



DETERMINANTS OF CO₂ EMISSIONS IN THE BALKANS, BLACK SEA, AND CAUCASUS REGION: EVIDENCE FROM PANEL ARDL-PMG AND DCCE MODELS

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Abstract: This study examines the determinants of carbon dioxide (CO₂) emissions in 12 countries from the Balkans, Black Sea, and Caucasus region over the period 1990–2024. It extends the literature by including freshwater withdrawal and aquaculture production as explanatory variables. The study also controls for GDP, population density, and electricity consumption as additional covariates. In doing so, the study proposes resource related determinants of on environmental pressure. The analysis uses annual panel data from the World Development Indicators database of the World Bank. To account for cross-sectional dependence and mixed orders of integration, the study applies a panel ARDL-PMG model. The Dynamic Common Correlated Effects(DCCE) estimator is also used as a robustness check. The results show that population density, electricity consumption, and freshwater withdrawal increase CO₂ emissions in the long run. In the short run, GDP and electricity consumption have positive and statistically significant effects on emissions. The DCCE estimates also show the positive effect of electricity consumption and a weaker positive effect of population density. They indicate a positive association between aquaculture production and emissions. In both estimation, the Environmental Kuznets Curve hypothesis is not supported. Overall, the findings suggest that environmental pressure is linked to energy use, population density, and resource usage in the sampled countries. Overall, the results indicate a need for greater emphasis on renewable energy, sustainable urban planning, better water management, and more environmentally friendly aquaculture practices.

Keywords: Carbon emissions, Electricity consumption, Freshwater withdrawal, Aquaculture production, Panel data

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1. Introduction

Carbon dioxide (CO₂) emissions are still a key issue in environmental economics. Developing effective climate policies requires a clear understanding of the economic and resource-based drivers behind environmental problems. Recent studies no longer focus solely on the link between gross domestic product and pollution. Rather, they show that emissions are shaped by the interaction of several variables, particularly those related to energy, water, and food. In particular, the water-energy-carbon nexus and the environmental footprint of aquaculture have become more visible in the recent literature.

The present study speaks directly to this broader agenda. It examines a panel of 12 countries in the Balkans, Black Sea, and Caucasus area. It also combines conventional determinants of emissions with two variables that are still less common in standard macro-panel carbon models: freshwater withdrawal and aquaculture production. Compared with the very large Environmental Kuznets Curve (EKC) and electricity-emissions literatures, the carbon implications of water withdrawals

and aquaculture are still relatively fragmented. They are often studied in sector-specific settings. By integrating these variables within a single empirical framework, the paper offers a more resource-sensitive account of environmental pressure in the sampled countries.

One major strand of the literature focuses on the growth-environment nexus through the EKC hypothesis. Recent review evidence shows that EKC findings remain highly sensitive to pollutant choice, country coverage, control variables, and econometric design (Guo and Shahbaz, 2024). More recent cross-country evidence also suggests that the hypothesis is not universal. Guliyev and Seyfullayev (2025), for example, find that the emissions-gross domestic product relationship differs across gross domestic product levels. It does not follow one common pattern for all countries. This implies that the effect of GDP on emissions should be treated as an empirical question, especially in heterogeneous regional panels. Population density is also considered an important factor in explaining emissions. In densely populated areas, the demand for housing, transportation, electricity, and infrastructure tends to rise. This can lead to higher



emissions. At the same time, higher density may also bring certain advantages. These include shorter travel distances, better public services, and more efficient use of resources. Because of this, the overall effect of population density on emissions is not always the same. It may vary depending on the context. For example, Pickson et al. (2024) found that population-related factors, including density, affect CO₂ emissions differently across gross domestic product levels. Similarly, Hong et al. (2022) showed that the impact of urban density on emissions changes according to city size and the source of carbon emissions.

Electricity consumption is still one of the main factors behind carbon emissions. This is especially true in countries where electricity is largely produced from fossil fuels. Munir (2023) shows that, in Europe, higher electricity use leads to higher CO₂ emissions over the long term. This result is based on a panel nonlinear ARDL model. In a similar way, Kakar et al. (2024) find that electricity consumption increases carbon emissions in Asian countries.

Freshwater withdrawal has received relatively limited attention in the literature. However, recent studies suggest that it is more closely connected to emissions than previously assumed. Flint et al. (2025) show that water withdrawals can alter inorganic carbon fluxes. They also find that these withdrawals may increase CO₂ releases after the water is extracted. Maziotis et al. (2024) describe water provision within a water, energy and carbon circle. This suggests that water supply systems are closely linked to both energy use and carbon emissions. Yateh et al. (2024) also show that drinking-water treatment requires substantial energy usage. This creates important carbon-management challenges. In their study, pumping is identified as one of the most energy-intensive stages. In the agricultural, Qin et al. (2024) estimate that irrigation alone uses 1,896 PJ of energy each year. It also produces around 216 Mt of CO₂ from energy use. Taken together, these studies indicate that freshwater withdrawal can influence emissions through pumping, transportation, treatment, irrigation, and cycling processes of carbon.

Aquaculture production is perhaps the novel variable in this study. Recent studies show that it has a real environmental impact. MacLeod et al. (2020) estimate that global aquaculture generated about 263 MtCO₂e in 2017. This finding shows that the sector already has a measurable climate footprint. More recent research also points to important technological and ecological differences within aquaculture. For instance, Shen et al. (2024) find that marine aquaculture can have a much lower carbon footprint than freshwater aquaculture. Garlock et al. (2024) also report considerable variation in environmental effects across different aquaculture systems. In addition, Ray et al. (2025) suggest that fisheries and aquaculture may alter the natural balance of carbon, nitrogen, and phosphorus in the environment. This indicates that their impact on the environment is not

limited to direct energy use. Overall, these findings suggest that aquaculture production may be an important determinant of CO₂ emissions, but its effect can vary by context.

This study fills a clear gap in the literature on what drives CO₂ emissions. Most prior work has concentrated on familiar factors, such as economic growth, energy consumption, and demographic change, while giving much less attention to freshwater withdrawal and aquaculture production, particularly within a single, integrated panel setting. Evidence for the Balkans, Black Sea, and Caucasus region is also relatively scarce, even though these countries exhibit strong cross-country linkages and meaningful structural differences.

Against this backdrop, the study offers three main contributions. First, it evaluates how GDP, population density, electricity consumption, freshwater withdrawal, and aquaculture production shape CO₂ emissions, broadening standard cross-country emissions models by incorporating resource-related determinants that remain underexplored in environmental economics. Second, it provides new empirical evidence for a region that is often overlooked despite its economic, environmental, and geopolitical importance. Third, the empirical design explicitly tackles cross-sectional dependence and differing integration properties by applying second-generation unit root tests, a panel ARDL-PMG framework, and the Dynamic Common Correlated Effects estimator as a robustness check. Together, these choices strengthen the reliability of the results and sharpen the study's contribution to the existing literature.

The empirical results show that population density, electricity consumption, and freshwater withdrawal increase CO₂ emissions in the long run. In contrast, GDP and aquaculture production do not appear to be statistically significant in the PMG long-run estimates. In the short run, GDP and electricity consumption are found to increase emissions. The DCCE results also confirm the positive effect of electricity consumption. They further suggest that population density has a weaker positive effect on emissions. In addition, they show a positive relationship between aquaculture production and emissions. The EKC hypothesis is not supported under either estimation approach. Overall, gross domestic product growth alone does not seem to explain environmental pressure in these countries. Energy use, population concentration, and resource management appear to play a bigger role.

2. Materials and Methods

2.1. Material

The study is based on annual panel data from 1990 to 2024. The sample includes 12 countries. These are Albania, Armenia, Azerbaijan, Bulgaria, Georgia, Greece, Moldova, North Macedonia, Romania, the Russian Federation, Türkiye, and Ukraine. In total, the dataset includes 420 observations. Each country has 35 annual observations. All data were taken from the World Bank's

World Development Indicators (WDI) database. This database is widely used because it provides reliable data and allows comparison across countries.

The dependent variable in this analysis is carbon dioxide (CO₂) emissions. It is measured as total emissions. Land-use change and forestry (LULUCF) are excluded. The variable is reported in million tons of CO₂ equivalent. In this study, CO₂ emissions are used to reflect environmental pressure. This pressure is linked to economic activity and resource use.

The model includes a set of explanatory variables grounded in a theoretical framework that links CO₂ emissions to economic activity, demographic pressures, energy demand, and resource-based production.

Electric power consumption (measured in kilowatt-hours per capita) is used as a proxy for energy demand. This variable is important because greater electricity use, especially in energy systems that rely heavily on fossil fuels, typically leads to higher carbon emissions. Economic activity is captured through GDP, measured in constant 2015 US dollars, which reflects the scale effect of growth on environmental pressure. To assess whether the Environmental Kuznets Curve (EKC) holds, the model also includes a squared GDP term.

Population density, measured as people per square kilometer of land area, is included to represent demographic pressure. Higher density can influence emissions through increased demand for housing, transportation, infrastructure, and the use of natural resources.

Beyond these conventional drivers, the model incorporates two resource- and production-related variables. Annual freshwater withdrawal (in billion cubic meters) is included because extracting, treating, distributing, and using water, particularly for irrigation,

can be energy-intensive and may therefore add to carbon emissions. Aquaculture production (measured in metric tons) is also included to capture the expanding role of aquaculture, whose environmental impacts may operate through energy use, feed production, processing, and water management. Overall, these variables allow the analysis to explain CO₂ emissions within a broader framework that goes beyond the usual emphasis on growth and energy consumption alone.

In addition, all variables were transformed into natural logarithms. All variables used in the econometric analysis are expressed in natural logarithmic form. The log-transformed variables are defined as follows. \ln_co2 refers to carbon dioxide emissions. \ln_gdp refers to GDP in constant 2015 US dollars. $\ln_popdens$ stands for population density. \ln_elec represents electric power consumption per capita. \ln_water refers to annual freshwater withdrawals. \ln_aqua represents aquaculture production. The squared gross domestic product variable used in the Environmental Kuznets Curve specification is written as \ln_gdp^2 . This step helps reduce heteroscedasticity. It also makes the variance more stable. Another advantage is that the coefficients can be interpreted as elasticities.

2.1.1. Summary statistics

Table 1 presents the descriptive statistics of the variables used in the analysis. The average level of CO₂ emissions is 231 kt, although the values vary considerably across countries. Mean GDP is about 197 billion USD in constant 2015 prices, reflecting large differences in economic size. Population density averages 83 people per square kilometer. Electricity consumption is about 3087 kWh per capita on average. Freshwater withdrawal and aquaculture production exhibit substantial variation within the sample.

Table 1. Summary statistics

Variable	Mean	Std. Dev.	Min	Max
CO ₂ emissions (kt)	231.27	499.81	1.58	2436.27
GDP (constant 2015 billion US\$)	197	356	1,610	2,740
Population density (people/km ²)	83.06	27.02	8.72	129.62
Electricity consumption (kWh per capita)	3,086.70	1,463.54	418.45	7,291.61
Freshwater withdrawal	1,796.03	23,409.26	0.49	346,799.00
Aquaculture production (metric tons)	40,907.92	83,458.43	0	609,556.40

2.2. Methods

Table 2 presents the correlation matrix. CO₂ emissions are positively related to GDP, electricity consumption, freshwater withdrawal, and aquaculture production. Population density shows a negative relationship with emissions. Overall, the results suggest that higher economic activity and energy use are associated with higher emissions. None of the pairwise correlations exceed the commonly used threshold of 0.80. This indicates that multicollinearity is not likely to be a serious problem (Gujarati and Porter, 2009).

Then, Table 3 reports the results of the cross-section dependence test. The Pesaran CD statistic rejects the null hypothesis of cross-section independence. This indicates the presence of cross-sectional dependence across the panel units. When cross-section dependence is present, first-generation panel unit root tests may produce biased results.

Given the presence of cross-sectional dependence, a second-generation panel unit root test is employed. Specifically, the Pesaran cross-sectionally augmented Dickey-Fuller (CADF) test is applied (Pesaran, 2007).

The results are reported in Table 4. GDP, electricity consumption, and aquaculture production are stationary in levels. In contrast, CO₂ emissions, population density, and freshwater withdrawal are non-stationary in levels. After taking the first difference, all variables become stationary. To examine the dynamic relationship among the variables, the panel ARDL approach is employed. This method is appropriate when the variables are integrated of mixed orders, such as a combination of I(0) and I(1), but not I(2). The unit root results indicate a mixed order

of integration across the variables. Within the panel ARDL framework, two estimators are commonly used. The Mean Group (MG) estimator allows all coefficients to vary across countries and captures heterogeneity in both the short-run and long-run relationships (Pesaran and Smith, 1995). In contrast, the Pooled Mean Group (PMG) estimator restricts the long-run coefficients to be homogeneous while allowing short-run dynamics and adjustment speeds to differ across countries (Pesaran, Shin, and Smith, 1999).

Table 2. Correlation matrix

Variables	(1)	(2)	(3)	(4)	(5)	(6)
(1) CO ₂ emissions	1.000					
(2) GDP	0.921	1.000				
(3) Population density	-0.628	-0.557	1.000			
(4) Electricity consumption	0.595	0.547	-0.580	1.000		
(5) Freshwater withdrawal	0.681	0.619	-0.340	0.285	1.000	
(6) Aquaculture production	0.555	0.675	-0.283	0.380	0.152	1.000

Table 3. Cross-section dependence test

Test	Statistic	P-value
Pesaran CD test	12.403	0.000
Average absolute correlation	0.47	—

Table 4. Panel unit root test results (Pesaran CADF)

Variables	Level t-bar	First Difference t-bar	Integration Order
CO ₂ emissions	-0.916	-4.260***	I(1)
GDP	-2.944***	-4.309***	I(0)
Population density	-1.200	-2.295**	I(1)
Electricity consumption	-2.662***	-4.123***	I(0)
Freshwater withdrawal	-1.728	-3.482***	I(1)
Aquaculture production	-3.134***	-4.555***	I(0)

The null hypothesis of the Pesaran CADF test is the presence of a unit root. ***, ** and * denote significance at the 1%, 5%, and 10% levels, respectively.

The Hausman specification test is used to select between the MG and PMG estimators (Hausman, 1978). The null hypothesis states that the difference in coefficients is not systematic and that the PMG estimator is efficient. The alternative hypothesis suggests that the MG estimator is preferred. The test fails to reject the null hypothesis as the p-value is greater than 0.05. Therefore, the PMG estimator is selected (Table 5).

The general form of the Autoregressive Distributed Lag (ARDL) model can be expressed as follows (equation 1):

$$Y_{it} = \alpha_i + \sum_{j=1}^p \beta_{ij} Y_{i,t-j} + \sum_{j=0}^q \gamma_{ij} X_{i,t-j} + \varepsilon_{it} \quad (1)$$

where Y represents the dependent variable, X denotes the independent variables, i indicates the cross-sectional unit, and t represents the time period. ε_{it} is the error

term. The error correction representation of the ARDL-PMG model can be written as follows (equation 2):

$$\Delta Y_{it} = \varphi_i (Y_{i,t-1} - \theta_i X_{i,t-1}) + \sum_{j=1}^{p-1} \lambda_{ij} \Delta Y_{i,t-j} + \sum_{j=0}^{q-1} \delta_{ij} \Delta X_{i,t-j} + \mu_{it} \quad (2)$$

where φ_i represents the error correction coefficient, which measures the speed of adjustment toward the long-run equilibrium. A negative and statistically significant coefficient indicates the existence of a long-run relationship among the variables.

Table 5. Hausman test results

Test	Chi-square	p-value	Decision
MG vs PMG	0.69	0.983	PMG preferred

H0= the difference in coefficients is not systematic. The PMG estimator is efficient and consistent. H1= the MG estimator is preferred.

The study also examines the Environmental Kuznets Curve (EKC) hypothesis. This idea suggests that the link between economic growth and environmental degradation may be non-linear. Put simply, environmental pressure may increase at the beginning of the development process. After a certain gross domestic product level, it may start to decline. Panayotou (1993) was among the early scholars to discuss this argument. Later, Grossman and Krueger (1995) presented empirical evidence for this inverted U-shaped relationship between gross domestic product and environmental degradation. Since then, the EKC hypothesis has been widely discussed in studies covering different countries and pollutants (Stern, 2004; Dinda, 2004). To account for this possible non-linear pattern, the squared term of GDP is included in the empirical model.

As a robustness check, the study uses the Dynamic Common Correlated Effects (DCCE) estimator proposed by Chudik and Pesaran (2015). Unlike standard panel methods, DCCE directly accounts for cross-sectional dependence. It does so by including cross-sectional averages of the dependent and independent variables in the regression. This helps capture unobserved common shocks that may affect all countries at the same time.

The DCCE model can be expressed as (equation 3):

$$y_{it} = \alpha_i + \beta'x_{it} + \gamma_i\bar{y}_t + \delta_i\bar{x}_t + \varepsilon_{it} \quad (3)$$

where y_{it} is the dependent variable. x_{it} represents the explanatory variables. \bar{y}_t and \bar{x}_t are the cross-sectional averages. These averages help capture common unobserved factors across units.

Table 6. ARDL-PMG estimation results

Variables	Coefficient	Std. Error
Long-run coefficients		
ln_gdp	-0.1377	(1.9715)
ln_popdens	2.5693***	(0.3038)
ln_elec	0.7675***	(0.0715)
ln_water	0.1221***	(0.0122)
ln_aqua	0.0043	(0.0071)
Short-run coefficients		
Δ ln_gdp	0.1650**	(0.0825)
ln_gdp ²	0.0019	(0.0012)
Δ ln_popdens	1.1138	(0.7485)
Δ ln_elec	0.3963**	(0.1673)
Δ ln_water	0.0118	(0.0479)
Δ ln_aqua	0.0204	(0.0126)
Error correction term		
ECT	-0.3391***	(0.1195)
Constant	-4.8790**	(2.0402)

Observations = 420. Number of countries = 12. Standard errors are reported in parentheses. ***P<0.01, **P<0.05, *P<0.10.

3. Results

3.1. Results of ARDL-PMG Estimates

Table 6 shows the results of the ARDL Pooled Mean Group estimation. The error correction coefficient is negative and statistically significant. The coefficient shows that about 34 percent of short-run imbalances are corrected within one period. These points to a fairly stable adjustment process.

The long-run results show that population density, electricity consumption, and water use all has positive and statistically significant effects on carbon emissions. A rise in population density is associated with higher emissions. Similar effect is observed for electricity consumption. Water use also has a positive effect, although the size of this effect is smaller. By contrast, economic growth and aquaculture production do not have statistically significant long-run effects on emissions.

Additionally, the short-run results show that carbon emissions rise with economic growth and electricity consumption. The other variables are not statistically significant in the short run. This suggests that energy use remains a major determinant of environmental pollution over shorter time periods.

The results do not support the Environmental Kuznets Curve hypothesis. The squared term of economic growth is not statistically significant. This outcome indicates that the data do not provide evidence of an inverted U shaped relationship between gross domestic product and environmental degradation as proposed in the Environmental Kuznets Curve literature.

3.2. Results of the Dynamic Common Correlated Effects (DCCE) estimator

Table 7 reports the results from the Dynamic Common Correlated Effects estimator. Unlike the ARDL PMG framework, this estimator does not explicitly estimate a long run equilibrium relationship. Instead, it provides coefficient estimates while controlling for cross sectional dependence across countries. The results show that electricity consumption has a positive and statistically significant effect on carbon emissions. Aquaculture production also enters with a positive and significant coefficient. Population density has a positive coefficient but is only weakly significant. In contrast, no statistically

significant effect is found for water use or economic growth.

Although the squared gross domestic product variable is negative, it is not statistically significant. This suggests that the results do not support the Environmental Kuznets Curve hypothesis. Overall, the DCCE estimates are broadly consistent with the baseline ARDL PMG results. Differences in coefficient estimates may reflect the ability of the DCCE estimator to account for cross sectional dependence and unobserved common factors across countries. Additionally, the results are different as this estimator does not explicitly estimate a long run equilibrium relationship as in the ARDL PMG framework.

Table 7. Dynamic common correlated effects estimation results

Variables	Coefficient	Std. Error
ln_gdp	2.3385	(9.2514)
ln_gdp2	-0.0298	(0.1881)
ln_popdens	1.1752*	(0.7184)
ln_elec	0.6162***	(0.1046)
ln_water	0.0765	(0.0695)
ln_aqua	0.0529**	(0.0206)

4. Discussion

This study examines the determinants of carbon emissions. The determinants used in the study are population density, electricity consumption, water use, economic growth, and aquaculture production. The analysis uses both the ARDL-PMG and Dynamic Common Correlated Effects estimators. The ARDL-PMG results point to the existence of a long-run relationship among the variables. This is supported by the negative and statistically significant error correction term. The coefficient shows that about 34 percent of short-run deviations from the long-run equilibrium are corrected within one period. This suggests that the adjustment process is gradual rather than immediate. Similar patterns of adjustment have also been reported in panel studies on energy use and environmental degradation across countries (Pesaran et al., 1999; Apergis and Payne, 2014).

Population density appears to be one of the main drivers of carbon emissions in the long run. The ARDL-PMG results show a strong positive and statistically significant relationship between population density and emissions. The DCCE estimator also points to a positive effect, although this result is only weakly significant. Together, these findings suggest that higher population concentration is linked to higher emissions. One possible reason is that denser populations create greater demand for housing, transport, electricity, and industrial activity. This can raise energy use and increase environmental pollution.

Earlier studies have also highlighted the role of demographic factors in shaping environmental outcomes. For example, Liddle (2014) shows that population growth and urbanization significantly increase energy

consumption and carbon emissions across countries. In a similar way, Zhou et al. (2021) find that urban population density contributes to higher emissions through rising infrastructure demand and consumption. At the same time, some studies argue that dense urban areas can improve environmental efficiency. This may happen through better infrastructure and more effective public transportation systems (Seto et al., 2014). In other words, in the sampled countries, the environmental costs linked to population concentration seem to outweigh the possible efficiency benefits.

Electricity consumption also stands out as an important determinant of carbon emissions. Both the ARDL-PMG and DCCE results show a positive and statistically significant relationship between electricity consumption and emissions. This suggests that energy systems play a key role in shaping environmental outcomes. In countries where electricity production still depends heavily on fossil fuels, higher electricity demand is often followed by higher carbon emissions.

This result is also consistent with earlier research in environmental economics. For example, Sadorsky (2014) shows that electricity consumption is a major source of emissions in emerging economies. The short-run ARDL-PMG results also point in the same direction. They show that electricity consumption has an immediate positive effect on emissions. This suggests that changes in energy demand can quickly lead to greater environmental pollution.

Water use has a positive and statistically significant long-run effect on carbon emissions in the ARDL-PMG results. However, the size of this effect is relatively small. This suggests that higher water use may still add to environmental degradation, even if its impact is limited.

One common explanation for this link is the connection between water and energy use. Extracting, treating, and distributing water often requires a large amount of energy. This is especially true in urban and agricultural systems. Because of this, higher water demand can lead to higher energy use and, in turn, higher carbon emissions.

Earlier studies have also pointed to this close connection between water usage and energy use. For example, Copeland and Carter (2014) show that water supply and desalination processes are energy intensive. They also note that these processes can significantly increase emissions when they rely on fossil fuels. Fang and Chen (2017) report a similar pattern. They find that the development of water infrastructure can raise energy demand in rapidly developing economies. However, the DCCE results do not show a statistically significant relationship between water use and emissions. This suggests that the effect of water use on emissions may differ across countries. Differences in technology, water policies, and infrastructure may help explain this variation.

Economic growth does not show a clear long-run effect on carbon emissions in the ARDL-PMG results. In the short run, however, higher GDP is correlated to higher emissions. This suggests that economic growth may put more pressure on the environment at first. As production increases, energy use may also rise. This can lead to higher emissions. Over time, however, the relationship becomes less clear. This may be related to technological progress, environmental regulations, and the growing role of service-based activities.

This result is also in line with earlier studies. These studies show that the relationship between economic growth and environmental degradation is not always simple. It can change across countries and over time. For example, Shahbaz et al. (2019) argue that technological innovation and environmental policy play an important role in shaping the environmental effects of economic growth. Dogan and Inglesi-Lotz (2020) report a similar finding. They show that the environmental impact of growth depends on factors such as the energy mix and institutional quality.

Aquaculture production produces somewhat different results across the two estimation approaches. In the ARDL-PMG model, its long-run coefficient is not statistically significant. In contrast, the DCCE estimates show a positive and statistically significant relationship with CO₂ emissions. This gap should not be viewed as purely a methodological artifact; it likely also points to real structural differences across countries in the region. As Ahmed et al. (2019) emphasize, aquaculture systems vary widely in their environmental footprint, and the magnitude (and even direction) of their impact depends on production methods, energy needs, and the intensity of farming practices. Some countries may rely on relatively low-input systems, while others operate more intensive models that require more electricity, generate

higher feed-related emissions, and involve more carbon-intensive processing. Cross-country differences in environmental regulation, monitoring capacity, and the uptake of cleaner technologies can further widen these disparities.

At the same time, the DCCE estimator explicitly controls for cross-sectional dependence and unobserved common factors. The positive and significant coefficient in this framework may therefore suggest that aquaculture's carbon impact is shaped not only by country-specific production practices, but also by shared regional dynamics—such as common energy price shocks, similar input structures, or parallel shifts toward more intensive production across countries. Overall, the contrast between the ARDL-PMG and DCCE findings indicates that aquaculture's environmental effects in the Balkans, Black Sea, and Caucasus region are heterogeneous and may become more apparent once common regional influences are properly accounted for.

Turning to the Environmental Kuznets Curve (EKC) hypothesis, the conventional expectation is that environmental degradation increases in the early stages of development but begins to decline after countries reach a higher income level (Grossman and Krueger, 1995). In this study, however, the squared GDP term is not statistically significant in either estimation method. In other words, the data do not provide evidence of an inverted U-shaped relationship between GDP and environmental degradation, and the EKC hypothesis is not supported.

This result is especially meaningful for the Balkans, Black Sea, and Caucasus region. One plausible explanation is that many countries in the sample still exhibit key features of transition economies, where the shift toward cleaner production and more environmentally efficient growth is still incomplete. Under these conditions, economic expansion may continue to be driven by energy-intensive sectors and carbon-heavy production structures, rather than being paired with sufficient technological upgrading. A second explanation is the region's ongoing reliance on fossil-fuel-based energy systems. When electricity generation and wider economic activity remain closely tied to fossil fuel use, higher income levels do not necessarily translate into lower emissions.

Institutional differences across countries may also weaken the conditions under which the EKC is expected to emerge. Variation in environmental regulation, enforcement capacity, governance quality, and policy continuity can lead to very different growth-emissions paths. Similarly, uneven technological development may limit the extent to which countries can decouple economic growth from environmental degradation. More broadly, recent studies have questioned whether the EKC pattern holds consistently across countries, arguing that growth alone is rarely sufficient to deliver environmental improvements. Instead, policy interventions, technological change, and progress in the energy

transition tend to be more decisive (Sarkodie and Strezov, 2018; Balsalobre-Lorente et al., 2021). Taken together, these points suggest that the lack of EKC support in this study is not just a statistical outcome, but also reflects the region's underlying structural and institutional realities.

5. Conclusion

This study examines how carbon emissions are related to economic growth, electricity consumption, water use, population density, and aquaculture production in a panel of twelve countries. It covers the period 1990–2024. The empirical analysis uses the ARDL–PMG estimator to assess long-run relationships and short-run effects. The Dynamic Common Correlated Effects estimator is also used as a robustness check.

The ARDL–PMG results suggest that in the long run, population density, electricity consumption, and water use all have positive and statistically significant effects on carbon emissions. The short-run results show that economic growth and electricity consumption increase carbon emissions.

The DCCE results are generally consistent with the main findings. They confirm the positive effect of electricity consumption on carbon emissions. At the same time, they suggest a weaker effect of population density and a significant positive effect of aquaculture production. Lastly, the paper does not provide evidence supporting the Environmental Kuznets Curve hypothesis.

The results point to several practical policy takeaways. First, the strong impact of electricity consumption underscores the urgency of shifting toward a cleaner energy mix in the sampled countries. Expanding domestic renewable energy, such as solar, wind, and hydropower, alongside stronger energy-efficiency measures in industry, buildings, and transport could materially reduce CO₂ emissions.

Second, the positive association with population density highlights the need for more sustainable urban development and infrastructure planning. Policies that encourage compact city design, improve public transportation, and promote energy-efficient buildings can help ease the environmental pressures that often accompany population concentration.

Third, the findings on freshwater withdrawal suggest that water and energy policies should be coordinated rather than treated separately. Investing in modern water infrastructure, such as leakage reduction, efficient irrigation systems, wastewater reuse, and pricing mechanisms that incentivize conservation, can lower water waste while also reducing the energy demand tied to extraction, pumping, and treatment, ultimately helping to curb emissions.

Finally, the DCCE results indicate that the aquaculture sector would benefit from more sustainability-focused interventions. This could involve supporting low-carbon production methods, improving feed efficiency, encouraging renewable energy use in aquaculture

facilities, and strengthening environmental standards and monitoring. Taken together, these targeted measures offer a clearer roadmap for reducing environmental pressures in the Balkans, Black Sea, and Caucasus region than broad, generic policy recommendations.

Despite these contributions, the study has some limitations. It focuses only on a specific group of countries. Because of this, the findings may not apply in the same way to other regions. This is especially true for regions with different economic conditions and energy structures. Future research could look at other country groups or regions. This would make it possible to see whether similar patterns appear in different settings. It could also help show how economic, institutional, and energy-related differences shape these relationships.

Author Contributions

The percentages of the author' contributions are presented below. The author reviewed and approved the final version of the manuscript.

	T.Ö.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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