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How Do Exports and Imports Drive Per Capita Carbon Emissions? A Spatial Panel Analysis of the Persian Gulf Region

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Abstract

This study investigates the distinct impacts of exports and imports on per capita CO_2 emissions in seven Persian Gulf countries (Iran, Qatar, Saudi Arabia, Kuwait, Bahrain, UAE, Oman) from 1995 to 2020. Recognizing that environmental pollution crosses national borders, we employ a spatial panel econometric model that captures cross-country spillover effects. Our results validate the Environmental Kuznets Curve (EKC) hypothesis: per capita GDP initially raises emissions but eventually reduces them after a turning point. More importantly, both trade flows show significant positive effects on emissions. A 1% increase in exports leads to a 0.04% rise in per capita CO_2 emissions, while a 1% increase in imports leads to a 0.10% rise. These findings indicate that trade expansion aggravates environmental degradation in this fossil-fuel-dependent region through higher industrial activity, transport, and energy use. To mitigate emissions without hindering trade, policymakers should promote cleaner production technologies, carbon-efficient trade structures, and environmentally conscious trade policies.

Keywords: Exports; Imports; Carbon emissions; Spatial model; EKC; Gulf region

Introduction

The volume of global trade has increased substantially over recent decades. Between 2005 and 2015, international trade expanded by approximately 62% [1]. Similarly, the share of international trade in global GDP rose from 23% in 1960 to nearly 58% in 2017 [2]. Within the global trade system, oil remains the dominant export commodity, accounting for approximately 5.9% of total global exports [1], and plays a pivotal role in oil-exporting economies as their economic growth is highly dependent on oil revenues [3].

The Persian Gulf region holds nearly three-quarters of the world's proven oil reserves, representing the most significant source of fossil energy globally [4]. Countries in this region—including Iran, Qatar, Saudi Arabia, Kuwait, Bahrain, Iraq, the United Arab Emirates, and Oman—collectively possess more than 804 billion barrels of oil reserves, accounting for over 54% of global proven reserves. By the end of 2017, Saudi Arabia, Iran, Iraq, Kuwait, and the United Arab Emirates held approximately 266, 155, 147, 101, and 97 billion barrels of proven reserves, respectively. Thus, global oil reserves are highly concentrated in the Persian Gulf region.

According to OPEC and the U.S. Energy Information Administration (EIA), nearly 13 billion tons of the 36 billion tons of global CO_2 emissions in 2017 were associated with oil consumption, highlighting the significant contribution of fossil fuels to global greenhouse gas emissions. Accordingly, oil-dependent economies are expected to experience higher levels of environmental degradation compared to other countries. Increasing attention to environmental sustainability and climate change mitigation has made the relationship between international trade and environmental quality a critical issue, particularly for resource-rich economies.

A large body of literature has investigated the trade–environment nexus. Tayebi et al. [5] found that trade liberalization and oil shocks reduce CO_2 emissions in both oil-exporting and importing countries. Golkhandan and Moazemi Nejad [6] reported that economic growth, population, energy consumption, and trade openness contribute to environmental degradation in MENA countries. Arefian et al. [7] showed that renewable energy consumption improves environmental quality, while non-renewable energy use increases emissions in OECD countries. Mahmood et al. [8] suggest that exports reduce CO_2 emissions, whereas imports increase them in North African countries. Essandoh et al. [9] found that trade openness reduces emissions in developed countries but increases them in developing economies. Thio et al. [10] and Nikkhah Sarnaghi et al. [11] confirm dynamic and bidirectional relationships between trade, growth, and environmental degradation. Spatial econometric evidence by Mahmood [12] and Jeetoo and Chinyanga [13] highlights significant spillover effects across countries.

Despite the extensive literature, several important gaps remain. First, most existing studies do not distinguish between the separate environmental effects of exports and imports, despite the possibility of asymmetric impacts. Second, although economic and environmental interdependencies are particularly strong in geographically connected regions, relatively few studies have incorporated spatial econometric approaches in the context of the Persian Gulf countries. Ignoring spatial dependence may lead to biased and incomplete results, as environmental pollution is inherently transboundary. Air pollution is not confined within national boundaries, and environmental degradation in one country can affect neighbors through cross-border transmission, representing a classic case of spatial externalities.

Accordingly, the main contribution of this study is threefold. First, it separately examines the effects of exports and imports on per capita CO_2 emissions, allowing for asymmetric trade–environment relationships. Second, it incorporates spatial econometric techniques to capture cross-country spillover effects. Third, it focuses specifically on the Persian Gulf region, a highly underexplored but economically and environmentally significant area characterized by intense fossil fuel dependence and strong regional interconnections. By addressing these gaps, this study provides a more comprehensive and region-specific understanding of the trade–environment nexus.

Material & Methods

The sample comprises seven Persian Gulf countries (Iran, Qatar, Saudi Arabia, Kuwait, Bahrain, UAE, Oman) over 1995–2020. Data were obtained from the World Bank database, and estimations were performed using STATA and EViews. Spatial econometric techniques are employed to account for spatial dependence and heterogeneity [14]. Spatial dependence means observations in one location are influenced by neighbors [15]:

$$y_i = F(y_j), i = 1, \dots, n, i \neq j (1)$$

A spatial weight matrix based on geographical distance was constructed using the inverse distance approach [16], giving larger weights to closer countries. Row standardization was then applied so that each row sums to one. The normalized matrix is defined as:

$$W_{ij}^{**} = \frac{w_{ij}^{*}}{\sum_{j=1}^{N} w_{ij}^{*}} (2)$$

Spatial models include SAR, SEM, SDM, and SAC. The SAC model incorporates spatial dependence in both the dependent variable and error term [17]:

$$Y = \rho W_1 Y + X\beta + u, u = \lambda W_2 u + \varepsilon, \varepsilon \sim N(0, \sigma_\varepsilon^2) (3)$$

where Y denotes the dependent variable, X represents the matrix of explanatory variables, W_1 and W_2 are spatial weight matrices, ρ is the spatial autoregressive coefficient, β is the vector of regression coefficients, and λ denotes the spatial autocorrelation coefficient in the error terms.

The Spatial Error Model (SEM) assumes spatial dependence only in the error term [18]:

$$Y = X\beta + u, u = \lambda W u + \varepsilon, \varepsilon \sim N(0, \sigma^2 I_N) (4)$$

This means no direct spatial dependence in CO_2 emissions across countries; instead, spatial correlation arises indirectly through error terms. If $\lambda = 0$, the model reduces to SAR [18]:

$$Y = \rho W Y + X\beta + \varepsilon, \varepsilon \sim N(0, \sigma^2 I_N) (5)$$

The Spatial Durbin Model (SDM) extends the SAR model by incorporating spatial lags of the explanatory variables in addition to the spatial lag of the dependent variable:

$$Y = \rho W Y + X\beta_1 + \beta_2 W X + \varepsilon, \varepsilon \sim N(0, \sigma^2 I_N) (6)$$

Moran's I statistic was used to detect spatial dependence in residuals. Rejection of the null hypothesis (no spatial effects) indicates spatial dependence, requiring Lagrange Multiplier tests. Moran's I is defined as:

$$I = \frac{N}{S}\left(\frac{e'We}{e'e}\right) (7)$$

where W is the spatial weight matrix, S is the sum of all matrix elements, and e is the OLS residual vector. The LM error test [19] examines $\lambda = 0$; rejection suggests the SEM model. The LM error statistic [20] is:

$$LM_{\text{error}} = \frac{[(e'We/e'e)/N]^2}{\text{tr}(W^2 + W'W)} (8)$$

Similarly, the LM-lag test examines the null hypothesis of no spatial lag dependence ($\rho = 0$). Rejection indicates that the SAR model should be estimated:

$$LM_{\text{lag}} = \frac{[(e'Wy/e'e)/N]^2}{D} (9)$$

where

$$D = \frac{(WX\beta)'(I - X(X'X)^{-1}X')(WX\beta)}{\sigma^2} + \text{tr}(W^2 + W'W) (10)$$

If both LM tests reject, robust versions determine the specification [18]. Conflicting results are resolved using common factor and LR tests [21]. Because OLS is biased in spatial models, Maximum Likelihood Estimation (MLE) was applied [16]. Following Elhorst's framework, the optimal model was selected using Moran's I, LR, Wald, and LM tests. The final SEM model is:

$$\ln CO_{2it} = \beta_0 + \beta_1 \ln EXPC_{it} + \beta_2 \ln IMPC_{it} + \beta_3 \ln GDPPC_{it} + \beta_4 \ln GDPPC_{it}^2 + U, U = \lambda W_2 u + \varepsilon, \varepsilon \sim N(0, \sigma^2 I_n) (11)$$

Following Mahmood et al. [8], variables are defined as: $\ln CO_{2it}$ (log of per capita CO_2 emissions), $\ln EXPC_{it}$ (log of per capita exports), $\ln IMPC_{it}$ (log of per capita imports), $\ln GDPPC_{it}$ (log of per capita GDP), and $\ln GDPPC_{it}^2$ (square) to test the EKC hypothesis.

Results and Discussion

To avoid spurious regression, the stationarity properties of the variables were first examined using the Levin–Lin–Chu (LLC) panel unit root test. According to the results reported in Table 1, the variables of exports, imports, and carbon dioxide emissions are stationary at the 10% significance level. However, GDP per capita and the square of GDP per capita become stationary after first differencing. Therefore, given the presence of non-stationary variables and the use of differencing, it is necessary to test for cointegration among the variables.

Table 1. Results of the Levin–Lin–Chu (LLC) Unit Root Test

Variable	At Level: Statistic	At Level: p-value	First Difference: Statistic	First Difference: p-value
CO_2 emissions	-1.63	0.05	–	–
Exports	-1.31	0.09	–	–
GDP per capita	-1.05	0.14	-1.48	0.06
GDP per capita squared	-1.16	0.12	-1.58	0.05
Imports	-2.28	0.01	–	–

Given the existence of non-stationary variables in the model and in order to avoid reliance on spurious regression, the existence of cointegration (a long-run equilibrium relationship) among the variables must be confirmed before estimating the model. In this study, the

Kao [22] cointegration test was employed. This test is based on the Augmented Dickey–Fuller (ADF) and Dickey–Fuller statistics, where the null hypothesis indicates the absence of cointegration and the alternative hypothesis indicates the existence of cointegration among the model variables. As shown in Table 2, the null hypothesis is rejected at the 90% confidence level, confirming the existence of a long-run relationship among the variables.

Table 2. Results of the Kao Cointegration Test

Statistic	Test Statistic	p-value
ADF	-1.49	0.06

According to the results reported in Table 3, the Moran's I, Geary's C, and LM-error statistics confirm the presence of spatial dependence in all models except the SDM model. Furthermore, the LM-lag statistic does not confirm spatial autocorrelation in the dependent variable across the estimated models. Therefore, the Spatial Error Model (SEM) was selected as the optimal specification.

Table 3. Diagnostic Tests for Spatial Dependence

Model	Moran	Geary	Walds	LR	LM-error	LM-lag	Robust LM-error	Robust LM-lag
SAR	-0.12 (0.01)	1.15 (0.00)	643.94 (0.00)	14.05 (0.00)	5.77 (0.01)	0.03 (0.85)	5.74 (0.01)	0.001 (0.97)
SEM	-0.12 (0.01)	1.15 (0.00)	648.70 (0.00)	15.07 (0.00)	5.77 (0.01)	0.03 (0.85)	5.74 (0.01)	0.001 (0.97)
SDM	-0.05 (0.36)	1.06 (0.21)	1352.27 (0.00)	10.29 (0.00)	0.92 (0.33)	0.003 (0.95)	0.91 (0.33)	0.001 (0.97)
SAC	-0.12 (0.01)	1.15 (0.00)	651.60 (0.00)	16.94 (0.00)	5.77 (0.01)	0.03 (0.85)	5.74 (0.01)	0.001 (0.97)
Note: p-values are reported in parentheses.								

The estimation results presented in Table 4 indicate that the coefficient of determination is approximately 0.80, suggesting a high explanatory power of the model. In the estimated SEM model, all explanatory variables except the squared GDP per capita variable exert positive and statistically significant effects on per capita carbon dioxide emissions.

GDP per capita exhibits the largest positive effect on carbon emissions. Specifically, a 1% increase in GDP per capita increases per capita CO_2 emissions by approximately 4.99%. This result implies that economic growth in the Persian Gulf countries has been accompanied by greater environmental degradation. In this context, pollution acts as a negative externality that imposes additional social costs on society. However, the squared GDP per capita variable has a negative and statistically significant coefficient, indicating that a 1% increase in this variable reduces CO_2 emissions by approximately 0.2%.

The simultaneous positive coefficient of GDP per capita and negative coefficient of its squared term confirms the validity of the Environmental Kuznets Curve (EKC) hypothesis for the Persian Gulf countries. Accordingly, in the early stages of economic growth, rising income levels intensify environmental pollution; however, after a certain threshold of economic development is reached, further growth contributes to environmental improvement and lower carbon emissions. One possible explanation is that although economic growth in these countries is largely driven by oil and gas export revenues rather than technological progress, higher income levels enable them to import cleaner and more advanced technologies, thereby mitigating environmental degradation. This finding is consistent with the results reported by Khani and Hoshmand [23] for oil-exporting countries.

The findings further reveal that both exports and imports exert positive and statistically significant effects on per capita CO_2 emissions. Specifically, a 1% increase in exports and imports raises carbon emissions by approximately 0.04% and 0.10%, respectively. This result suggests that the expansion of foreign trade contributes to environmental degradation in the Persian Gulf region. One explanation is that a substantial share of these countries' exports consists of fossil fuels such as oil and natural gas, whose production processes rely heavily on carbon-intensive technologies. Moreover, many

non-oil export industries in the region still employ relatively outdated production technologies. This finding contrasts with the results reported by Mahmood et al. [8].

On the import side, a significant portion of imports in the Persian Gulf countries consists of industrial machinery and capital goods, which are closely associated with higher energy consumption and carbon emissions. According to trade statistics, machinery imports account for a considerable share of total imports in countries such as Iran, Bahrain, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. Consequently, imports indirectly contribute to higher CO_2 emissions through increased industrial activity and energy use. This result is consistent with the findings of Khan et al. [1].

Table 4. Estimation Results of the Spatial Error Model (SEM)

Variable	Coefficient	Standard Error	Prob.
Exports	0.04	0.02	0.04
Imports	0.10	0.05	0.03
GDP per capita	4.99	1.72	0.004
GDP per capita squared	-0.20	0.08	0.01
Sigma	0.25	0.01	0.00
Lambda	-0.76	0.19	0.00
R^2	0.80	–	–
Adjusted R^2 (Buse)	0.80	–	–
Raw Moments R^2	0.99	–	–
Adjusted Raw Moments R^2	0.99	–	–

Conclusion

This study examined the effects of exports and imports on environmental quality in seven Persian Gulf countries over the period 1995–2020 using a spatial econometric approach.

Based on the results of Moran's I, Geary's C, LM-error, LM-lag, Robust LM-error, and Robust LM-lag tests, the Spatial Error Model (SEM) was selected as the most appropriate specification.

The empirical findings indicate that GDP per capita and the squared term of GDP per capita exert positive and negative effects on carbon dioxide emissions, respectively. These results confirm the validity of the Environmental Kuznets Curve (EKC) hypothesis for the Persian Gulf countries. In the early stages of economic growth, increases in GDP per capita intensify environmental degradation through higher carbon dioxide emissions. However, as economic growth continues, the level of pollution gradually declines. One plausible explanation is that rising oil and gas export revenues enable these countries to import more advanced and environmentally friendly technologies. Consequently, technological progress in the Persian Gulf region is achieved primarily through external technological transfer rather than endogenous innovation, which ultimately contributes to reducing carbon emissions and improving environmental quality.

The results further reveal that both exports and imports have positive and statistically significant effects on per capita carbon dioxide emissions. Specifically, a 1% increase in exports and imports increases CO_2 emissions by approximately 0.04% and 0.10%, respectively. These findings suggest that the expansion of international trade has contributed to environmental degradation in the region. On the export side, the economies of Persian Gulf countries are heavily dependent on fossil fuel exports such as oil and natural gas, whose production processes are highly carbon intensive and often rely on outdated technologies. Moreover, even non-oil export sectors in these countries frequently lack modern and efficient production technologies.

On the import side, a substantial share of imports consists of industrial machinery and equipment, which are major contributors to carbon emissions through increased industrial activity and energy consumption. Therefore, both export expansion and import growth have intensified environmental pressures in the Persian Gulf region.

Based on the findings of this study, several policy implications can be proposed. First, in order to mitigate the environmental impacts of economic growth driven by oil and gas exports, policymakers should prioritize the adoption of cleaner, more advanced, and

energy-efficient production technologies. In addition, efforts should be made to develop domestic technological capabilities and reduce dependence on imported technologies in the long run.

Second, governments in the region should internalize environmental externalities by implementing environmental taxation policies, such as carbon taxes or pollution charges on firms with high emission levels. Such policies would encourage producers to adopt cleaner technologies and improve energy efficiency. Policymakers should also create appropriate institutional frameworks that facilitate cooperation and negotiation among stakeholders, including governments, industries, and environmental agencies.

Finally, promoting the import of environmentally friendly machinery and low-carbon technologies can simultaneously reduce the environmental impact of imports and mitigate the negative spillover effects associated with export-oriented production. Such strategies would contribute not only to lowering greenhouse gas emissions but also to achieving sustainable economic growth and environmental protection in the Persian Gulf region.

Statements

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Competing interests

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Amir Dadrasmoghadam. The first draft of the

manuscript was written by Amir Dadrasmoghadam and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability

The datasets generated and/or analyzed during the current study are available in the World Bank repository (https://data.worldbank.org).

Clinical Trial Number:

not applicable

Consent to Publish declaration:

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Ethics declaration:

not applicable

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