“Dynamic relationships among environmental quality, economic growth, and trade: A panel VAR analysis of Asia-Pacific economies”

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DYNAMIC RELATIONSHIPS AMONG ENVIRONMENTAL QUALITY, ECONOMIC GROWTH, AND TRADE: A PANEL VAR ANALYSIS OF ASIA-PACIFIC ECONOMIES

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Abstract

This study examines the dynamic relationships among environmental quality, economic growth, and trade across a sample of Asia-Pacific economies during the period 2000–2024. While previous studies have extensively investigated the links between economic growth, trade, and environmental degradation, relatively limited attention has been devoted to examining these variables simultaneously within a dynamic multivariate framework. To address this gap, the study employs a Vector Autoregression (VAR) approach to analyze the interdependencies among economic and environmental indicators. Environmental quality is represented by CO2 emissions, land-use change, biocapacity, and ecological footprint, while economic activity and trade are measured using GDP and trade indicators. The empirical results reveal significant dynamic relationships among economic growth, trade, and environmental variables. The estimated coefficients indicate substantial persistence across several economic and environmental indicators, suggesting important temporal dependencies within the system. The impulse response analysis further shows that shocks originating from environmental variables generate measurable responses in economic indicators, while economic disturbances are also associated with subsequent changes in environmental conditions. In addition, the stability analysis indicates that the estimated VAR system satisfies the stability condition over the sample period. The findings suggest that economic growth, trade activity, and environmental quality evolve within an interconnected dynamic framework. These results contribute to the literature on environmental–economic interactions and highlight the importance of incorporating environmental considerations into broader economic and trade policy discussions aimed at supporting long-term sustainable development.

Keywords environmental quality, economic growth, trade, panel VAR, sustainable development, Asia-Pacific economies

JEL Classification Q56, C33, Q53, F18

INTRODUCTION

Environmental dynamics have increasingly become a central concern in contemporary economic research, particularly as countries seek to balance growth, trade expansion, and ecological sustainability. The Asia-Pacific economies are especially relevant in this discourse due to their rapid economic transformation, rising environmental pressures, and diverse structural characteristics (Sabir et al., 2025; Imran et al., 2025). Existing theoretical perspectives suggest that environmental conditions can influence both economic performance and trade patterns through production costs, technological adaptation, resource availability, and regulatory frameworks (Rahman Razak et al., 2025; Acheampong & Opoku, 2023; Gabriel et al., 2024). Yet despite its importance, empirical evidence on how environmental factors simulta-

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neously shape economic growth and trade, especially within an integrated dynamic framework, remains limited and fragmented.

Most prior studies have examined the environment and economy nexus through single-equation models or linear specifications (Raihan, 2023; Idris & Rahman Razak, 2025; Aftab et al., 2021), often focusing on isolated relationships such as the Environmental Kuznets Curve or the trade–environment hypothesis (Nasreen & Anwar, 2015; Wang et al., 2024; Shahbaz, 2019; Ulucak & Bilgili, 2018). However, these approaches tend to overlook the endogenous and mutually reinforcing interactions among environment, growth, and trade. In reality, environmental changes may not only be outcomes of economic and commercial activities but may also serve as determinants that feed back into macroeconomic trajectories (Dechezlepretre & Sato, 2025). This complexity highlights the need for methodological frameworks capable of capturing dynamic adjustments across variables.

The Asia-Pacific economies present a compelling empirical setting due to their heterogeneity in economic development, trade openness, environmental policies, and ecological vulnerabilities (Reviane et al., 2025). Countries in the region face simultaneous pressures: Sustaining growth, protecting environmental quality, and remaining competitive in global markets (Cheng et al., 2024). These competing objectives raise a fundamental question that remains insufficiently addressed: To what extent do environmental factors actively shape economic growth and trade dynamics, rather than merely being influenced by them? Understanding this issue is not only academically significant but also essential for designing forward-looking development and trade policies that incorporate environmental constraints.

1. LITERATURE REVIEW

1.1. Environmental degradation and economic expansion

The relationship between environmental quality, economic growth, and trade has long been examined in economic and environmental sciences, yet the empirical evidence remains inconclusive. Foundational theories such as the Environmental Kuznets Curve (EKC) propose that environmental degradation initially increases with economic expansion but eventually declines as incomes rise and societies adopt cleaner technologies (Wang et al., 2023; Wang et al., 2024; Prieur, 2006). Although influential, this theoretical proposition has been criticized for oversimplifying complex structural dynamics and ignoring variations across countries with different institutional capacities and trade structures. More recent scholarship argues that environmental constraints may directly influence macroeconomic performance by altering production costs, resource availability, and investment behavior, thereby suggesting a need to study the environment not only as an outcome but as a determinant of economic processes (Erdoğdu et al., 2025; Mihut et al., 2025; Shapiro, 2025). Parallel research has explored how environmental degradation, resource depletion, and climate-related shocks affect economic performance. Studies documenting biodiversity loss, extreme weather events, and air pollution demonstrate substantial adverse effects on productivity, human health, and long-term growth (Leddin, 2024; Lawrance et al., 2022; Gkouliaveras et al., 2025).

Despite extensive empirical investigation, the magnitude and persistence of these environmental impacts differ considerably across regions and development stages. These inconsistencies suggest that environmental degradation and economic expansion interact through complex and multidirectional mechanisms that require more comprehensive analytical frameworks.

1.2. Environmental challenges among Asia-Pacific economies

In the Asia-Pacific region, where environmental challenges such as deforestation, land-use change, and rising emissions are acute, the economic implications of environmental pressures may be more pronounced than in advanced economies (Barati et al., 2023; Barbier, 2022; Tal, 2025). Regional analyses focusing on Asia-Pacific economies reveal substantial heterogeneity in both economic structures and environmental vulnerabilities. Rapid industrialization in emerging economies has amplified energy consumption and emissions, while advanced economies have shifted toward cleaner production and service-based industries (Kakar et al., 2024; Stephen, 2025). These differences influence the way countries experience and respond to environmental pressures.

Previous studies have highlighted that ecological degradation may undermine economic resilience by reducing ecosystem services, limiting resource availability, and increasing vulnerability to climate-related shocks. Yet the magnitude and persistence of these impacts differ widely across regions. Nevertheless, empirical evidence focusing specifically on the Asia-Pacific economies remains fragmented, and relatively few studies examine how environmental quality dynamically shapes economic growth and trade simultaneously within a regional context.

1.3. Trade liberalization and environmental outcomes

The classical and neoclassical frameworks emphasize comparative advantage and factor endowments in international trade (Sen, 2010; Schumacher, 2013), whereas contemporary studies highlight how environmental regulations, carbon intensity, and ecological risks shape trade flows (An, 2024; Cao et al., 2025; Sun et al., 2025). Some argue that stringent environmental standards can reduce competitiveness in pollution-intensive industries, while others argue that such standards encourage innovation and long-run productivity (Zhang et al., 2024; Kaiwen et al., 2023; Yirong, 2022). These divergent perspectives reveal that trade–environment interactions depend on institutional quality, market size, and technological factors. However, much of the empirical literature relies on static cross-sectional or single-equation models, limiting the understanding of dynamic feedback effects and endogeneity among variables.

Trade liberalization and environmental outcomes offer similarly contrasting views. Some studies suggest that increased openness may exacerbate pollution through the scale effect, while others provide evidence of improvements through technology transfer (Yingjun et al., 2024; Liu et al., 2025), cleaner production methods (Liu & Zhang, 2025; Jain, 2024), and stricter environmental commitments (Xuan, 2025), which are embedded in trade agreements. These mixed findings underscore the need for more nuanced approaches that consider how countries at different development stages respond to environmental constraints while participating in global markets. Much of this literature focuses on how trade affects the environment, whereas far fewer studies examine how environmental conditions, in turn, shape trade patterns, leaving a significant conceptual gap.

1.4. Aim

This study employs a Vector Autoregression (VAR) framework to examine the dynamic relationships among environmental quality, economic growth, and trade across regional Asia-Pacific economies. The VAR approach treats all variables as endogenous within a unified system and enables the analysis of lagged interdependencies and feedback effects among economic and environmental indicators. By modeling environment, growth, and trade as jointly evolving processes, this study provides a more comprehensive understanding of their dynamic interactions over time. The findings contribute to the broader literature on sustainable development and offer empirical insights for policymakers seeking to incorporate environmental considerations into economic and trade policy design.

2. METHODOLOGY

2.1. Data

In this study, we employ a panel dataset covering the period 2000–2024 for 31 Asia-Pacific countries. The selection of countries is based on structural and representational considerations reflecting the diverse economic, trade, and environmental dynamics across the Asia-Pacific economies and their surrounding areas. The sample comprises countries with markedly different economic structures and environmental conditions, thereby enabling a more comprehensive examination of the dynamic relationships among environmental quality, economic growth, and trade (Kong et al., 2025). By incorporating countries from multiple

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sub-regions and different stages of development, this study aims to capture structural variation and cross-country heterogeneity in the relationships among environmental quality, economic growth, and trade. This approach facilitates the identification of systemic and cross-regional dynamic patterns that cannot be observed through single-country analyses. Data availability and consistency are treated as necessary technical conditions to ensure balanced panel estimation, rather than as the primary criteria for country selection. The inclusion of Armenia, Azerbaijan, the Kyrgyz Republic, Tajikistan, Turkmenistan, Uzbekistan, Lebanon, and Gulf economies is motivated by their increasing participation in Asia-Pacific trade and environmental cooperation frameworks. Their inclusion allows the analysis to capture broader regional environmental-economic linkages beyond conventional geographical classifications. The complete list of sample countries is provided in Appendix A, Table A1.

The panel VAR framework incorporates six key variables: Gross Domestic Product (GDP), Trade (TR), CO_2 Emissions (CO_2), Land Use Change (LUCE), Biocapacity (BIO), and the Ecological Footprint (EFC). To address heteroscedasticity and ensure comparability across units, all variables are transformed into their natural logarithms prior to estimation (Usman et al., 2022; Gabriel & Ribeiro, 2019), except for the Land Use Change variable. Detailed descriptions of the variables, including their definitions, units of measurement, and data sources, are provided in Table 1. Descriptive statistics are reported in the original measurement units prior to logarithmic transformation. The logarithmic transformation was subsequently applied during the estimation stage of the VAR model to reduce heteroscedasticity, improve comparability across variables, and mitigate the influence of extreme observations.

2.2. Methods

In this study, we employ a Vector Autoregressive (VAR) framework to control for country-specific fixed effects when analyzing the dynamic interactions among Gross Domestic Product (GDP), Trade (TR), CO_2 Emissions (CO_2), Land Use Change (LUCE), Biocapacity (BIO), and the Ecological Footprint (EFC) across 31 Asia-Pacific countries over the period 2000–2024. The VAR approach offers a flexible structure that allows all variables to be treated as endogenous, making it particularly suitable for capturing the complex feedback mechanisms that characterize environmental and economic systems.

The methodological procedures follow a structured sequence of estimation steps, consistent with best practices for dynamic panel analysis and transformations expressed in natural logarithmic growth rates. The VAR methodology has been widely used in empirical studies examining policy transmission and macro-environmental linkages, as it integrates the strengths of both traditional VAR models and panel data techniques. As a VAR-type model, it effectively addresses potential endogeneity issues, while the panel dimension enhances estimation efficiency

Table 1. Variables used

Variable	Measurement	Source
Gross Domestic Product (GDP)	Gross Domestic Product (GDP) Total (Constant 2015 US$, annual GDP)	World Development Indicators, World Bank
Trade (TR)	The total value of trade, as a share of GDP or total trade volume (% of GDP)	World Development Indicators, World Bank
CO_2 Emissions (CO_2)	Total carbon dioxide emissions from fuel combustion and other anthropogenic activities (Metric tons per capita)	Global Carbon Budget
Land Use Change (LUCE)	Changes in land cover or land use categories, measured as annual land conversion or land-use indicators (hectares)	Global Carbon Budget
Biocapacity (BIO)	The capacity of ecosystems to regenerate biological resources and absorb waste materials, measured in global hectares (GHA)	Global Footprint Network
Ecological Footprint (EFC)	The total ecological footprint representing human demand on nature, expressed in global hectares per capita (GHA)	Global Footprint Network

and statistical precision (Yuan & Chen, 2015). Moreover, it facilitates the evaluation of variable interdependencies through impulse response functions (IRFs) and improves the accuracy of panel-based Granger causality tests, allowing for the identification of predictive relationships among variables.

The standard fixed-effects VAR specification can be formalized as follows:

$$Y_{i,t} = b_i + \sum_{j=1}^{m} \theta_j Y_{i,t-j} + \mu_{i,t}, \tag{1}$$

where $Y_{i,t}$ denotes an $N \cdot 1$ vector of endogenous variables, θ_j is an $N \cdot N$ matrix of autoregressive coefficients, and b_i represents country-specific fixed effects that account for unobserved heterogeneity. The index $i=1, \ldots, N$ refers to the countries, and $t=1, \ldots, T$ corresponds to the time dimension of the panel.

The VAR model is estimated using a VAR framework that accounts for bidirectional dynamic relationships, treats all variables as endogenous, and captures dynamic interdependencies among them. This approach helps mitigate endogeneity concerns arising from simultaneity and reverse causality among the variables. The estimation utilizes first-difference transformations and clustered standard errors to improve the robustness of statistical inference.

High-dimensional VAR systems often suffer from substantial reductions in degrees of freedom. However, incorporating the panel data structure mitigates this issue by expanding the number of observations, thus improving the reliability of inference and producing more stable confidence intervals for IRFs (Sims, 1980). Previous studies have noted that VAR coefficient estimates alone are often insufficient for policy interpretation (Balcilar et al., 2022). Therefore, IRFs are considered the most informative and robust tool for evaluating dynamic responses among environmental and economic variables.

To investigate the dynamic interactions among economic growth, trade, CO_2 emissions, land-use change, biocapacity, and ecological footprint, this study employs the VAR-based Granger causality framework. The causality tests are conducted after confirming the stationarity properties of the variables and estimating the VAR system. This procedure allows the identification of predictive relationships among economic and environmental indicators within the dynamic panel framework.

Following the procedure proposed in prior VAR literature, the Granger causality equations can be expressed as (Hartwig, 2010):

$$X_{i,t} = \alpha_0 + \sum_{j=1}^{m} \alpha_{1,j} Y_{i,t-j} + \sum_{j=1}^{m} \alpha_{2,j} X_{i,t-j} + \tau_i + u_{i,t}, \tag{2}$$

$$Y_{i,t} = \delta_0 + \sum_{j=1}^{m} \delta_{1,j} X_{i,t-j} + \sum_{j=1}^{m} \delta_{2,j} Y_{i,t-j} + \eta_i + n_{i,t}, \tag{3}$$

where m denotes the selected lag order, $u_{i,t}$ and $n_{i,t}$ are disturbance terms assumed to follow white-noise properties, and τ_i and η_i capture the country-specific fixed effects. The indices i and t refer respectively to the cross-sectional units and the time period.

In this setup, the differenced form of variable Y is said to Granger-cause variable X if the lagged terms of Y significantly improve the prediction of X. Conversely, if lagged values of X provide statistically significant information about Y, then X Granger-causes Y. The null hypotheses for the panel VAR Granger causality tests are stated as follows:

$$H_0 : \alpha_{2,1} = \alpha_{2,2} = \cdots = \alpha_{2,m} = 0; \tag{4}$$

$$H_0 : \delta_{2,1} = \delta_{2,2} = \cdots = \delta_{2,m} = 0. \tag{5}$$

These hypotheses are evaluated using a chi-square (χ^2) statistic to determine whether the excluded variables exert predictive power in the corresponding VAR equations.

The empirical framework employed in this study is theoretically grounded in the multidirectional interactions among environmental quality, econom-

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ic growth, and trade activity. Existing theories in environmental economics and international trade suggest that economic expansion and trade liberalization may intensify environmental degradation through increased industrial production, energy consumption, and resource extraction. At the same time, environmental degradation may also affect economic and trade performance by reducing ecological capacity, increasing production costs, disrupting supply chains, and weakening long-run productivity. These reciprocal interactions imply that the relationships among the variables are inherently endogenous and dynamically interdependent rather than unidirectional.

Based on this theoretical foundation, the VAR framework is considered appropriate because it allows all variables to be treated as endogenous within an integrated dynamic system. Unlike conventional single-equation approaches, the VAR methodology captures both short-run adjustments and long-run feedback mechanisms among GDP, trade, CO_2 emissions, land-use change, biocapacity, and ecological footprint. The inclusion of lagged structures further reflects the assumption that current economic and environmental conditions are influenced by their historical trajectories and past shocks. Consequently, the estimated system enables the analysis of how environmental pressures propagate through economic and trade channels over time while simultaneously accounting for bidirectional dynamic relationships.

The hypotheses examined in this study are derived from the expectation that significant dynamic relationships exist among economic growth, trade openness, and environmental indicators across the sampled Asian and Pacific economies. Specifically, the study posits that: (i) economic growth and trade are associated with changes in environmental degradation and ecological capacity; (ii) environmental conditions are linked to variations in economic and trade performance through dynamic feedback mechanisms; and (iii) these relationships evolve over time through lagged interactions among the variables. By employing a VAR framework, this study seeks to investigate these dynamic interdependencies and adjustment processes within the regional environmental–economic system while accounting for the endogenous nature of the variables in a multivariate setting.

3. RESULTS

Table 2 reports the descriptive statistics for the variables examined in this study. The results indicate that, in terms of levels, GDP and ecological footprint exhibit the highest mean values, reflecting their large economic magnitudes, while land use change and trade display comparatively lower averages. Biocapacity also records a sizable mean, although still far below that of GDP and ecological footprint. Conversely, the minimum values for land use change and CO_2 suggest substantial variability across countries and over time. Regarding dispersion, the standard deviations and variances are relatively high for GDP, CO_2, and ecological footprint, implying considerable heterogeneity in economic size and emission patterns within the Asia-Pacific economies. In contrast, trade and land use change demonstrate more moderate variability, although not negligible.

The skewness coefficients indicate that all variables are positively skewed, with GDP, CO_2, land use change, and ecological footprint showing particularly high skewness, suggesting long right tails and the presence of extreme positive observations. Kurtosis values for all variables exceed the benchmark value of 3, confirming that the distributions are leptokurtic with heavy tails. The exceptionally high kurtosis for GDP, CO_2, land use change, and ecological footprint further supports the presence of outliers and thick-tailed distributions.

The descriptive properties highlight significant non-normality and cross-country heterogeneity in the dataset. These characteristics justify the use of logarithmic transformations and panel econometric techniques, as such approaches help stabilize variance, mitigate the influence of extreme values, and improve the overall goodness-of-fit of the empirical model.

Table 3 highlights several important dynamic causal relationship patterns among the variables examined in this study. Economic activity shows positive relationships with key environmental indicators, suggesting that higher levels of growth tend to coincide with increased environmental pressure as well as greater ecological capacity. Trade, however, exhibits predominantly negative associations with both economic and environmen-

Table 2. Descriptive statistics

Statistic	GDP	TR	CO2	LUCE	BIO	ECF
Mean	$7.20759e^{11}$	89.4926643	134.298019	12.2726474	84518403.49	125767052.4
Std. Dev	$2.03301e^{12}$	62.2762532	436.310659	44.9714917	191844575.2	318630995.5
Variance	$4{,}13314e^{24}$	3878.33172	190366.991	2022.43506	$3.68043e^{16}$	$1.01526e^{17}$
Skewness	5.4587843	2.74761489	5.411863946	5.00613234	3.605417503	3.371894193
Kurtosis	34.832179	9.97643232	30.464408	32.8958486	13.56042247	9.970124217
Minimum	72741746.6	18.1256307	0,10831633	-99,1628	98263.23284	596863
Maximum	$1.84881e^{13}$	437.326714	3353.99474	466.64473	1050103135	1450935791
Obs.	775	775	775	775	775	775

Table 3. Correlation matrix

Variable	GDP	TR	CO2	LUCE	BIO	ECF
GDP	1.00000					
TR	–0.347679	1.00000				
CO2	0.441755	–0.320974	1.00000			
LUCE	0.184127	–0.070477	0.191199	1.000000		
BIO	0.437021	–0.519758	0.486814	0.316277	1.00000	
ECF	0.411810	–0.435714	0.260646	0.260646	0.575348	1.00000

tal variables, indicating that more open economies in the region are generally linked to lower levels of environmental intensity. Environmental indicators such as CO2 emissions, land-use change, biocapacity, and ecological footprint demonstrate mutually reinforcing relationships, reflecting their interconnected roles within the regional ecological system. The correlation structure reveals complex and heterogeneous linkages among economic, trade, and environmental dimensions, underscoring the importance of employing a dynamic panel VAR framework to capture their dynamic interrelationships.

Based on Table 4, the CIPS panel unit-root test results account for the heterogeneity and cross-sectional dependence characterizing the sampled Asian and Pacific economies. The findings indicate that most variables are non-stationary at their levels, although trade exhibits weak stationarity under the specification including a constant and trend at the 10% significance level. Overall, the results suggest that GDP, trade, CO2 emissions, land-use change, biocapacity, and ecological footprint are non-stationary in their level form but become stationary after first differencing. Under both specifications, with a constant only and with a constant and trend, the null hypothesis of a unit root cannot generally be rejected at levels but is strongly rejected after first differencing for all variables. These findings confirm that all variables are integrated of order one, I(1). The results therefore support the use of a differenced panel VAR framework to examine the dynamic relationships among economic growth, trade, and environmental indicators while reducing the risk of spurious regression.

Table 5 presents the VAR process stability results. VAR stability results reveal that the modulus (M) and the eigenvalues (E), that is, the absolute value of the root of the (VAR process feature) equation,

Table 4. CIPS panel unit-root tests

Variable	At Level		First Difference	
	Constant	Constant and trend	Constant	Constant and trend
GDP	–0.62711	1.35410	–8.70419***	–8.76346***
TR	–1.10097	–2.10146*	–4.0640***	–7.1168***
CO2	0.97073	0.02306	–12.670***	–11.1056***
LUCE	–1.12999	–1.92519	–14.6499***	–11.4282***
BIO	–0.96186	0.54055	–14.0650***	–12.6708***
ECF	1.25513	0.07959	–13.4483***	–11.3367***

Note: ***, **, and * indicate rejection of the null hypotheses at the 1%, 5%, and 10% level of significance, respectively.

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are less than one (M < 1) and (E < 1). The results indicate that both the eigenvalues and their moduli, representing the absolute values of the characteristic roots of the VAR system, are all below one. This finding confirms the stationarity of the panel variables included in the analysis as well as the overall stability of the VAR framework. It is important to note that, due to the inherent properties of VAR-type models, direct interpretation of the estimated coefficients may have limited explanatory value, with more meaningful insights obtained through impulse response and causality analyses.

Table 5. VAR stability test

Eigenvalue	Modulus
0.998071	0.998071
0.990144	0.990148
0.984873	0.984873
0.970646	0.970645
0.960630	0.960630
0.473956	0.473956
0.373461	0.373461
0.111039	0.115480
0.096638	0.096638
0.010649	0.010649

Note: All eigenvalues lie within the unit circle, confirming that the VAR model satisfies the stability condition.

The estimates reported in Table 6 reveal substantial dynamic interactions among economic growth, trade, environmental quality, land-use change, biocapacity, and ecological footprint. Economic growth exhibits strong persistence, as both the first and second lags of GDP significantly affect current GDP. The positive coefficient of GDP_{t-1} and the negative coefficient of GDP_{t-2} indicate a dynamic adjustment process in which economic growth follows a partially self-correcting pattern over time. Lagged GDP also exerts significant effects on CO_2 emissions and biocapacity, suggesting that changes in economic activity generate both environmental pressures and ecological responses across subsequent periods.

Trade displays a pronounced autoregressive structure. The first lag of trade positively affects current trade, whereas the second lag exerts a negative influence, indicating short-run persistence followed by adjustment effects. In addition, trade responds significantly to lagged GDP, confirming the close linkage between economic performance and trade activity. The results further indicate that trade is influenced by ecological variables, particularly land-use change and ecological footprint, highlighting the interaction between environmental conditions and economic exchange.

The CO_2 emission equation demonstrates strong temporal dependence. Past emissions significantly influence current emissions, while lagged GDP and trade also contribute to emission dynamics. The positive impact of GDP_{t-1} on emissions supports the view that economic expansion increases environmental pressure, whereas the negative coefficient of GDP_{t-2} suggests subsequent adjustment effects. These findings indicate that environmental degradation evolves through cumulative and dynamic processes rather than through immediate responses alone.

Land-use change exhibits substantial persistence, particularly through its own lagged values, with both $LUCE_{t-1}$ and $LUCE_{t-2}$ significantly affecting current land-use change. Moreover, lagged trade and ecological footprint significantly influence land-use dynamics, suggesting that economic activity and ecological demand contribute to changes in land utilization patterns over time.

Biocapacity is characterized by strong autoregressive behavior, as evidenced by the highly significant coefficient of BIO_{t-1}. The results also show that GDP, CO_2 emissions, land-use change, and ecological footprint exert significant lagged effects on biocapacity, indicating that ecological capacity adjusts gradually in response to both economic expansion and environmental pressures. This finding underscores the sensitivity of ecological resources to long-term socioeconomic and environmental changes.

Similarly, ecological footprint exhibits considerable persistence, with ECF_{t-1} strongly and positively influencing current ecological footprint. Several environmental variables, including land-use change and biocapacity, also significantly affect ecological footprint dynamics. The presence of significant own-lag and cross-lag effects across multiple equations confirms the existence of interconnected feedback mechanisms among economic activity, environmental degradation, ecological capacity, and ecological demand. The results support the suitability of the VAR framework for capturing the multidirectional and dynamic rela-

Table 6. Vector autoregression estimates

Variables	GDP_t	$Trade_t$	$CO2_t$	$LUCE_t$	BIO_t	ECF_t
GDP_{t-1}	1.441145*** (0.03499) [41.1862]	−0.282406** (0.10227) [−2.76141]	0.172234* (0.08838) [1.94871]	−5.774993 (15.5944) [−0.37033]	0.480027 (0.09479) [0.50664]	0.238248 (0.14296) [1.66651]
GDP_{t-2}	−0.450898*** (0.03449) [−13.0725]	0.272648*** (0.10081) [2.70452]	−0.169416* (0.08712) [−1.94454]	6.444833 (15.3721) [0.41926]	−0.47305 (0.09344) [−0.50675]	−0.235562 (0.14092) [−1.67155]
Tr_{t-1}	−0.004936 (0.01280) [−0.38569]	1.117919*** (0.03741) [29.8863]	−0.010980 (0.03233) [−0.33966]	15.79358*** (5.70378) [2.76897]	−0.009723 (0.03467) [−0.28043]	−0.054702 (−1.04613) [−1.04613]
T_{t-2}	0.006935 (0.01269) [0.54636]	−0.149109*** (0.03710) [−4.01930]	0.020210 (0.03206) [0.63025]	−14.39448** (5.65689) [−2.54460]	0.003320 (0.03439) [0.09656]	0.050850 (0.05186) [0.98054]
$CO2_{t-1}$	0.033100** (0.01599) [2.06946]	0.066449 (0.04675) [1.42145]	1.090705*** (0.04040) [26.9974]	−5.058810 (7.12824) [−0.70969]	0.056370 (0.04333) [−1.30092]	−0.015371 (0.06535) [−0.23522]
$CO2_{t-2}$	−0.026955 (0.01589) [−1.69617]	−0.059421 (0.04645) [−1.27934]	−0.099624** (0.04014) [−2.48189]	4.389884 (7.08236) [0.61983]	0.051928 (0.04305) [1.20616]	0.017237 (0.06493) [0.26547]
$LUCE_{t-1}$	$-2.59e^{-05}$ ($7.8e^{-05}$) [−0.33426]	−0.000368 (0.00023) [1.57201]	0.000142 (0.00020) [0.72240]	0.569815*** (0.03458) [16.4775]	−0.000649*** (0.00021) [−3.08837]	−0.000928** (0.00032) [−2.92807]
$LUCE_{t-2}$	$3.98e^{-05}$ ($7.8e^{-05}$) [0.51060]	0.000358 (0.00023) [1.57201]	−0.000108 (0.00020) [−0.54866]	0.390070*** (0.03476) [11.2208]	0.000630*** (0.00021) [2.98107]	0.000894** (0.00032) [2.80373]
BIO_{t-1}	0.006165 (0.02362) [0.26103]	−0.079376 (0.06903) [−1.14980]	0.020111 (0.05966) [0.33709]	−0.636309 (10.5267) [−0.06045]	0.918422*** (0.06399) [14.3527]	0.050015 (0.08650) [0.51827]
BIO_{t-2}	−0.006328 (0.02358) [−0.26838]	0.072288 (0.06892) [1.04890]	−0.014274 (0.05956) [−0.23966]	1.198769 (10.5089) [0.11407]	0.079048 (0.06388) [1.17282]	−0.047857 (0.09650) [−0.49674]
ECF_{t-1}	−0.001380 (0.01589) [−0.08686]	0.040659 (0.04644) [0.87551]	−0.004155 (0.04014) [−0.10354]	6.228804 (7.08148) [0.87959]	0.050486 (0.04305) [1.17282]	0.971787*** (0.06492) (14.9690)
ECF_{t-2}	0.004888 (0.01579) [0.30962]	−0.035681 (0.04614) [−0.77328]	0.002685 (0.03988) [0.06732]	−6.851028 (7.03594) [−0.96372]	−0.046798 (0.04277) [−1.09419]	−0.015532 (0.06450) [0.24079]
Countries				31		
Observations				713		
Lag Order				2		

Note: ***, **, and * denote significance levels at 1%, 5%, and 10%, respectively. Standard errors are reported in parentheses and t-statistics in brackets. All variables are expressed in logarithmic growth rates.

tionships among the variables in the Asia-Pacific economies included in the sample.

The results presented in Table 7 summarize the Granger causality tests within the panel VAR framework, which examine whether past values of one variable provide useful information for predicting changes in another variable within the dynamic system. Significant chi-square statistics indicate the presence of statistically meaningful predictive relationships, suggesting that the variables are dynamically interconnected rather than evolving independently over time. Several relationships are significant at conventional significance levels, highlighting temporal linkages among economic growth, trade activity, environmental quality, and ecological indicators.

Furthermore, the "All χ^2-Stat" column shows that the explanatory variables are jointly significant in each equation. This result indicates that the variables operate within an integrated dynamic framework in which developments in one dimension are associated with subsequent changes in other dimensions of the system. The Granger causality results support the suitability of the panel VAR framework for examining the dynamic interrelationships among economic, trade, environmental, and ecological variables, providing additional evidence of the temporal dependencies embedded in the dataset.

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Table 7. VAR granger causality test results

Dependent Variable	GDP_t	$Trade_t$	$CO2_t$	$LUCE_t$	BIO_t	ECF_t	*All* χ^2*–Stat*
GDP_t	...	8.23262***	5.79746*	7.15019**	2.570180	2.794578	22.32861***
$Trade_t$	5.712737**	...	1.851040	8.11294**	0.691235	2.122566	18.83339***
$CO2_t$	11.34951***	2.960550	...	2.895148	2.080359	1.114114	16.05487***
$LUCE_t$	3.369467	2.681522	6.599552**	...	9.58565***	8.66859***	21.58890***
BIO_t	1.08721	4.431431*	5.087129*	1.917632	...	1.404347	23.68220***
ECF_t	2.127952	1.123570	6.062526**	6.23676**	1.552725	...	22.81998***

Note: χ2 statistics are reported for Wald tests of Granger causality. ***, **, and * denote significance levels at the 1%, 5%, and 10% levels, respectively. The last column reports the joint significance of all explanatory variables in each equation.

Figures 1–6 present the impulse response functions (IRFs) describing the dynamic responses of the variables to one-standard-deviation shocks within the panel VAR system. The IRFs provide information on the direction, magnitude, and persistence of the responses over a ten-period forecast horizon.

Figure 1 illustrates the responses of GDP to shocks originating from the other variables in the system. The results indicate that GDP responds immediately to external disturbances, with the magnitude of the response varying across different shocks. In most cases, the responses are strongest during the initial periods and gradually decline over subsequent horizons. The confidence intervals suggest that the effects are concentrated in the short to medium term, while the responses tend to converge toward zero as the forecast horizon increases.

Figure 2 presents the responses of trade following shocks to the economic and environmental variables. Trade exhibits noticeable short-run reactions, particularly during the early periods after the shock. The magnitude of the responses gradually diminishes over time, indicating that the effects of the disturbances become weaker as the forecast horizon progresses. Overall, the results suggest that trade dynamics are influenced by both economic and environmental developments within the system.

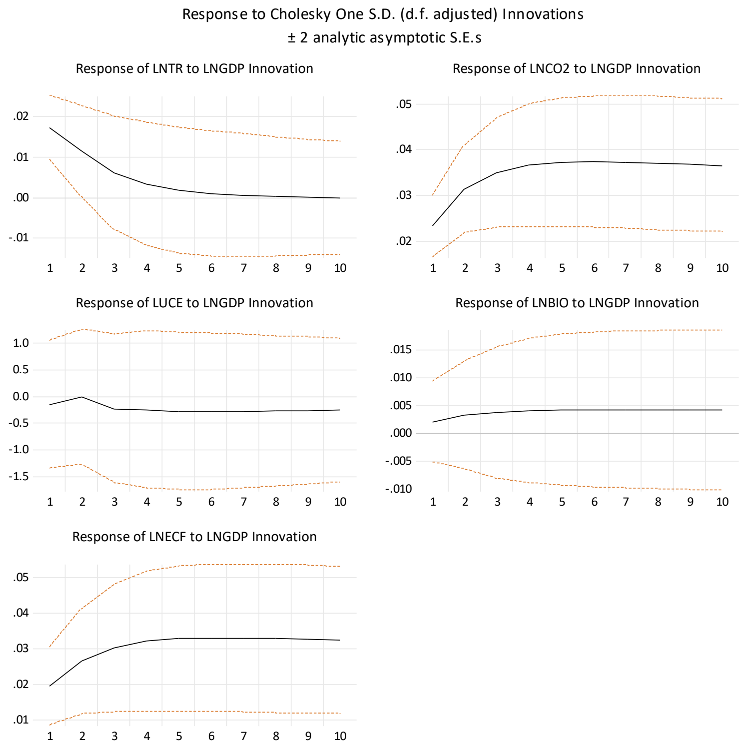

Figure 1. Response of Gross Domestic Product (GDP)

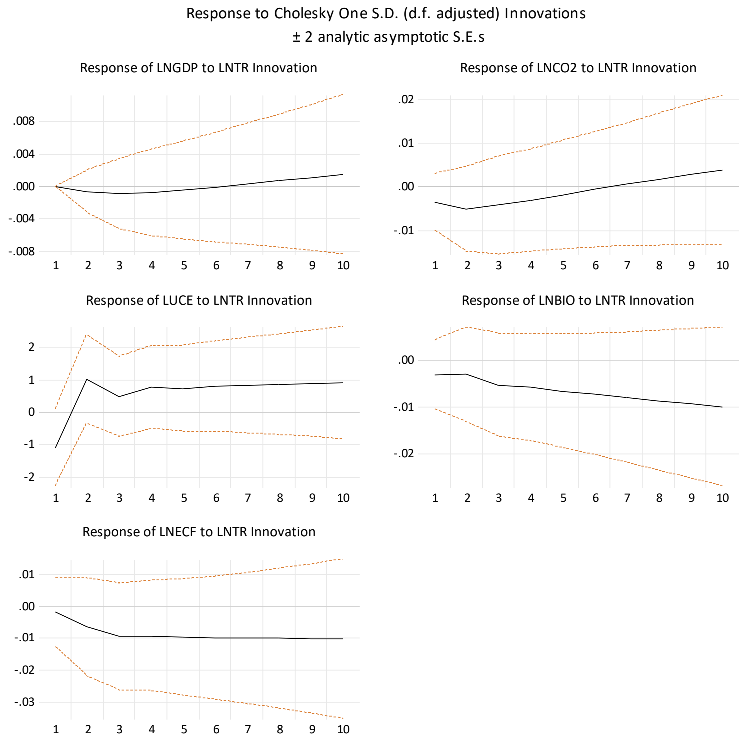

Figure 2. Response of trade (TR)

Figure 3 reports the impulse responses of CO_2 emissions. The results show that emissions respond to shocks from economic growth, trade, and ecological indicators, with the strongest adjustments generally occurring during the initial periods. The responses gradually decline over time, indicating that the effects of the shocks are not permanent. The confidence intervals narrow

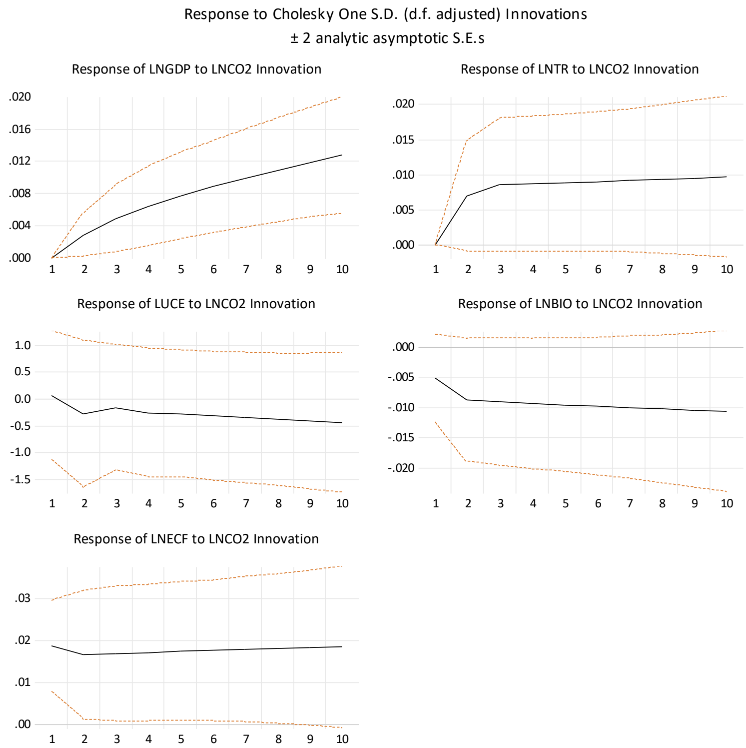

Figure 3. Response of CO2 emissions (CO2)

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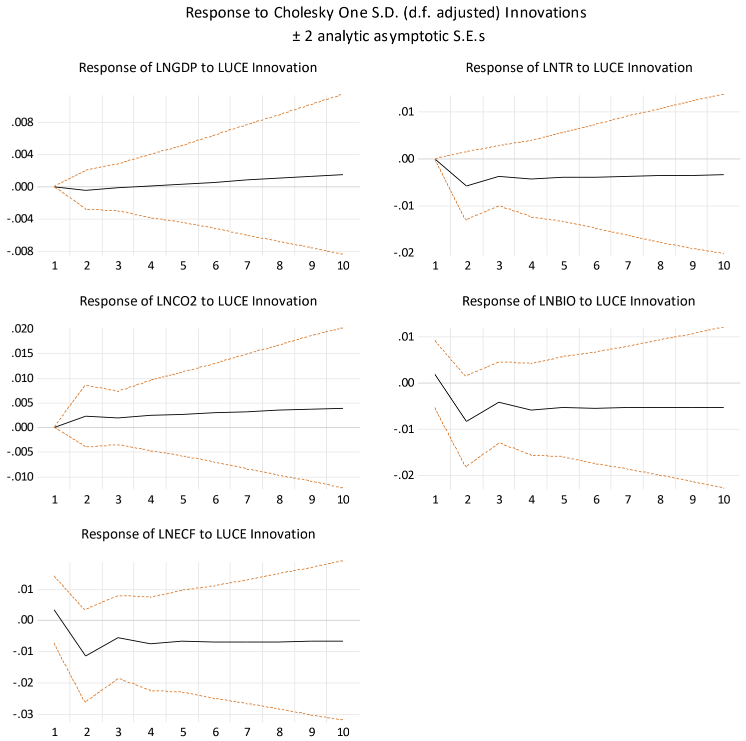

Figure 4. Response of land use change (LUCE)

as the horizon increases, suggesting a reduction in uncertainty surrounding the estimated responses.

Figure 4 displays the responses of land-use change (LUCE) to shocks within the system. The results indicate that LUCE reacts immediately following external disturbances and exhibits varying response patterns depending on the source of the shock. The magnitude of the responses generally decreases over time, suggesting that the effects

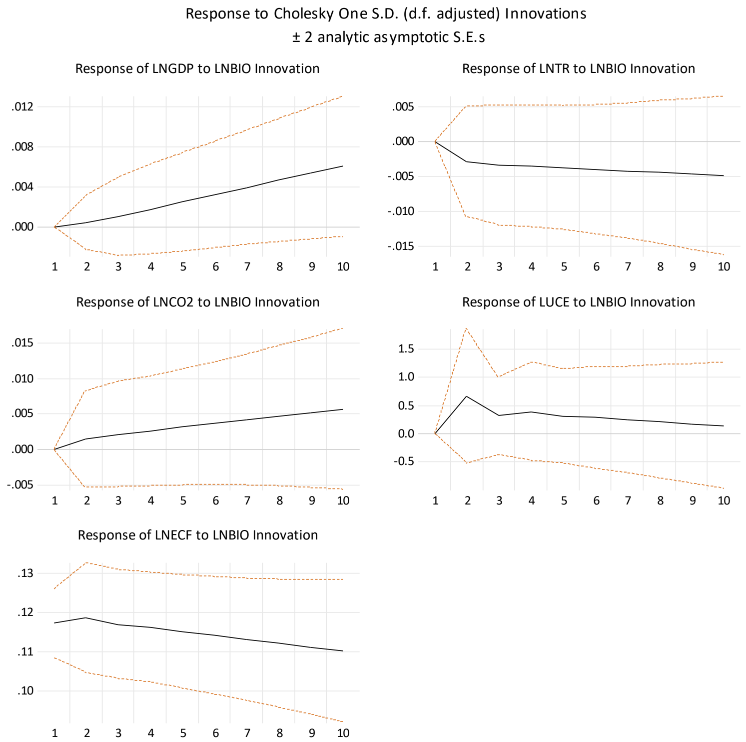

Figure 5. Response of biocapacity (BIO)

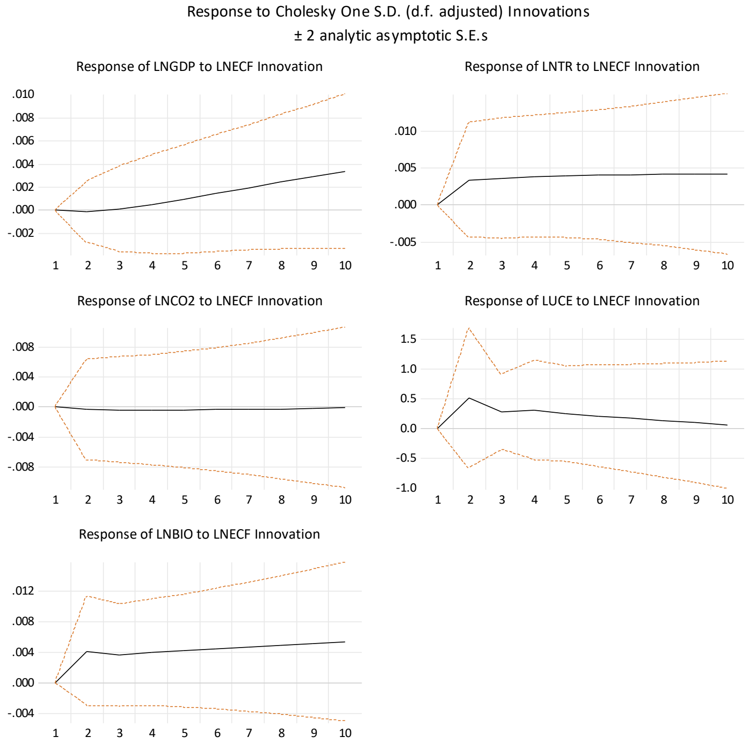

Figure 6. Response of ecological footprint (ECF)

of the shocks become less pronounced at longer horizons.

Figure 5 presents the impulse responses of biocapacity. The results show that biocapacity is sensitive to shocks originating from both economic and environmental variables. The strongest responses occur during the early forecast periods, after which the effects gradually weaken. This pattern suggests that biocapacity adjusts dynamically to changes within the broader economic–environmental system.

Figure 6 illustrates the responses of ecological footprint (ECF). Similar to the other variables, ECF exhibits immediate reactions following shocks and subsequently displays a gradual reduction in response magnitude over time. The results indicate that ecological demand is dynamically linked with economic activity, environmental pressures, and ecological capacity within the system.

Overall, the impulse response functions indicate that economic growth, trade, CO_2 emissions, land-use change, biocapacity, and ecological footprint are dynamically interconnected. The responses are generally strongest during the early periods following a shock and tend to diminish as the forecast horizon increases, highlighting the presence of short- and medium-term dynamic interactions among the variables.

Table 8 reports selected impulse response values to facilitate interpretation of the magnitude and persistence of several key dynamic relationships identified in the IRF analysis. The results indicate that positive shocks to CO_2 emissions generate positive responses in GDP throughout the forecast horizon, increasing from 0.0233 in the first period to 0.0372 in period five before moderating to 0.0128 by period ten. Similarly, positive shocks to biocapacity and ecological footprint produce positive GDP responses across all selected horizons, although the magnitudes remain relatively modest.

The results further show that a positive shock to GDP initially increases trade by 0.0173 in the first period. However, the magnitude of the response gradually declines over time, reaching 0.0078 in period five and becoming approximately zero by period ten. These findings suggest that the effects of economic and environmental shocks are strongest in the short run and tend to weaken over longer horizons.

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Table 8. Selected IRF values

Response	Horizon 1	Horizon 5	Horizon 10
GDP ← CO_2	0.0233	0.0372	0.0128
GDP ← BIO	0.0021	0.0042	0.0061
GDP ← ECF	0.0019	0.0033	0.0032
Trade ← GDP	0.0173	0.0078	−0.0001

Note: Values are extracted from the impulse response functions reported in Figures 1, 3, 5, and 6. The selected horizons are presented to facilitate interpretation of the magnitude and persistence of the dynamic responses.

4. DISCUSSION

4.1. Dynamic relationships between economic growth and environmental quality

The empirical results indicate that economic growth and environmental quality are dynamically interconnected across the sampled Asian and Pacific economies. The VAR estimates reveal that lagged GDP significantly affects several environmental indicators, particularly CO_2 emissions and biocapacity, while environmental variables themselves display strong persistence through their own lagged structures. These findings suggest that economic and environmental conditions evolve jointly over time and cannot be adequately examined as independent processes.

The estimated coefficients further indicate that GDP exhibits substantial autoregressive behavior, reflecting the persistence commonly observed in macroeconomic systems. At the same time, environmental indicators such as CO_2 emissions, biocapacity, and ecological footprint also demonstrate significant dependence on their historical values. This pattern implies that environmental conditions are shaped not only by current economic activity but also by accumulated historical developments and past environmental pressures.

The impulse response functions provide additional evidence of these dynamic interactions. Positive shocks to CO_2 emissions generate positive responses in GDP over several forecast horizons, while shocks to biocapacity and ecological footprint also produce measurable GDP responses. Although the magnitudes differ across indicators, the results suggest that environmental conditions and economic performance remain closely associated within the regional system.

These findings are broadly consistent with previous studies emphasizing the close relationship between environmental quality and economic performance. Barati et al. (2023) and Barbier (2022) argue that environmental conditions increasingly influence economic development through resource availability, production efficiency, and environmental constraints. Similarly, Lawrance et al. (2022) and Leddin (2024) highlight the growing importance of ecological systems in supporting long-run economic activity.

However, the present findings extend the existing literature by demonstrating that these relationships operate within a dynamic multivariate framework rather than through isolated bivariate associations. While many previous studies have focused primarily on the impact of economic growth on environmental degradation, the current results suggest that environmental indicators are also associated with subsequent economic developments, highlighting dynamic feedback mechanisms within the regional economy.

Overall, the findings indicate that economic growth and environmental quality are embedded within an interconnected system characterized by persistence and temporal dependence. The results reinforce the importance of incorporating environmental considerations into economic analyses and support the view that environmental conditions represent an integral component of long-run development processes.

4.2. Trade and environmental interactions

The results also reveal important dynamic relationships between trade activity and environmental indicators. The VAR estimates indicate that trade is influenced by its own historical values as well as by lagged movements in economic and environmental variables. This finding suggests that trade dynamics are shaped not only by market conditions but also by broader environmental and ecological developments occurring within the regional system.

The estimated coefficients show that trade exhibits a strong autoregressive structure, indicating substantial persistence over time. In addition, several environmental indicators, particularly land-use change and ecological footprint, display significant associations with trade dynamics. These findings imply that changes in environmental conditions may be accompanied by subsequent adjustments in trade activity, reflecting the interconnected nature of production, resource utilization, and international exchange.

The impulse response analysis provides further support for these relationships. Trade responds positively to economic shocks during the initial forecast periods, although the magnitude of the response gradually diminishes over time. Similar adjustment patterns are observed following shocks to environmental indicators, suggesting that the effects of environmental disturbances on trade are not instantaneous but unfold progressively across multiple periods.

These findings are consistent with previous studies examining the trade–environment nexus. An (2024), Cao et al. (2025), and Sun et al. (2025) argue that trade and environmental outcomes are closely connected through production structures, energy consumption, and resource utilization. Likewise, Yingjun et al. (2024) and Liu et al. (2025) suggest that trade expansion may simultaneously generate environmental pressures through scale effects while facilitating environmental improvements through technology diffusion and efficiency gains.

The present results support the view that trade and environmental conditions should be considered jointly rather than separately. The observed dynamic interactions suggest that environmental developments may influence trade performance, while trade activity may also be associated with subsequent environmental changes. Such findings highlight the complexity of the trade–environment relationship and suggest that its effects cannot be fully understood through static analytical approaches.

Taken together, the results indicate that trade constitutes an important transmission channel linking economic and environmental processes within the sampled economies. The persistence of these relationships across several forecast horizons highlights the importance of considering environmental conditions when evaluating long-run trade dynamics and regional economic development.

4.3. Dynamic environmental adjustments and system interdependencies

The responses of land-use change, biocapacity, and ecological footprint reveal substantial environmental persistence and gradual adjustment processes within the regional system. The impulse response functions indicate that environmental indicators react immediately following shocks but generally display declining response magnitudes as the forecast horizon increases. This pattern suggests that environmental conditions adjust progressively rather than instantaneously to changes occurring elsewhere in the economic–environmental system.

The VAR estimates further demonstrate that environmental variables are characterized by strong autoregressive behavior. In particular, biocapacity and ecological footprint display significant dependence on their own lagged values, indicating that current ecological conditions are strongly influenced by previous states of the system. Such persistence is consistent with the long-term nature of ecological processes, where environmental changes often accumulate gradually over time.

The Granger causality results provide additional evidence of dynamic interdependencies among economic growth, trade, and environmental indicators. Several statistically significant predictive relationships are identified across the equations, suggesting that historical movements in one variable contribute useful information for understanding future developments in others. The joint significance tests further indicate that the variables operate within an integrated framework rather than evolving independently.

These findings are consistent with previous methodological and empirical studies emphasizing the importance of dynamic approaches in environmental-economic analysis. Saidi (2025), Wu et al. (2015) and Ullah et al. (2018) argue that environmental and economic variables are inherently

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interconnected and should be analyzed within systems capable of capturing temporal dependencies and feedback processes. The present results provide additional support for this perspective by demonstrating the presence of significant lagged relationships across multiple dimensions of the regional system.

The findings also contribute to the broader sustainable development literature. Rather than treating environmental quality as a passive outcome of economic activity, the results suggest that environmental indicators are dynamically associated with subsequent economic and trade developments. This observation is consistent with arguments advanced by Acheampong and Opoku (2023) and Shapiro (2025), who emphasize the growing role of environmental conditions in shaping broader development outcomes.

Overall, the empirical evidence indicates that economic growth, trade activity, environmental quality, and ecological capacity form a dynamically interconnected system characterized by persistence, adjustment processes, and temporal dependencies. Although the analysis does not establish structural causality, it provides robust evidence of significant dynamic relationships among the variables and highlights the importance of considering environmental and economic dimensions simultaneously when examining long-run development processes.

CONCLUSION

This study examines the dynamic relationships among environmental quality, economic growth, and trade across a sample of Asia-Pacific economies during the period 2000–2024. Using a Vector Autoregression (VAR) framework, the analysis investigates how economic and environmental variables evolve over time through lagged interactions and dynamic feedback mechanisms. The empirical results indicate significant dynamic interrelationships among GDP, trade, CO_2 emissions, land-use change, biocapacity, and ecological footprint, suggesting that economic and environmental processes are closely interconnected within the regional system.

The estimated VAR coefficients reveal substantial persistence across both economic and environmental variables. Several variables exhibit significant autoregressive behavior, indicating that current outcomes are influenced by previous developments and that adjustment processes occur gradually over time. The results further show that lagged economic conditions are associated with subsequent changes in environmental indicators, while environmental variables also display statistically significant relationships with future economic and trade developments. These findings suggest the existence of important temporal dependencies within the environmental–economic system.

The impulse response analysis provides additional evidence regarding the dynamic interactions among the variables. Shocks originating from environmental indicators generate measurable responses in GDP and trade, while economic disturbances are also associated with subsequent changes in environmental conditions. Although the magnitude and persistence of these responses vary across variables, the overall pattern indicates that economic activity, trade, environmental pressures, and ecological capacity evolve within an integrated dynamic framework. The impulse response functions further show that most responses are strongest during the initial periods following a shock and gradually diminish over longer horizons.

The Granger causality results complement these findings by identifying several statistically significant predictive relationships among the variables. The joint significance tests indicate that economic, trade, and environmental indicators contribute useful information for explaining subsequent movements within the system. Collectively, the VAR estimates, impulse response functions, and Granger causality analysis provide evidence that the variables are dynamically interconnected rather than evolving independently over time.

From a policy perspective, the findings suggest that environmental considerations should be incorporated into broader economic and trade policy frameworks. The observed dynamic relationships imply that environmental conditions and economic performance are closely linked, highlighting the importance of promoting cleaner production processes, improving resource efficiency, strengthening ecosystem management, and encouraging environmentally sustainable trade practices. Integrating environmental and economic objectives may contribute to more balanced and sustainable development outcomes across the region.

Several avenues for future research remain open. Future studies may incorporate additional variables such as institutional quality, environmental governance, renewable energy adoption, or technological innovation in order to better understand the mechanisms underlying environmental–economic interactions. Further research may also conduct country-specific or subregional analyses to explore potential heterogeneity across economies. In addition, alternative dynamic modeling approaches and complementary analytical techniques may provide further insights into the complexity of environmental, economic, and trade relationships.

Overall, this study provides empirical evidence of significant dynamic relationships among environmental quality, economic growth, and trade across the sampled Asia-Pacific economies. By applying a panel VAR framework, the study contributes to the growing literature on environmental–economic interactions and highlights the importance of considering economic and environmental dimensions jointly when evaluating long-term development processes.

AUTHOR CONTRIBUTIONS

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Supervision: Nur Dwiana Sari Saudi.
Validation: Nur Dwiana Sari Saudi, Muhammad Ashary Anshar.
Visualization: Muhammad Ashary Anshar.
Writing – original draft: Nur Dwiana Sari Saudi, Abd. Rahman Razak, Muhammad Ashary Anshar.
Writing – review & editing: Nur Dwiana Sari Saudi, Abd. Rahman Razak, Nurul Badriyah.

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APPENDIX A

Table A1. List of sample countries

No.	Country	No.	Country	No.	Country
1	Armenia	12	Bhutan	23	Cambodia
2	Azerbaijan	13	India	24	Indonesia
3	Kyrgyz Republic	14	Nepal	25	Malaysia
4	Tajikistan	15	Pakistan	26	Philippines
5	Turkmenistan	16	Sri Lanka	27	Singapore
6	Uzbekistan	17	Bahrain	28	Thailand
7	China	18	Kuwait	29	Viet Nam
8	Japan	19	Lebanon	30	Australia
9	Korea, Rep.	20	Oman	31	New Zealand
10	Mongolia	21	Qatar		
11	Bangladesh	22	Saudi Arabia		

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