How Does Green Trade Openness Affect Carbon Productivity in Central and Eastern Europe?

Busra Agan Celik
ORCID iD: 0000-0003-1485-9142
busra.agancelik@ostimteknik.edu.tr
OSTİM Technical University, Economics and Business Faculty, Economics
Ankara, Türkiye

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Abstract: This study investigates the impact of green trade openness on carbon productivity in eight Central and Eastern European (CEE) economies from 2000 to 2024. A novel Green Trade Openness Index (GTOI), based on environmentally related exports and imports relative to GDP, is constructed and analyzed using a panel Quantile Autoregressive Distributed Lag (QARDL) model. The findings reveal substantial distributional heterogeneity. In the long run, green trade openness exerts a statistically significant negative effect across most quantiles, with stronger impacts at higher levels of carbon productivity. This finding is consistent with the persistence of carbon-intensive production structures and limited realization of the technique effect, as suggested in the trade–environment literature. Energy intensity emerges as the most robust determinant across quantiles, while income positively affects middle and upper quantiles. Short-run effects remain limited, indicating gradual structural adjustment. These results suggest that improving energy efficiency and strengthening technological absorption capacity are essential for translating green trade integration into sustainable productivity gains.

Keywords: green trade openness, carbon productivity, energy intensity, quantile ARDL, Central and Eastern Europe

JEL Classification codes: F18, Q56, Q44

INTRODUCTION

In recent decades, Central and Eastern European (CEE) economies have undergone profound structural transformation, deepening their integration into global trade networks while simultaneously adapting to the European Union's environmental and climate policy framework. As members of the EU or closely integrated transition economies, these countries face increasing pressure to decarbonize their production systems and align with sustainability objectives under the European Green Deal. Within this context, understanding the interaction between trade openness and environmental performance has become a central policy and research concern.

Traditional trade openness measures primarily focus on the overall volume of exports and imports relative to GDP, overlooking the environmental composition of trade flows. However, not all trade contributes equally to environmental outcomes. Trade in environmentally related goods, such as renewable energy technologies, pollution-control equipment, and energy-efficient machinery, may facilitate technology diffusion, enhance production efficiency, and accelerate structural shifts toward less carbon-intensive sectors. Therefore, incorporating the environmental dimension of trade integration is essential for evaluating its impact on sustainable economic performance.

This study examines how green trade openness influences carbon productivity in eight Central and Eastern European countries, Poland, the Czech Republic, Slovakia, Hungary, Slovenia, Croatia, Romania, and Bulgaria, over the period 2000–2024. To capture the environmental dimension of trade integration, the paper constructs a Green Trade Openness Index (GTOI), combining environmentally related exports and imports with overall trade openness. The empirical analysis employs a panel Quantile Autoregressive Distributed Lag (QARDL) model, allowing the investigation of both short- and long-run effects across different conditional distributions of carbon productivity. This approach is particularly relevant for transition economies, where structural heterogeneity may generate asymmetric responses to trade and energy-related factors.

This study contributes to the literature in three main ways. First, it introduces a trade-based measure of green openness tailored to transition economies in the CEE region. Second, it provides new empirical evidence on the trade–environment–productivity nexus by focusing on carbon productivity rather than emissions or energy intensity alone. Third, by applying a distribution-sensitive econometric framework, the study uncovers heterogeneous effects of green trade openness across different levels of carbon efficiency.

The findings offer important policy implications for the CEE region. While environmentally oriented trade integration has the potential to support sustainable productivity, the results indicate that its effects are conditional and not automatically beneficial. In particular, the negative long-run relationship suggests that without complementary structural transformation, improvements in energy efficiency, and stronger technological absorptive capacity, green trade openness may not translate into higher carbon productivity. In the context of accelerating decarbonization targets and evolving global trade patterns, identifying these underlying mechanisms is crucial for effective policy design.

1 LITERATURE REVIEW

The relationship between trade openness and environmental performance has long been examined within the trade–environment literature. The foundational framework developed by Grossman and Krueger (1991) identifies three principal channels through which trade influences environmental outcomes: the scale, composition, and technique effects. The scale effect suggests that increased economic activity resulting from trade expansion may intensify emissions. In contrast, the composition effect reflects structural shifts toward less pollution-intensive sectors, while the technique effect captures technological upgrading and efficiency improvements that may reduce environmental pressure. Consequently, the overall environmental impact of trade openness depends on the relative dominance of these interacting mechanisms. Building on this framework, the empirical literature has produced mixed evidence, often linked to the pollution haven hypothesis and the uneven realization of the technique effect, particularly in transition economies. These dynamics highlight that trade openness does not automatically lead to environmental improvements, but rather depends on structural characteristics, energy composition, and technological absorptive capacity.

Empirical findings on the trade–environment nexus, however, remain inconclusive. Several studies provide evidence supporting the pollution haven hypothesis, indicating that trade openness may increase emissions, particularly in developing or energy-intensive economies (Cole, 2004; Managi et al., 2009). Conversely, other contributions argue that trade facilitates access to cleaner technologies and international knowledge spillovers, thereby improving environmental quality (Antweiler et al., 2001; Frankel and Rose, 2005). These contrasting results suggest that aggregate trade openness measures may obscure important structural and technological dimensions embedded within trade flows.

Recognizing this limitation, recent research increasingly focuses on the environmental composition of trade. Instead of treating trade openness as a purely quantitative indicator, scholars examine trade in environmentally related goods and services. Costantini and Crespi (2008) show that trade in renewable energy technologies and environmental equipment enhances technological diffusion and supports low-carbon transitions. Similarly, Aichele and Felbermayr (2015) demonstrate that environmentally oriented trade induces structural reallocation toward cleaner sectors. This strand of literature highlights the necessity of refined trade indicators that explicitly incorporate environmental content rather than relying solely on total exports and imports.

Parallel to the evolution of trade measures, carbon productivity has emerged as a key indicator of sustainable economic performance. Unlike emission levels alone, carbon productivity reflects the efficiency with which economies generate output relative to their carbon footprint. Empirical studies emphasize the roles of renewable energy expansion, energy efficiency improvements, structural transformation, and institutional quality in enhancing carbon productivity (Zhang et al., 2017). Renewable energy adoption generally improves carbon efficiency, whereas high energy intensity and fossil fuel dependence weaken it. Moreover, structural shifts toward service-oriented economies are associated with higher environmental efficiency (Sadorsky, 2011; Apergis & Payne, 2014). Despite these advances, the interaction between environmentally oriented trade integration and carbon productivity remains relatively underexplored.

More recent contributions extend the trade–carbon literature by incorporating nonlinearities, institutional frameworks, and innovation channels. Dou et al. (2020) provide international evidence of an inverted U-shaped relationship between trade openness and CO_2 emissions, confirming the mediating roles of scale, composition, and technique effects. In a related study, Dou et al. (2021) demonstrate heterogeneous effects of trade openness across China–Japan–ROK FTA countries, showing that exports and imports exert asymmetric impacts on emissions and that trade agreements may mitigate emission increases. Later, Bakri et al. (2025) identify an optimal level of trade openness beyond which carbon emissions decline, further supporting nonlinear Environmental Kuznets Curve (EKC) dynamics.

The literature also emphasizes the roles of institutional quality and green innovation in shaping the trade–environment nexus. Almulhim et al. (2025) show that green trade openness, institutional quality, and R&D investment enhance environmental sustainability, whereas natural resource rents increase emissions. Likewise, Kim et al. (2024) find that trade openness promotes green technological progress, conditional on environmental policy stringency. In developing economies, Sakilu and Chen (2025) demonstrate that green innovation reduces CO_2 emissions and mediates the trade–emissions relationship through energy consumption, while Anser et al. (2020) confirm the long-run interlinkages among trade openness, energy use, economic growth, and emissions. In transition economies, particularly in Central and Eastern Europe (CEE), this relationship is further shaped by post-socialist restructuring and EU integration. Although technological modernization and regulatory convergence have progressed (Kellenberg, 2009; Cole et al., 2017), CEE countries remain relatively energy-intensive, and their carbon efficiency trajectories vary considerably.

Furthermore, the existing literature demonstrates that the trade–environment relationship is nonlinear, structurally contingent, and institutionally mediated. Despite these advances, two important gaps persist. First, limited attention has been paid to environmentally adjusted trade measures when analyzing carbon productivity rather than emissions. Second, transition economies in Central and Eastern Europe have received insufficient focus within distribution-sensitive frameworks. Addressing these gaps, the present study constructs a Green Trade Openness Index (GTOI) that captures the environmental composition of trade flows and employs a panel QARDL methodology to explore heterogeneous short- and long-run effects of green trade openness on carbon productivity in CEE economies.

2 METHODOLOGY

Model Specification

This study examines the impact of green trade openness on carbon productivity in eight CEE countries over the period 2000–2024. Carbon productivity (CP) is defined as the ratio of real GDP to CO_2 emissions and captures the efficiency with which economies generate output relative to their carbon footprint. In logarithmic form, carbon productivity is expressed as:

$$\ln CP_{it} = \ln GDP_{it} - \ln CO2_{it} \quad (1)$$

To evaluate the determinants of carbon productivity, the baseline empirical model is specified as follows:

$$\ln CP_{it} = \alpha_i + \beta_1 \ln GTOI_{it} + \beta_2 RE_{it} + \beta_3 \ln EI_{it} + \beta_4 \ln GDPpc_{it} + \beta_5 IND_{it} + \varepsilon_{it} \quad (2)$$

where i denotes country and t denotes time. GTOI represents Green Trade Openness, RE is renewable energy consumption as a share of total final energy use, EI denotes energy intensity, GDPpc captures income level, and IND reflects industrial structure. Country-specific fixed effects ε_{it} control for unobserved heterogeneity.

Construction of the Green Trade Openness Index (GTOI)

To capture the environmental dimension of trade integration, this study constructs a Green Trade Openness Index (GTOI). Conventional trade openness indicators, typically measured as total exports plus imports relative to GDP, do not differentiate between environmentally harmful and environmentally beneficial trade flows. The GTOI incorporates environmentally related exports and imports based on internationally recognized environmental goods classifications. It is calculated as:

$$GTOI_{it} = \frac{GreenExports_{it} + GreenImport_{it}}{GDP_{it}} \quad (3)$$

where $GreenExports_{it}$ and $GreenImports_{it}$denote the value of environmentally related exports and imports, respectively, in country i at time t, and GDP_{it} represents real gross domestic product. Environmentally related trade flows are identified based on internationally recognized environmental goods classifications, including renewable energy technologies, pollution abatement equipment, and energy-efficient capital goods. By scaling green trade flows to GDP, the index captures the intensity of environmentally oriented trade relative to economic size.

Econometric Strategy: Panel QARDL Approach

The trade–environment relationship may exhibit nonlinear and heterogeneous dynamics across countries and different levels of carbon efficiency. Conventional mean-based panel estimators assume homogeneous effects and may mask distributional differences. To address this limitation, the study employs the panel Quantile Autoregressive Distributed Lag (QARDL) model. The QARDL framework allows for the estimation of both short- and long-run relationships across different quantiles of the dependent variable. This approach is particularly appropriate for transition economies characterized by structural heterogeneity and asymmetric adjustment processes. The long-run relationship can be expressed in error-correction form as:

$$Q_\tau(\ln C\,P_{it}) = \phi_i(\tau) + \lambda_i(\tau)\,[\ln C\,P_{i,t-1} - \theta_1(\tau)\ln G\,TOI_{it} - \theta_2(\tau)X_{it}] + \sum_{j=1}^{p}\delta_{ij}(\tau)\Delta\ln C\,P_{i,t-j} + \sum_{j=0}^{q}\psi_{ij}(\tau)\Delta Z_{i,t-j} + u_{it}(\tau) \quad (4)$$

where τ denotes the quantile level, $\lambda_i(\tau)$ represents the speed of adjustment toward long-run equilibrium, and X_{it} includes the explanatory variables. Estimating the model across multiple quantiles enables the identification of heterogeneous responses of carbon productivity to green trade openness.

3 RESULTS AND DISCUSSION

This study aims to examine whether environmentally oriented trade integration enhances carbon productivity in Central and Eastern European (CEE) economies. By focusing on carbon productivity, defined as the ratio of real GDP to CO_2 emissions, the analysis evaluates the extent to which green trade openness contributes to generating higher economic output per unit of carbon emissions. The empirical investigation is based on a balanced panel dataset covering eight CEE countries over the period 2000–2024, yielding a total of 200 observations.

Before presenting the estimation results, Table 1 provides information on the variables employed in the analysis, including their definitions and measurement units.

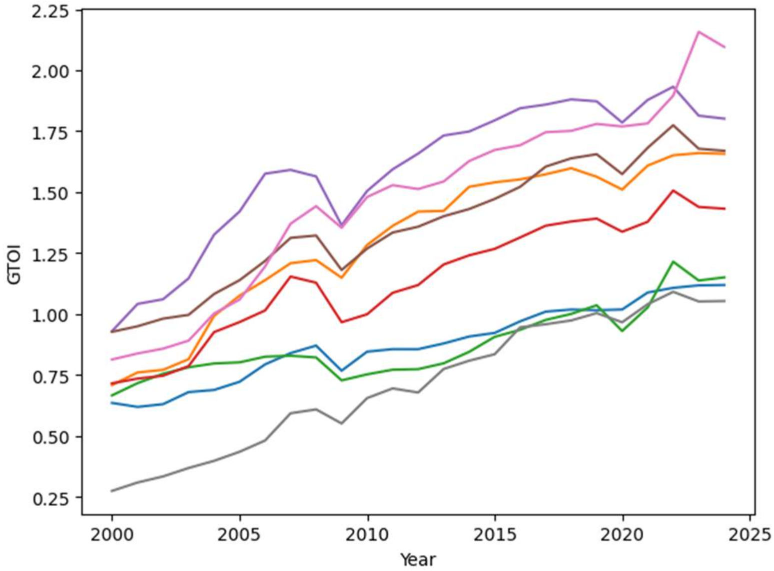
Tab. 1 Data Information

Variable	Definition	Measurement
CP	Carbon productivity	GDP / CO_2 emissions
GTOI	Green Trade Openness Index	(Green Exports + Green Imports) / GDP
RE	Renewable energy consumption	% of total final energy use
FDI	Foreign direct investment	Net inflows (USD)
LEI	Energy intensity	MJ per unit of GDP
LIND	Industrial value added	Log of industry value added
LNGDP	Income level	Log of real GDP

Source: World Bank, 2024

Carbon productivity (CP) serves as the dependent variable and captures environmental efficiency in output generation. The key explanatory variable, Green Trade Openness (GTOI), measures the intensity of environmentally related trade relative to economic size, distinguishing environmentally beneficial trade flows from aggregate trade openness. Renewable energy consumption (RE) reflects the share of renewables in total energy use and represents the energy transition dimension. Energy intensity (LEI) captures production efficiency, while industrial value added (LIND) controls for structural composition effects. Income level (LNGDP) accounts for economic development dynamics, and FDI controls for external capital flows that may influence technological upgrading and energy use.

Fig. 1 Trends in Green Trade Openness across Central and Eastern European Countries (2000–2024)



Source: Authors' calculations based on data from World Bank (2024).

Figure 1 illustrates the evolution of Green Trade Openness (GTOI) across CEE economies over the period 2000–2024. The overall pattern indicates a gradual upward trend in environmentally oriented trade integration across most countries. A temporary slowdown is observed around the 2008–2009 global financial crisis, followed by renewed growth in subsequent years. Notable cross-country heterogeneity persists throughout the sample, with some economies exhibiting consistently higher levels of green trade intensity. These dynamics provide preliminary evidence of structural divergence within the region and further justify the use of a heterogeneous panel framework in the empirical analysis. Following the presentation of variable definitions, Table 2 reports descriptive statistics for the dataset.

The descriptive statistics reveal considerable heterogeneity across CEE economies. Carbon productivity exhibits moderate dispersion, indicating variation in environmental efficiency across countries and time. Green Trade Openness shows relatively balanced distributional characteristics, suggesting that environmentally oriented trade integration varies but does not exhibit extreme outliers. Renewable energy consumption displays substantial variation, reflecting differences in energy transition pathways within the region.

Tab. 2 Descriptive Statistics

Variables	Obs	Mean	Std. Dev.	Min	Max	Skew.	Kurt.
CP	200	.056	.029	0	.155	.998	4.045
GTOI	200	1.17	.398	.275	2.157	.163	2.241
RE	200	16.377	7.291	3.7	34.1	.459	2.636
FDI	200	-3.9e+09	4.68e+09	-2.9e+1	2.77e+09	-2.438	10.894
LEI	200	.64	.123	.326	.958	.156	3.223
LIND	200	10.447	.369	9.872	11.251	.41	2.09
LNGDP	200	11.014	.339	10.483	11.818	.502	2.356

Source: Authors' calculations.

Moreover, FDI presents the largest dispersion and strong negative skewness, consistent with volatile capital movements and occasional capital outflows typical of transition economies. Energy intensity and income levels show comparatively stable distributions, indicating gradual structural adjustments over time. Thus, the variability observed in carbon productivity, renewable energy use, and green trade integration supports the application of a distribution-sensitive econometric framework. The presence of heterogeneity across observations justifies the use of the panel QARDL model to capture asymmetric short- and long-run dynamics.

Following the descriptive statistics, Table 3 reports the pairwise correlation coefficients. Focusing on the associations between the dependent variable, carbon productivity (CP), and the explanatory variables, several noteworthy patterns emerge. CP exhibits a statistically significant negative correlation with green trade openness and renewable energy consumption. In transition economies, periods of structural adjustment and energy transformation may temporarily weaken the output–emissions ratio, thereby generating negative short-run associations. CP is strongly and positively correlated with energy intensity, indicating a substantial linear association between these two variables. This highlights the central role of energy structure in shaping carbon efficiency across CEE economies. The relatively weak correlations between CP and FDI, industrial structure, and income level suggest that the direct linear association between these variables and carbon productivity is limited at the bivariate level. Therefore, the correlation results provide preliminary insights but do not imply causality. The mixed signs and varying magnitudes further justify the use of a multivariate and distribution-sensitive framework to uncover the short- and long-run determinants of carbon productivity.

Tab. 3 Correlation Matrix

	CP	GTOI	RE	FDI	LEI	LIND	LNGDP
CP	1.0000						
GTOI	-0.4261*	1.0000					
RE	-0.5021*	-0.0385	1.0000				
FDI	-0.0505	0.2101*	0.1990*	1.0000			
LEI	0.7385*	-0.1580*	-0.7141*	0.1339	1.0000		
LIND	-0.1046	-0.0806	-0.3296*	-0.6342*	-0.2480*	1.0000	
LNGDP	-0.1191	-0.0818	-0.2896*	-0.6613*	-0.2841*	0.9889*	1.0000

Notes: *, ** and *** indicate significance at 10%, 5% and 1% level, respectively. Source: Authors' calculations.

Table 4 shows the results of the cross-sectional dependence (CSD) tests. Given the economic integration of CEE countries within the European Union framework and their exposure to common external shocks, testing for cross-sectional dependence is essential before proceeding with panel estimations. The results of the Pesaran CSD, Friedman CSD, and Frees CSD tests consistently reject the null hypothesis of cross-sectional independence at the 1% significance level. The reported probability values ($p < 0.01$) indicate strong evidence of cross-sectional dependence among the panel units. This suggests that shocks affecting one CEE country are likely to spill over to others, reflecting regional economic interlinkages and policy coordination. Therefore, the existence of cross-sectional dependence justifies the adoption of panel techniques that are robust to interdependencies and dynamic heterogeneity, such as the QARDL framework employed in this study.

Tab. 4 Cross-sectional Dependence Test

Test	Test Statistic	Prob.
Pesaran CSD	1.451	0.0000
Friedman CSD	25.380	0.0006
Frees CSD	2.360	0.0001

Notes: 5% critical values for the Pesaran CSD Test ≈ 1.96, for the Friedman Test ≈ 1.645, and for the Frees Test ≈ 1.645. Source: Authors' calculations.

Table 5 reports the slope heterogeneity test results. Both and statistics are significant at the 1% level, leading to the rejection of the null hypothesis of slope homogeneity. This indicates that the effects of the explanatory variables on carbon productivity differ across CEE countries. The presence of slope heterogeneity supports the use of a heterogeneous panel framework, such as the QARDL model, which allows coefficients to vary across countries and across different levels of carbon productivity.

Tab. 5 Slope Heterogeneity Tests

Test	Test Statistic	Prob.
$\widetilde{\Delta}_{HAC}$	5.901	0.000
$\widetilde{\Delta}_{adj, HAC}$	7.156	0.000

Source: Authors' calculations.

Table 6 reports the panel unit root test results based on CIPS and CADF statistics. Considering cross-sectional dependence, second-generation tests are employed. The findings indicate a mixture of I(0) and I(1) variables across specifications. While some variables exhibit stationarity at levels, all series become stationary after first differencing. Importantly, none of the variables is integrated of order two. The presence of mixed integration orders confirms the suitability of the ARDL-based panel QARDL framework for the subsequent analysis.

Tab. 6 Panel Unit Root Test Results

		Level		First Difference	
Series	Model	CIPS	CADF	CIPS	CADF
CP	Constant	-2.300*	-1.799	-4.624***	-3.338***
	Constant&Trend	-2.782*	-2.368	-4.197***	-3.695***
GTOI	Constant	-1.947	-1.725	-4.870***	-2.260***
	Constant&Trend	-1.695	-1.805	-4.180***	-2.535***
RE	Constant	-2.361**	-1.624	-5.402***	-3.215***
	Constant&Trend	-2.513**	-1.956	-5. 593***	-3.658***
FDI	Constant	-3.876***	-2.032*	-5.394***	-3.257***
	Constant&Trend	-4.540***	-2.513*	-5.513***	-3.972**
LEI	Constant	-2.109**	-1.312	-5.112***	-3.118**
	Constant&Trend	-3.197***	-2.104*	-5.699***	-3.351***

		Level		First Difference	
LIND	Constant	-1.834	-1.245	-3.791***	-2.156**
	Constant&Trend	-1.612	-1.591	-4.522***	-2.443***
LNGDP	Constant	-1.839	-1.042	-3.616***	-3.085**
	Constant&Trend	-1.425	-1.566	-3.975***	-3.315***

Notes: *, ** and *** indicate significance at 10%, 5% and 1% level, respectively. Source: Authors' calculations.

Table 7 reports the diagnostic test results for the estimated model. The Breusch–Godfrey LM test indicates no evidence of serial correlation, suggesting that the residuals are not autocorrelated. However, the Breusch–Pagan–Godfrey test reveals the presence of heteroskedasticity, and the Jarque–Bera statistic rejects the null hypothesis of normality. The Ramsey RESET test is statistically significant, indicating potential functional form misspecification. Nevertheless, the mean VIF value of 5.90 suggests that multicollinearity is within acceptable limits and does not pose a severe concern. Thus, while heteroskedasticity and non-normality are detected, common in macro-panel datasets, the absence of serial correlation and acceptable multicollinearity levels support the robustness of the model, particularly when employing heteroskedasticity-robust estimation methods.

Tab. 7 Diagnostic Tests

Tests	Statistic / Value	Prob.
Ramsey RESET	3.31	0.0000
Breusch–Godfrey Serial Correlation (LM)	12.00	0.8812
Breusch–Pagan–Godfrey Heteroskedasticity	63.78	0.0000
Jarque–Bera Normality	556.8	0.0000
Variance Inflation Factor (VIF)	Mean VIF	5.90

Source: Authors' calculations.

Table 8 reports the short-run P-QARDL estimates across different quantiles of carbon productivity. The results reveal notable heterogeneity in the short-run dynamics. The short-run impact of green trade openness (DGTOI) is generally weak and statistically insignificant across most quantiles, except for limited significance at specific distributional levels. This suggests that the effects of environmentally oriented trade integration do not materialize immediately. Instead, the influence of green trade on carbon productivity appears to operate through gradual structural adjustments rather than short-term fluctuations. Renewable energy changes show mixed effects across quantiles. At lower quantiles, renewable energy exerts a statistically significant negative short-run effect, while at the median quantile the coefficient becomes positive and significant. This indicates that in less carbon-efficient economies, short-term renewable expansion may initially involve adjustment costs.

Changes in energy intensity are consistently positive and statistically significant across most quantiles. This suggests that short-run increases in energy intensity are associated with changes in carbon productivity, reflecting the strong structural link between energy use efficiency and environmental performance in CEE economies. FDI exhibits limited and inconsistent short-run effects, indicating that capital inflows do not immediately translate into improvements in carbon efficiency. Similarly, changes in industrial structure and income show modest and largely insignificant short-run effects across quantiles.

The error correction term (ECT) is negative and statistically significant across all quantiles, confirming the existence of a stable long-run equilibrium relationship. The magnitude of the adjustment coefficients varies across the distribution, ranging approximately between −0.11 and −0.17 in most quantiles. This implies that deviations from long-run equilibrium are corrected at a moderate speed, with approximately 11–17% of disequilibrium adjusted within each period. The stronger adjustment observed at higher quantiles suggests that more carbon-efficient economies converge faster toward equilibrium.

Tab. 8 Short-run P-QARDL Estimates

Quantile (τ)	DGTOI	DRE	DFDI	DLEI	DLIND	DLNGDP	ECT	Const.
0,10	0.00571	-0.0007*	-0.003	0.0874**	-0.0428	-0.0926	-0.149***	-0.0029***
	(0.023)	(0,001)	(0.00)	(0.087)	(0.089)	(0.160)	(0,064)	(0,001)
0,25	0.0020	-0.0003**	-0.004	0.1135***	-0.0115	0.0155	-0.1279***	-0.0016***
	(0,001)	(0,001)	(0.00)	(0.016)	(0.006)	(0,001)	(0,011)	(0.013)
0,50	0.0018	-0.0005***	-0.0011***	0.1087***	-0.0074	0.0209	-0.1186***	-0.007***
	(0,001)	(0,002)	(0.002)	(0.009)	(0.01)	(0,018)	(0,017)	(0,011)
0,75	-0.0034	-0.0002**	-0.0078	0.1028***	0.0051	0.0126	-0.1153***	0.0027***
	(0,005)	(0,001)	(0,002)	(0,021)	(0.021)	(0,039)	(0,016)	(0,034)
0,90	0.0172	0.0004	0.0042	0.2704	-0.0007	0.0582	-0.1696**	0.0051***
	(0,01)	(0,03)	(0,00)	(0.29)	(0,24)	(0,531)	(0,021)	(0,007)

Notes: Values in parentheses represent standard errors. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. Source: Authors' calculations.

Table 9 reports the long-run P-QARDL estimates across different quantiles of carbon productivity. The results reveal substantial heterogeneity in the long-run determinants of carbon productivity across the conditional distribution. The coefficient of green trade openness (GTOI) is negative and statistically significant across most quantiles, with its magnitude increasing toward the upper quantiles. At τ = 0.25, 0.5, 0.75, and 0.9, the effect becomes progressively stronger, reaching −0.0356 at the 90th quantile. This indicates that higher levels of green trade openness are associated with lower carbon productivity in the long run, particularly in relatively carbon-efficient economies. The increasing magnitude across quantiles suggests that the structural effects of environmentally oriented trade differ depending on the initial level of carbon efficiency.

Energy intensity (LEI) consistently exhibits a positive and highly significant coefficient across all quantiles. This confirms the strong role of energy structure in shaping carbon productivity. The magnitude of LEI remains large and stable, indicating that long-run improvements in energy efficiency are central to enhancing carbon productivity in CEE economies. Renewable energy (RE) shows limited significance in most quantiles, with a statistically significant negative coefficient only at the upper quantile. This suggests that the long-run impact of renewable energy on carbon productivity is conditional and may depend on broader structural factors. Foreign direct investment (FDI) does not exhibit robust long-run significance across quantiles, indicating that external capital inflows do not systematically influence carbon productivity in the region.

Tab. 9 Long-run P-QARDL Estimates

Quantile (τ)	GTOI	RE	FDI	LEI	LIND	LNGDP
0,10	-0.0152	-0.0053	0.0017	0.0730***	-0.0282	0.0366
	(0,005)	(0,004)	(0,01)	(0,07)	(0,04)	(0,00)
0,25	-0.0178***	0.0016	0.0021	0.1373***	-0.055**	0.0297*
	(0,004)	(0,113)	(0.02)	(0.015)	(0.015)	(0,01)
0,50	-0.0209***	-0.0008	-0.0025	0.1304***	-0.0047*	0.0287**
	(0,003)	(0,00)	(0.01)	(0.014)	(0.014)	(0,015)
0,75	-0.0292***	-0.0059	-0.0026	0.1467***	-0.0702**	0.0709
	(0,006)	(0,005)	(0.01)	(0.013)	(0,04)	(0,042)
0,90	-0.0356***	-0.0012***	-0.0024	0.1199***	-0.0601***	0.0397***
	(0,006)	(0,16)	(0.02)	(0.022)	(0.20)	(0,22)

Notes: Values in parentheses represent standard errors. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. Source: Authors' calculations.

Industrial structure (LIND) displays negative and significant effects at several quantiles. This implies that greater industrial value added may exert downward pressure on carbon productivity, reflecting the carbon-intensive nature of industrial activities in certain CEE economies. Income level (LNGDP) shows positive and statistically significant effects at middle and upper quantiles, suggesting that higher economic development supports long-run carbon efficiency improvements. The stronger effects at higher quantiles indicate that more advanced economies are better positioned to translate income gains into environmental efficiency improvements. As a result, the long-run results demonstrate pronounced distributional asymmetry. The determinants of carbon productivity differ significantly between lower and higher quantiles, underscoring the importance of using a quantile-based dynamic framework. The findings highlight the central role of energy efficiency and structural transformation in driving long-run carbon productivity in CEE economies.

To further interpret the negative long-run effect of green trade openness, it is important to consider the structural characteristics of CEE economies. Green trade integration often reflects increased imports of environmental goods rather than a transformation of domestic production, which remains largely carbon intensive. In addition, the persistence of energy-intensive production systems and reliance on fossil fuels limit potential efficiency gains. Finally, adjustment costs and limited absorptive capacity may delay the effective integration of green technologies. These factors suggest that without simultaneous industrial upgrading and energy transition, green trade openness alone may not enhance carbon productivity.

These findings can also be interpreted considering the pollution haven hypothesis and the technique effect discussed in the literature. The negative long-run impact of green trade openness is consistent with the pollution haven argument, suggesting that carbon-intensive production may persist or even expand in transition economies despite increased trade in environmental goods. At the same time, the expected technique effect, where trade integration leads to cleaner production technologies, appears to be limited or delayed in the CEE context. This indicates that the benefits of green trade in terms of technological upgrading and efficiency improvements may not materialize automatically, particularly in the presence of structural rigidities and limited absorptive capacity.

CONCLUSION

This study investigated the impact of green trade openness on carbon productivity in eight CEE economies over the period 2000–2024 using a panel QARDL framework. By constructing the GTOI that captures the environmental composition of trade flows, the analysis moved beyond conventional aggregate trade openness measures and provided a distribution-sensitive evaluation of trade–environment dynamics.

The empirical findings reveal pronounced heterogeneity across the conditional distribution of carbon productivity. In the long run, green trade openness exhibits a statistically significant negative effect across most quantiles, with stronger magnitudes at higher levels of carbon productivity. This suggests that environmentally related trade integration does not automatically improve carbon efficiency in CEE economies. Instead, the results indicate that structural characteristics and energy composition critically shape reflecting the persistence of carbon-intensive industrial structures, energy-dependent production systems, and limited absorptive capacity for green technologies. Energy intensity emerges as the most robust and strong determinant of carbon productivity across all quantiles, underscoring the central role of energy efficiency in the region's sustainability trajectory. Income level shows positive and significant effects at middle and upper quantiles, indicating that more advanced economies are better positioned to convert economic growth into environmental efficiency gains. In contrast, renewable energy and FDI display limited and distribution-dependent effects, suggesting that their impact operates through more complex structural mechanisms.

These findings carry important policy implications. The results indicate that expanding environmentally related trade flows alone is insufficient to enhance carbon productivity unless accompanied by structural transformation and improvements in energy efficiency. Policymakers in CEE economies should therefore prioritize reducing energy intensity through technological upgrading, industrial retrofitting, and modernization of energy systems. Strengthening domestic absorptive capacity, via investments in innovation, R&D, and human capital, appears essential to ensure that green trade flows translate into effective technology diffusion. Moreover, aligning industrial policy with green trade strategies and supporting a shift toward less carbon-intensive sectors can help convert trade integration into sustainable productivity gains. Given the regional interdependencies identified in the analysis, coordinated EU-level climate and energy policies may further enhance positive spillovers across CEE economies.

From a methodological standpoint, this study contributes to the literature by introducing an environmentally adjusted trade indicator tailored to transition economies and by employing a panel QARDL approach that captures heterogeneous short- and long-run dynamics. This distribution-sensitive framework uncovers effects that would remain obscured under conventional mean-based estimators. Despite these contributions, several limitations should be acknowledged. The GTOI is based on available classifications of environmental goods, which may not fully capture qualitative differences in technological sophistication. In addition, the analysis does not explicitly account for sectoral heterogeneity or institutional conditions that may influence the trade–environment nexus. Future research could extend this framework by incorporating sector-level data, alternative measures of carbon efficiency, and institutional moderators. Moreover, applying nonlinear threshold models may help identify potential turning points and better capture the conditional nature of the relationship between green trade openness and carbon productivity.

In sum, the relationship between green trade openness and carbon productivity in CEE economies is complex, heterogeneous, and structurally conditioned. Sustainable gains from environmentally oriented trade integration require complementary reforms in energy efficiency and structural transformation, rather than reliance on trade expansion alone.

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