments in green technologies and sustainable energy policies. A similar finding was reported by Karaaslan and Camkaya (2022), who showed that economies not guided by sustainability principles tend to exacerbate ED and intensify FA exploitation, particularly in developing countries that heavily rely on natural resources. On the other hand, GEG models have been shown to reduce pressure on natural resources by promoting energy efficiency, sustainable energy diversification, and the protection of FA functions (Anser et al., 2021). A study by Taşkın et al. (2020) demonstrated that bioenergy trade and the implementation of green policies had a positive impact on GEG and contributed to FA preservation in tropical regions. Unfortunately, this dimension remains under-integrated in quantitative analyses or systemic modeling, highlighting the need for a paradigm shift toward more integrative and transformative approaches, where GEG is not merely positioned as a policy alternative, but as a fundamental prerequisite for achieving balance among economic development, energy demands, and ecological sustainability.

Based on the various empirical phenomena discussed above, this study addresses the existing gap by offering a more holistic approach through the VAR model, which is capable of capturing simultaneous relationships and the dynamics of interdependence among variables endogenously. This approach allows for a more accurate evaluation of how changes in one variable, such as REC, NREC, ED, GEG, and POP, can influence FA, while also assessing how changes in FA provide feedback to those variables. By focusing on MINT countries, which are currently experiencing simultaneous pressures from economic development, energy transition, and ecological stress, this study makes an important contribution to explaining the complex configurations behind FA degradation, configurations often overlooked in conventional linear models.

3. METHODOLOGY

3.1. Data and Variables

This study utilizes secondary panel data covering four developing countries that are members of the MINT group, over the period from 1990 to 2024. The data were collected from various credible international sources and relevant institutions. The variables analyzed include FA, REC, NREC, ED, GEG, and POP (Table 1).

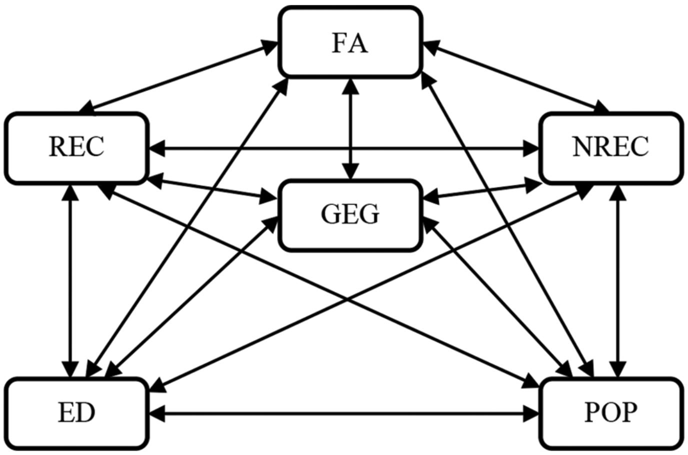
In this study, the energy race is represented by two main variables: REC and NREC. These variables reflect the dynamics of substitution or competition between clean energy sources and conventional energy sources, which contribute to pressure on natural resources, including FA. Ecological pressure is assessed through three indicators: ED, which captures ecosystem degradation due to human activity; POP, which represents demographic pressure on space and natural resources; and imbalanced GEG, which reflects economic activities that are not yet fully aligned with environmental sustainability principles.

All variables in the model are treated as endogenous, meaning that the relationships among them are assumed to be mutually influential (Figure 1). The selection of these variables aims to explore the complex linkages among FA change, energy consumption dynamics, and ecological pressures within the framework of sustainable development in developing countries.

Table 1: Operational definitions of variables

Variable	Description	Source
FA	The total forest area covered by naturally grown or planted tree stands with a minimum height of 5 meters at maturity, whether productive or not, excluding tree stands within agricultural production systems; measured in million hectares (million ha)	Food and Agriculture Organization of the United Nations
REC	The total final consumption of biofuels; measured in terajoules (TJ)	International Energy Agency
NREC	The total final consumption of fossil fuels; measured in TJ	International Energy Agency
ED	Degradation reflected by carbon dioxide emissions resulting from forestry-related activities; measured in megatons of carbon dioxide (Mt CO_2)	International Energy Agency
GEG	Green economic growth adjusted for natural resource depletion and environmental damage from carbon emissions; measured in percent	World Bank
POP	Population density, referring to the number of people living per square kilometer of land area; measured in people per square kilometer (km²)	World Bank

Figure 1: Research framework



3.2. Analytical Model

To examine the dynamic relationships among mutually influential variables across countries, this study employs the VAR approach. This model allows each endogenous variable to be treated symmetrically. In this study, six key variables are modeled as endogenous. These variables influence one another, as illustrated in Equations (1) through (6). Each equation represents the dynamic behavior of one variable with respect to both its own past values and those of the other variables.

$$FA_{it} = \alpha_1+\beta_{11}FA_{i,t-j}+\beta_{12}REC_{i,t-j}+\beta_{13}NREC_{i,t-j}+\beta_{14}GEG_{i,t-j}+\beta_{15}ED_{i,t-j}+\beta_{16}POP_{i,t-j}+\varepsilon_{1i,t} \quad (1)$$

$$REC_{it} = \alpha_2+\beta_{21}FA_{i,t-j}+\beta_{22}REC_{i,t-j}+\beta_{23}NREC_{i,t-j}+\beta_{24}GEG_{i,t-j}+\beta_{25}ED_{i,t-j}+\beta_{26}POP_{i,t-j}+\varepsilon_{2i,t} \quad (2)$$

$$NREC_{it} = \alpha_3+\beta_{31}FA_{i,t-j}+\beta_{32}REC_{i,t-j}+\beta_{33}NREC_{i,t-j}+\beta_{34}GEG_{i,t-j}+\beta_{35}ED_{i,t-j}+\beta_{36}POP_{i,t-j}+\varepsilon_{3i,t} \quad (3)$$

$$GEG_{it} = \alpha_4+\beta_{41}FA_{i,t-j}+\beta_{42}REC_{i,t-j}+\beta_{43}NREC_{i,t-j}+\beta_{44}GEG_{i,t-j}+\beta_{45}ED_{i,t-j}+\beta_{46}POP_{i,t-j}+\varepsilon_{4i,t} \quad (4)$$

$$ED_{it} = \alpha_5+\beta_{51}FA_{i,t-j}+\beta_{52}REC_{i,t-j}+\beta_{53}NREC_{i,t-j}+\beta_{54}GEG_{i,t-j}+\beta_{55}ED_{i,t-j}+\beta_{56}POP_{i,t-j}+\varepsilon_{5i,t} \quad (5)$$

$$POP_{it} = \alpha_6+\beta_{61}FA_{i,t-j}+\beta_{62}REC_{i,t-j}+\beta_{63}NREC_{i,t-j}+\beta_{64}GEG_{i,t-j}+\beta_{65}ED_{i,t-j}+\beta_{66}POP_{i,t-j}+\varepsilon_{6i,t} \quad (6)$$

Notation:
t: time period
i: cross-section unit (country)
j: lag order of the variable
α: intercept
β: coefficient
ε: residual (error term)

3.3. Data Analysis Technique

The data analysis in this study follows a structured sequence of econometric procedures based on the VAR framework. The first step involves testing the stationarity of all variables using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) methods to ensure that the variables do not contain unit roots and are stationary. Next, the optimal lag length is determined using various information criteria, including the Akaike Information Criterion (AIC), Schwarz Criterion (SC), Hannan-Quinn (HQ), Final Prediction Error (FPE), and Likelihood Ratio (LR). Following lag selection, a stability test is conducted through the analysis of autoregressive (AR) characteristic polynomial roots. Panel cointegration tests are then used to identify long-term relationships among the variables. Once the model is established, the Granger causality test is applied to determine the direction of causal relationships among the variables. This is followed by the Impulse Response Function (IRF) analysis to observe how one variable responds to shocks from other variables over a given time horizon, and the Variance Decomposition (VD) analysis to assess the relative contribution of each variable to the overall variance in the system. These sequential steps form a comprehensive VAR analytical framework—from data preconditions and model construction to the examination of dynamic interactions among variables and their contributions within the system.

4. RESULTS AND DISCUSSION

4.1. Descriptive Statistical Analysis

To gain an overall understanding of the characteristics of the data used in the analysis, descriptive statistics were calculated for all observed variables. These statistics include the mean, standard deviation, skewness, and quartiles for each variable. A summary of the results is presented in Table 2 below.

Table 2 presents the descriptive statistics for all variables analyzed. The average FA is 53.18 million ha, with a relatively large standard deviation of 33.26 million ha, indicating a high degree of variation across countries. REC and NREC have average values of 534,943 TJ and 1,699,085 TJ, respectively. ED shows a mean of 5.78 Mt CO_2, while GEG exhibits a negative mean of −1.29%, indicating a weak or declining trend in GEG. Meanwhile, the average POP is 2,321,041 people per km². The skewness values for most variables are close to zero, indicating relatively symmetrical distributions, except for GEG, which has a significantly negative skewness, suggesting a left-skewed distribution. The quartile values also reveal diversity in the distributions, with GEG showing the widest interquartile range, indicating the presence of several extreme values in the positive direction.

4.2. Stationarity Test Results

Before estimating the VAR model, an essential preliminary step is to test the stationarity of each variable used in the analysis (Table 3). Stationarity testing is necessary to ensure that the variables do not contain unit roots, which could lead to biased or invalid estimation results. In this study, the ADF and PP tests are employed to evaluate the order of integration of the variables at level (I(0)) and first difference (I(1)).

Table 3 presents the results of the stationarity tests using the ADF and PP methods for each variable at both level and first-difference forms. The results indicate that most variables are non-stationary at I(0) but become stationary at I(1), as shown by their significance levels. An exception is found in the GEG variable, which is already

Table 2: Descriptive statistics results

Data Description	Variable					
	FA	REC	NREC	ED	GEG	POP
	Million ha	TJ	TJ	Mt CO_2	Percent	People per km^2
Mean	53183350	534943	1699085	5.78	−1.29	2321041
Standard Deviation	33260933	310035	936552	3.97	5.89	1298323
Skewness	0.41	0.47	0.13	-0.21	−1.11	0.47
Kuortis	−1.41	−0.93	−1.37	−0.95	2.33	−0.92

Table 3: Stationarity test results

Variable	I (0)		I (1)	
	ADF	PP	ADF	PP
FA	0.9599	0.6873	0.0033***	0.0000***
REC	0.9221	0.8148	0.0002***	0.0000***
NREC	0.9579	0.9313	0.0000***	0.0000***
ED	0.3172	0.2079	0.0000***	0.0000***
GEG	0.0006***	0.0000***	-	-
POP	0.3196	0.8557	0.0000***	0.0192**

***Significant at α = 1%; **Significant at α = 5%

stationary at I(0), with strong significance in both tests. This indicates that most variables are integrated at I(1), except for GEG.

4.3. Optimal Lag Selection Results

Before constructing the VAR model, determining the optimal lag length is a crucial preliminary step to ensure the model's stability and validity. The optimal lag is selected by considering several information criteria. The computed results for each criterion are presented in Table 4.

Table 4 presents the results of the optimal lag selection based on various information criteria. Based on the values shown, the third lag is identified as optimal according to both AIC and FPE, as indicated by the lowest scores. The LR test also supports the third lag, showing the strongest significance relative to previous lags. In contrast, SC suggests the first lag, while HQ points to the second. Despite these differences, the third lag is chosen as the most appropriate for subsequent analysis, as AIC and FPE are commonly prioritized in VAR-based studies due to their sensitivity in capturing complex dynamics.

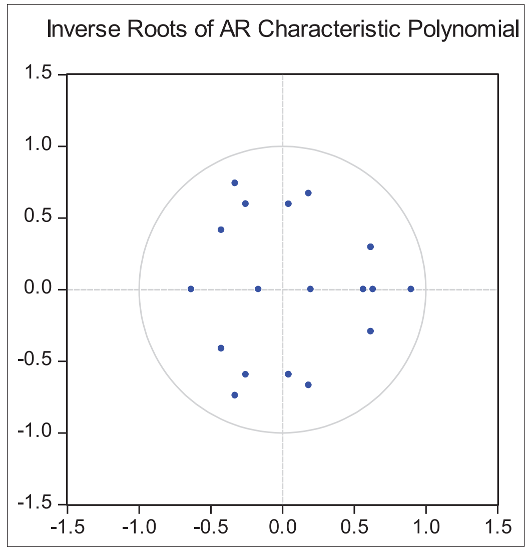
4.4. Stability Test Results

To ensure that the VAR model is stable, a stability test was conducted using the characteristic roots of the AR polynomial. The results are presented in Table 5 and visualized in Figure 2. Based on both Table 5 and Figure 2, the model satisfies the stability condition, indicating that the estimation results and subsequent analyses can be carried out with confidence in the model's validity and reliability.

Table 5 shows that all characteristic roots have moduli less than one, with the highest value being 0.900163. This indicates that the VAR model is dynamically stable.

Figure 2 displays the characteristic roots of the AR polynomial for the VAR model. Each blue dot represents the modulus value of the corresponding root. All points lie within the unit circle (radius = 1), which is indicated by the black circular line. This confirms that the model is dynamically stable.

Figure 2: Stability graph



4.5. Cointegration Test Results

After confirming the model's stability, the next step is to test for long-run relationships among the variables using panel cointegration tests (Table 6). This test is crucial for determining whether a Vector Error Correction Model (VECM) is required in the analysis. If cointegration is detected, it indicates the presence of long-term equilibrium relationships among the variables, and these relationships must be incorporated into the model. Conversely, if no cointegration is found, the analysis can proceed using the standard VAR model without the error correction component.

Table 6 shows that all P-values from the panel cointegration tests are well above the significance threshold, indicating no evidence of cointegration among the variables. This implies that the variables in the model do not share a long-term equilibrium relationship. Therefore, a VECM is not required, and the analysis can proceed using a standard VAR model to trace the dynamic interactions among variables.

4.6. Granger Causality Test Results

To identify the direction of causality among the variables in the model, the Granger causality test was conducted. The discussion focuses on statistically significant results, as only these can be meaningfully interpreted from an econometric standpoint. Table 7 presents the Granger causality test results between FA and several key determinants, including REC, NREC, ED, GEG, and POP.

NREC can influence changes in FA, and conversely, changes in FA can also affect the demand for NREC. In MINT countries, this is reflected in the reliance on fossil energy sources, which is often

Table 4: Optimal lag selection results

Lag	LogR	LR	FPE	AIC	SC	HQ
0	−8298.05	NA	5.93E+50	133.9362	134.0727	133.9917
1	−6936.38	2569.589	3.07E+41	112.5546	113.5098*	112.9426
2	−6856.23	143.5	1.51E+41	111.8424	113.6165	112.5631*
3	−6818.36	64.13553*	1.48e+41*	111.8122*	114.4051	112.8655
4	−6787.3	49.59373	1.64E+41	111.8919	115.3036	113.2778

Table 5: Stability test results

Root	Modulus
0.900163	0.900163
−0.328273−0.739790i	0.809353
−0.328273+0.739790i	0.809353
0.185496+0.668836i	0.694082
0.185496−0.668836i	0.694082
0.618234−0.294975i	0.684999
0.618234+0.294975i	0.684999
−0.254232−0.596398i	0.648325
−0.254232+0.596398i	0.648325
0.634173	0.634173
−0.63335	0.633349
0.044857−0.593603i	0.595296
0.044857+0.593603i	0.595296
−0.424016−0.412720i	0.591715
−0.424016+0.412720i	0.591715
0.566284	0.566284
0.199614	0.199614
−0.16586	0.165860

Table 6: Cointegration test results

Panel cointegration test	Statistic	Prob.	Weighted statistic	Prob.
Panel v-Statistic	−1.446603	0.9260	−2.19368	0.9859
Panel rho-Statistic	1.984774	0.9764	0.36073	0.6408
Panel ADF-Statistic	2.552622	0.9947	−0.65124	0.2574

Table 7: Granger causality test results

Null Hypothesis	Obs	F-Statistic	Prob.
NREC does not Granger Cause FA	128	2.50883	0.0620*
FA does not Granger Cause NREC		4.22182	0.0071***
REC does not Granger Cause FA	128	3.29771	0.0228**
FA does not Granger Cause REC		0.56007	0.6424
ED does not Granger Cause FA	128	2.16116	0.0961*
FA does not Granger Cause ED		0.85774	0.4651
GEG does not Granger Cause FA	128	2.88417	0.0386**
FA does not Granger Cause GEG		0.47921	0.6973
POP does not Granger Cause FA	128	1.25257	0.2938
FA does not Granger Cause POP		2.44696	0.0671*
REC does not Granger Cause NREC	128	0.47721	0.6987
NREC does not Granger Cause REC		0.78378	0.5052
ED does not Granger Cause NREC	128	1.67595	0.1758
NREC does not Granger Cause ED		0.38272	0.7656
GEG does not Granger Cause NREC	128	0.11950	0.9485
NREC does not Granger Cause GEG		0.64301	0.5888
POP does not Granger Cause NREC	128	0.91423	0.4363
NREC does not Granger Cause POP		3.01823	0.0325**
ED does not Granger Cause REC	128	5.13811	0.0022***
REC does not Granger Cause ED		0.74041	0.5300
GEG does not Granger Cause REC	128	0.11248	0.9527
REC does not Granger Cause GEG		0.09308	0.9637
POP does not Granger Cause REC	128	1.85902	0.1402
REC does not Granger Cause POP		1.73652	0.1631
GEG does not Granger Cause ED	128	0.32500	0.8073
ED does not Granger Cause GEG		0.37919	0.7682
POP does not Granger Cause ED	128	3.37567	0.0207**
ED does not Granger Cause POP		3.50507	0.0175**
POP does not Granger Cause GEG	128	0.42755	0.7336
GEG does not Granger Cause POP		0.09845	0.9607

*Significant at $\alpha = 10\%$

associated with deforestation for energy extraction activities, such as in Nigeria and Indonesia. On the other hand, deforestation also alters access to and distribution of energy in rural areas, affecting demand for traditional fossil fuels. Several studies support these findings. For instance, Amin et al. (2024) highlights that increases in NREC significantly accelerate the rate of deforestation in developing countries, particularly through extractive activities such as coal mining, oil exploration, and the expansion of energy infrastructure. In Indonesia, the expansion of palm oil plantations and coal mining in Kalimantan and Sumatra is often linked to the loss of FA for mining roads and energy facilities (Farobie and Hartulistiyoso, 2022). In Nigeria, oil exploration in the Niger Delta has also been documented to cause large-scale FA degradation due to pipeline construction, drilling, and pollution (Onyena and Sam, 2020). Conversely, changes in FA also contribute to the increase in NREC, as deforestation reduces the availability of biomass such as firewood. As a result, communities tend to shift toward more accessible and relatively inexpensive fossil energy sources, such as kerosene or coal, to meet household energy needs (Usman and Makhdum, 2021). In studies conducted in Mexico and Indonesia, for example, it was found that the loss of access to FA accelerated household energy transitions toward fossil-based commercial fuels, albeit with higher costs and emissions (Psistaki et al., 2024). The two-way interaction between the forestry and fossil energy sectors demands cross-sectoral policy integration. As stated by (Iyiola et al., 2023), the economic dynamics of the energy sector significantly influence land-use decisions, including the conversion of FA.

In line with these dynamics, the relationship between POP and ED is also proven to be mutually significant. An increase in POP exerts pressure on land and natural resources, and generates more waste and emissions, ultimately accelerating ED. Conversely, deteriorating environmental conditions also influence POP dynamics, through impacts on health, resource availability, and patterns of migration and POP concentration in certain areas. These findings align with the study by Daskalova et al. (2020) which shows that POP directly increases the ecological footprint, a key indicator of ED. Furthermore, a panel study by Gambo (2024) in Sub-Saharan Africa, including Nigeria, also demonstrates that POP growth worsens environmental quality through agricultural expansion, deforestation, and NREC. Similar phenomena occur in MINT countries. In Indonesia and Mexico, for instance, urbanization and migration from rural to urban areas have driven the conversion of FA and agricultural land into residential areas. This expansion not only increases emissions and waste but also causes habitat fragmentation and loss of FA functions. Meanwhile, in Nigeria, the exploitation of resources such as oil in the Niger Delta has led to massive land and water degradation, directly affecting public health and prompting POP mobility due to declining environmental carrying capacity (Fasona et al., 2022). On the other hand, ED also significantly impacts social and demographic conditions. ED is closely linked to declining quality of life. A global study by Bologna and Aquino (2020) concluded that polluted environments contribute to 23% of global deaths and 26% of deaths among children under five. In Mexico City, crises in air and water quality have led to increased respiratory and waterborne illnesses, triggering migratory pressure from urban areas and their surroundings.

In addition, REC has been shown to significantly influence FA. This finding reinforces the view that increasing REC not only reduces emissions but can also directly contribute to FA preservation. In MINT countries, energy transition has become a key strategy in reducing pressure on FA, particularly in areas previously affected by deforestation for traditional energy needs. For example, in Indonesia, the development of bioenergy based on palm oil waste and wood biomass from FA has shown potential in replacing dependence on firewood or fossil energy mining expansion in tropical FA zones. Research by Harahap (2021) indicates that the use of biomass waste from the palm oil industry in Sumatra and Kalimantan significantly reduces the need for land-based energy expansion. A similar study by Akpanke et al. (2023) also shows that REC adoption positively affects environmental quality and deforestation reduction, especially in developing countries with vulnerable ecosystems. In Mexico, the development of solar power plants in desert regions has helped ease energy pressures in the mountainous FA areas of the Sierra Madre, as revealed in a study by (Ponce et al., 2021). Furthermore, Turkey and Nigeria have begun adopting clean energy mix policies to reduce pressure on FA. A study by Taşbaşı (2024)) supports this finding, showing that a 1% increase in REC in Turkey can reduce deforestation pressure by 0.3% in the long run.

Still within the context of ecological pressure, ED has been shown to significantly affect FA. Environmental pressures such as air and soil pollution, erosion, FA fires, and ecological disasters driven by human activity and climate change accelerate FA loss, particularly in developing countries. In MINT regions, this phenomenon is commonly observed as a direct consequence of deforestation, large-scale agricultural expansion, and unsustainable mining and plantation practices. For example, in Turkey and Mexico, illegal mining activities and overgrazing in mountainous and semi-arid areas have caused severe damage to natural vegetation, accelerating land degradation and reducing FA regeneration capacity. A study by Karaaslan and Camkaya (2022) in Turkey found that uncontrolled metal mining led to soil contamination and disrupted the natural succession processes of pine and fir FA in the Anatolian region. Meanwhile, Alcocer and Escobar (2024) reported that in Mexico, commercial agricultural expansion and slash-and-burn practices have worsened erosion and increased FA fire occurrences, particularly in southern regions such as Chiapas and Oaxaca. In Nigeria, oil and gas drilling activities in the Niger Delta have also shown a strong negative correlation with mangrove FA conditions and coastal ecosystems, as noted by Fasona et al. (2022). Additional empirical support comes from research by Izuchukwu et al. (2025), which revealed that increasing ED due to CO_2 emissions has led to declining FA in Southeast Asia, including Indonesia.

Furthermore, GEG has been shown to significantly influence FA, indicating that the adoption of a GEG model can help preserve or even expand FA. In MINT countries, the shift toward a greener economy is becoming increasingly evident through various policies and initiatives, such as the development of REC, improvements in resource efficiency, and the strengthening of sectors like ecotourism and sustainable agriculture. Indonesia and Mexico, for instance, have implemented Payment for Environmental Services (PES) schemes that provide incentives for local communities to conserve FA ecosystems and protect biodiversity. In addition, a study by Reyes-Hernández (2023) on PES implementation in Mexico found that financial incentives to local communities successfully slowed deforestation and raised conservation awareness. In Indonesia, a similar initiative has been developed through the REDD+ (Reducing Emissions from Deforestation and Forest Degradation) scheme, which provides compensation for tropical FA conservation efforts and encourages the participation of indigenous peoples and smallholder farmers in sustaining FA ecosystems. Research by Tawiah et al. (2021) also supports this finding, showing that investments in GEG sectors, such as ecotourism and FA management positively correlate with increased community income and FA stability. Moreover, Mustafa et al. (2022) argues that the transition toward GEG promotes the integration of environmental policies into national economic and fiscal systems, ultimately creating more conducive structural conditions for the preservation of natural resources, including FA.

Interestingly, FA has been found to significantly influence POP. This finding underscores the importance of FA ecosystems in shaping a region's carrying capacity for human life. FA not only provides basic necessities such as food, clean water, and fuel, but also ensures ecological stability essential for sustaining human settlements, particularly in rural areas and indigenous communities across MINT countries. In Indonesia and Nigeria, FA remains a primary source of livelihood for indigenous peoples and smallholder farmers. When FA declines due to deforestation or degradation, POP that depend on FA tend to migrate to major cities or economically promising areas. This phenomenon has been documented by Bologna and Aquino (2020), who shows that the loss of FA can trigger internal migration, especially when no viable livelihood alternatives are provided by the state. A similar observation was made by Gambo (2024) in Nigeria, where FA degradation was found to contribute to growing ecological pressure in urban areas by worsening socio-economic problems such as unemployment and poverty.

In addition, NREC has been shown to influence POP dynamics. Energy is one of the main drivers of economic development and spatial transformation, where regions with access to energy sources tend to experience a concentration of human activities. In MINT countries, areas with well-established NREC infrastructure often become centers of POP growth and urbanization. For example, coal and oil mining regions in Mexico and energy-based industrial hubs on Java Island, Indonesia, have attracted significant internal migration due to the availability of jobs and supporting facilities. However, heavy dependence on NREC also brings ecological consequences that affect the quality of life for the POP. Carbon emissions, air pollution, and land degradation resulting from fossil energy exploitation can lead to health problems, reduced land productivity, and overall discomfort in affected areas. This is reinforced by Kurniadi et al. (2021), who notes that in the long run, NREC can degrade environmental quality and put pressure on POP well-being. A study by Aimon et al. (2021) also points out that although NREC supports development, its negative environmental impacts can undermine social stability if not accompanied by adequate regulation and energy diversification.

In response to environmental pressures, ED has been shown to drive the transition to REC. As environmental quality declines due to high carbon emissions, air pollution, land degradation, and decreasing water quality, countries are increasingly compelled to shift toward cleaner and more sustainable energy sources. In MINT countries, this trend is reflected in policy shifts toward REC development as a response to growing ecological stress. For example, Turkey has significantly expanded its wind energy potential and increased hydroelectric power generation as part of its efforts to combat urban air pollution and address drought risks associated with climate change. These findings are consistent with the study by Hakim et al. (2025), which shows that rising ED increases demand for REC in developing countries as part of mitigation strategies. Additionally, a study by Kurniadi et al. (2024) found that high environmental pressures act as a catalyst for increased green energy investment. In Indonesia, initiatives such as waste-to-energy development and bioenergy derived from palm oil waste have also emerged as responses to growing environmental burdens caused by fossil fuel dependence and land conversion (Romianingsih, 2023).

4.7. IRF Results

This analysis illustrates both the direction and magnitude of a variable's response to a one standard deviation shock from another variable within the VAR system. The explanation focuses on the interactions between significant variables over the next 10-year period, as illustrated in Figure 3.

The response of D(FA) indicates a negative reaction to shocks from NREC, suggesting that increases in NREC can accelerate deforestation. In contrast, shocks from REC have a positive impact on FA during the early periods, reflecting that investment in REC may support forest preservation. Shocks from ED, GEG, and POP also have negative effects on FA, reinforcing the evidence that ecological pressures contribute to land-use change.

The reciprocal relationship between FA and REC becomes evident in the response of D(REC), where REC reacts positively to shocks from FA, indicating synergy between forest conservation and REC development. Shocks from NREC have a negative effect, suggesting a substitutive relationship between REC and NREC. Shocks from ED and GEG stimulate REC, while the impact of POP is minor but slightly positive.

The response of D(NREC) also shows negative reactions to shocks from FA and REC, confirming the potential to reduce NREC dependence through forest conservation and energy transition. In contrast, ED and POP drive up NREC, indicating that both remain closely associated with NREC consumption. GEG exerts a decreasing influence on NREC, aligning with a greener economic direction.

In the response of D(ED), ED reacts positively to shocks from FA, NREC, and POP, indicating that these factors are key drivers of ecological stress. REC and GEG generate negative responses, demonstrating their potential to alleviate environmental pressure, although their effects emerge over time.

The response of D(GEG) reveals a negative reaction to shocks from FA and NREC, suggesting that deforestation and fossil fuel reliance hinder progress toward green transformation. In contrast, shocks from REC result in a positive response, affirming its crucial role. Negative responses to ED and a neutral reaction to POP imply that environmental stress impedes green development, while POP dynamics have yet to become a major driver of GEG.

Finally, the response of D(POP) shows a negative reaction to FA, suggesting that forest loss reduces regional carrying capacity. Shocks from NREC and ED yield positive effects on POP, reflecting a tendency toward POP concentration in areas with high NREC use and ecological stress. The response to REC is relatively flat but slightly positive, while the effect of GEG is neutral, indicating that green transition has not yet been fully embedded in broader ecological dynamics.

4.8. VD Results

Following the IRF analysis, which examined the direction and duration of responses among variables within the VAR system, the next step involves assessing the relative contribution of each variable to the observed variation through VD analysis. This approach provides information on the proportion of fluctuations in an endogenous variable that can be explained by itself and by other variables over a given time horizon. Accordingly, Table 8 summarizes the VD results, complementing the IRF findings and offering a quantitative overview of the dominance or interdependence among variables in the medium and long term.

Fluctuations in D(FA) are still largely explained by its own past values, although its contribution declines from 100% in the first period to approximately 78.3% by the tenth period. The increasing contributions of other variables such as ED (13.9%), REC (2.76%), and POP (2.62%) indicate that environmental quality and ecological pressures are beginning to influence changes in FA.

On the other hand, variation in D(REC) is highly dominated by its own dynamics (approximately 99.88% in the first period, remaining high at 79.3% by the tenth period), but also increasingly influenced by D(NREC) (8.95%) and D(ED) (7.03%) in the medium term. This suggests that while REC remains relatively

Table 8: VD test results

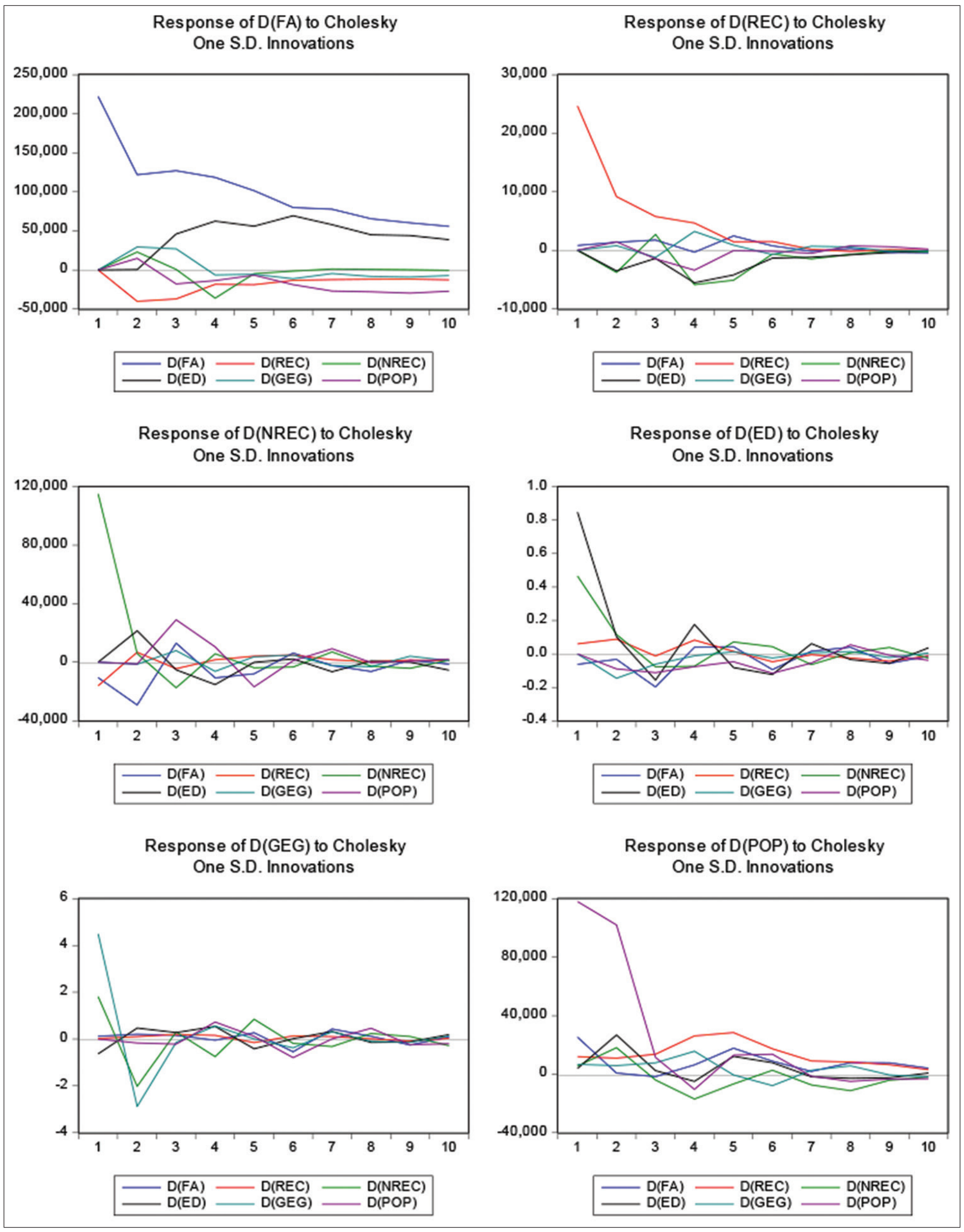
Period	S.E.	D (FA)	D (REC)	D (NREC)	D (ED)	D (GEG)	D (POP)
VD of D (FA)							
1	222086.7	100.0000	0.000000	0.000000	0.000000	0.000000	0.000000
2	259616.1	95.20458	2.422956	0.771287	0.000279	1.278796	0.322102
3	296815.0	91.17192	3.430113	0.590534	2.391665	1.803675	0.612096
4	328494.8	87.42927	3.121571	1.698062	5.567098	1.511132	0.672870
5	348961.3	85.90784	3.064225	1.524072	7.506382	1.364702	0.632779
6	365570.9	83.05641	2.927806	1.390191	10.43831	1.341029	0.846252
7	379403.7	81.31508	2.826323	1.291412	12.00766	1.259622	1.299904
8	388926.5	80.22269	2.785260	1.229131	12.75486	1.246643	1.761409
9	397396.1	79.13071	2.756496	1.177339	13.44207	1.246875	2.246512
10	404339.9	78.34026	2.762990	1.137430	13.89828	1.236055	2.624984
VD of D (REC)							
Period	**S.E.**	**D (FA)**	**D (REC)**	**D (NREC)**	**D (ED)**	**D (GEG)**	**D (POP)**
1	24672.55	0.113696	99.88630	0.000000	0.000000	0.000000	0.000000
2	26904.05	0.364297	95.59544	1.941483	1.708276	0.087275	0.303229
3	27804.65	0.750390	93.81657	2.773738	1.837581	0.267470	0.554247
4	29699.51	0.667582	84.70145	6.321209	5.106800	1.429015	1.773945
5	30574.40	1.273964	80.15663	8.746685	6.714100	1.434483	1.674138
6	30665.42	1.329613	79.92147	8.735964	6.865073	1.481132	1.666744
7	30736.52	1.326308	79.55521	8.925607	6.979162	1.527661	1.686048
8	30770.83	1.332654	79.38190	8.955076	7.026057	1.559393	1.744918
9	30782.18	1.343999	79.32466	8.949600	7.036106	1.560951	1.784681
10	30786.82	1.360099	79.30079	8.956462	7.034043	1.560540	1.788068
VD of D (NREC)							
Period	**S.E.**	**D (FA)**	**D (REC)**	**D (NREC)**	**D (ED)**	**D (GEG)**	**D (POP)**
1	116584.5	0.813600	1.894399	97.29200	0.000000	0.000000	0.000000
2	122439.9	6.441853	2.026692	88.43780	3.069651	0.013479	0.010528
3	128114.3	6.914502	1.968229	82.62600	2.969160	0.401080	5.121024
4	130171.9	7.366671	1.922558	80.23571	4.247249	0.620443	5.607372
5	131668.9	7.554683	1.974909	78.50715	4.151251	0.688431	7.123574
6	132063.1	7.735828	2.101062	78.10031	4.153442	0.822181	7.087180
7	132780.1	7.681574	2.094658	77.53708	4.344765	0.844817	7.497107
8	132994.4	7.881863	2.088553	77.32853	4.334650	0.893151	7.473249
9	133138.8	7.876259	2.096444	77.25663	4.325288	0.986895	7.458488
10	133290.3	7.868082	2.097647	77.09076	4.486879	0.990093	7.466538
VD of D (ED)							
Period	**S.E.**	**D (FA)**	**D (REC)**	**D (NREC)**	**D (ED)**	**D (GEG)**	**D (POP)**
1	0.970949	0.419888	0.375877	22.97244	76.23180	0.000000	0.000000
2	1.002392	0.499363	1.115950	22.89339	72.57562	2.101832	0.813840
3	1.044774	4.067279	1.041604	21.62829	69.06156	2.291665	1.909599
4	1.068902	4.020965	1.584645	21.14809	68.70071	2.201397	2.344194
5	1.076447	4.120378	1.581166	21.28727	68.31797	2.185352	2.507864
6	1.095906	4.718179	1.716607	20.69118	67.18285	2.162648	3.528537
7	1.101037	4.694814	1.702765	20.84285	66.86710	2.145615	3.746851
8	1.104014	4.795010	1.744483	20.73350	66.60349	2.151115	3.972407
9	1.108773	5.011677	1.889189	20.67886	66.30711	2.169379	3.943788
10	1.110517	5.012423	1.896235	20.66694	66.20757	2.164874	4.051955
VD of D (GEG)							
Period	**S.E.**	**D (FA)**	**D (REC)**	**D (NREC)**	**D (ED)**	**D (GEG)**	**D (POP)**
1	4.891960	0.060135	0.002222	13.70785	1.675545	84.55425	0.000000
2	6.054241	0.157405	0.027401	20.07602	1.695110	77.96498	0.079083
3	6.078814	0.221972	0.136801	20.15622	1.888077	77.39444	0.202488
4	6.219040	0.219698	0.194517	20.71252	2.563045	74.74831	1.561911
5	6.298423	0.394007	0.248499	21.99298	2.932123	72.87616	1.556226
6	6.387244	1.112993	0.286446	21.47304	2.851646	71.21406	3.061818
7	6.426191	1.537216	0.308249	21.46608	3.076492	70.58709	3.024878
8	6.450517	1.557380	0.306013	21.43959	3.106737	70.07915	3.511133
9	6.464560	1.713915	0.325918	21.37649	3.130062	69.81863	3.634982
10	6.478476	1.726971	0.326591	21.47297	3.202211	69.55148	3.719784

(*Contd...*)

Table 8: (*Continued*)

VD of D (POP)							
Period	**S.E.**	**D (FA)**	**D (REC)**	**D (NREC)**	**D (ED)**	**D (GEG)**	**D (POP)**
1	121642.0	4.303057	0.969183	0.213242	0.100431	0.303148	94.11094
2	162498.5	2.413351	0.998075	1.363329	2.777595	0.300395	92.14725
3	163724.8	2.388992	1.674663	1.403641	2.756890	0.515975	91.25984
4	167917.3	2.415205	4.013145	2.367176	2.705326	1.353637	87.14551
5	172285.6	3.348879	6.533640	2.402252	3.075421	1.286755	83.35305
6	174292.5	3.530246	7.376265	2.368980	3.205511	1.462639	82.05636
7	174727.6	3.523913	7.607310	2.534314	3.201382	1.477700	81.65538
8	175645.0	3.688490	7.745684	2.917902	3.195757	1.567081	80.88509
9	176032.7	3.862374	7.848666	2.960084	3.201837	1.561294	80.56575
10	176156.0	3.909084	7.867066	2.968610	3.198770	1.570618	80.48585

Figure 3: IRF graphs



resilient, it is beginning to respond to external pressures such as the rise in NREC and ED.

For D(NREC), around 97.3% of the initial variation is explained by its own history, but this proportion decreases to 77.1% by the tenth period. The significant contributions of D(FA) (rising to 7.8%) and D(POP) (7.46%) indicate that deforestation and POP dynamics are important factors in the increase of NREC.

Variation in D(ED) is explained by its own past at 76.2% in the first period, declining to 66.2% by the tenth period. The consistently high contribution of D(NREC) (around 20%) confirms that NREC is a primary driver of ED. The growing role of D(POP) (up to 4.05%) also reflects ecological pressure stemming from POP changes.

Meanwhile, variation in D(GEG) initially shows strong self-dependence (84.5%), which decreases to about 69.6% by the tenth period. The influence of D(NREC) becomes the second-largest contributor (around 21.47%), consistently throughout the period, indicating that reliance on NREC contributes significantly to GEG patterns. D(FA) also starts to play a role (1.72%), indicating a linkage between FA preservation and GEG.

Finally, variation in D(POP) remains largely self-explained (>94% in the first period and still 80.5% in the tenth). However, the contribution of D(REC) steadily increases to 7.86%, along with D(FA) at 3.9%, indicating that changes in the availability of energy resources and FA are gradually affecting POP dynamics.

5. CONCLUSION

Based on the analysis of MINT countries, this study identifies several key findings that reflect the complex dynamics between energy and ecological factors in influencing FA. A bidirectional causal relationship exists between FA and NREC, indicating that increased fossil energy use accelerates deforestation, while declining FA, in turn, heightens dependency on fossil energy. In addition, REC, ED, and GEG exert a unidirectional influence on FA. Increases in REC and the strengthening of GEG support FA preservation, whereas rising ecological pressures accelerate FA loss. Moreover, POP plays a significant role in both ecological pressure and energy demand, while also being affected by changes in FA, illustrating the complexity of ecological interactions.

The implications of these findings highlight the need for an integrative approach to natural resource management, particularly for MINT countries facing substantial pressure to balance development with environmental preservation. In this context, MINT countries should pursue more harmonized spatial and energy planning—such as designating conservation zones that account for deforestation risk and directing low-carbon energy infrastructure development outside of primary FA areas. Furthermore, increasing investment in sustainable energy within buffer zones surrounding FA is a crucial strategy to reduce reliance on fossil energy and to prevent the encroachment of FA for traditional energy sources. Governments should also strengthen economic incentive schemes for conservation actors, such as payments for environmental services supporting agroforestry practices and FA protection.

On an institutional level, governance reform through enhanced monitoring capacity, the involvement of local and Indigenous communities, and the enforcement of land-use regulations is essential to maintaining environmental quality. Moreover, public education campaigns about the importance of FA conservation and clean energy transitions must be intensified, especially in areas under high ecological pressure. School-based approaches, social media, and community partnerships can help build collective awareness and drive behavioral change.

Based on the series of analytical results, several directions for future research are recommended. These include expanding the scope of variables by incorporating indicators such as green fiscal policy, energy access, and social welfare metrics to achieve a more comprehensive understanding of the interplay between development, the environment, and energy transition. Additionally, future research should strengthen the integration of dynamic systems approaches or environmental input-output modeling frameworks to capture long-term feedback effects. Such approaches will be highly beneficial in designing evidence-based sustainable development strategies that are responsive to cross-sectoral ecological, social, and economic dynamics.

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