Modeling the Impact of Green Trade Barrier Information Systems on Industrial Relocation:

A Spatio-Temporal Analysis With GVC Mediation

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ABSTRACT

This study analyzes how disparities in green trade barrier information systems (GTB-IS)—covering regulatory transparency, compliance monitoring, and standard interoperability—affect industrial relocation, with global value chain (GVC) integration as a mediator. Using panel data (2005–2022), the authors develop a spatio-temporal model to assess GTB-IS asymmetry impacts. Findings show advanced GTB-IS drives polluting industries to relocate, while green sectors remain stable due to technological and data dependencies. Manufacturing shifts to regions with lower GTB-IS maturity to reduce compliance burdens, whereas R&D activities stay in high-maturity areas with robust data infrastructure and standard-setting advantages. This research contributes to the literature by integrating dynamic modeling with GVC analysis, offering nuanced insights into the evolving interplay between environmental regulation and global production networks.

KEYWORDS

Green Trade Barriers, Regional Industrial Transfer, Dynamic Effects, Panel Data, Highly Polluting Industries

INTRODUCTION

In recent years, the global trade landscape has been undergoing profound adjustments, and the growing popularity of green development concepts has increasingly intertwined environmental protection with trade activities (Sarangi, 2019). Green trade barriers (GTBs)—represented by carbon tariffs, environmental certifications, and technical standards—are gradually replacing traditional tariffs as a core factor influencing the direction of international trade (Cao & Wang, 2017). Under the banner of ecological protection, these barriers reshape the comparative advantages of industries across countries by establishing differentiated environmental entry requirements: developed countries leverage their technological and standard-setting advantages to strengthen their trade influence, while developing countries face the challenge of sharply rising compliance costs (Guo, 2024). At the same time, regional industrial transfer, as a key manifestation of global value chain (GVC) restructuring, is exhibiting new characteristics—encompassing not only the gradient relocation of labor-intensive

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industries but also the cross-regional agglomeration of green technology industries (Niu & Yang, 2024). The rise of GTBs undoubtedly introduces more complex variables into this process.

Against this backdrop, this paper aims to explore the dynamic mechanisms through which GTBs affect regional industrial transfer. Specifically, it examines not only the immediate impact of such barriers on industrial spatial distribution upon initial implementation but also tracks their long-term, continuous effects through transmission channels such as cost dynamics and policy signals. It analyzes the differential impacts of various types of barriers and investigates the heterogeneous responses across different industries. By clarifying the dynamic relationship between GTBs and industrial relocation, this study seeks to provide theoretical insights and practical guidance for countries to facilitate orderly industrial transfer and avoid the risk of "low-end lock-in" during the green transition.

LITERATURE REVIEW

Over the past years, research on GTBs has expanded significantly in both academic and policy domains, with particular attention being paid to their evolution and future trajectories. Early forms of GTBs were largely voluntary, driven by buyers through environmental certifications and supply chain standards (Hsu et al., 2013). These were later institutionalized into mandatory national and regional technical regulations and environmental standards. In the most recent stage, exemplified by the European Union's carbon border adjustment mechanism (CBAM; Bellora & Fontagné, 2023), carbon pricing has been explicitly embedded into border policies, transforming GTBs from simple market-entry requirements into price-based, institutionalized cross-border adjustments. Scholars have argued that the CBAM is designed to prevent carbon leakage but is also restructuring global supply chains and trade patterns (Bao & Jin, 2025; Grácová, 2024).

The literature suggests that the future trajectory of GTBs will be shaped by three critical dimensions. First, the scope of coverage and the definition of emission boundaries will determine their economic and distributive effects. Expanding from direct emissions to indirect emissions and upstream supply chains can exponentially increase their impact (Clora et al., 2023). Second, GTBs are increasingly integrated into global climate governance, linking carbon pricing, emissions trading schemes, and discussions on "climate clubs." While broader institutional coordination could mitigate adverse effects on developing economies, unilateral implementation risks exacerbating global inequality (Amendola, 2025). Third, complementary measures—such as green finance, technology transfer, and transition assistance—are emphasized as essential for ensuring fairness and effectiveness. Without such measures, the CBAM could intensify "economic–carbon inequality" and trigger trade rerouting, leading to displacement rather than genuine emission reductions (Dobranschi et al., 2024). The relationship between regional industrial relocation and environmental policies has also drawn increasing attention, especially in debates around the "pollution haven hypothesis" versus the "upgrading pathway." The "pollution haven hypothesis" refers to the notion that polluting industries tend to relocate from regions with stringent environmental policies to those with lax regulations, as weaker environmental standards reduce compliance costs and create a "haven" for pollution-intensive production—an idea repeatedly discussed in prior studies on global industrial relocation (e.g., analyses of carbon-intensive sectors shifting to low-GTB regions in the document). In contrast, the "industrial upgrading pathway" describes an alternative trajectory: instead of relocating, industries respond to strict environmental policies by investing in green technology, improving production efficiency, and moving up global value chains. While traditional studies emphasized the relocation of pollution-intensive industries to regions with weaker environmental regulations, recent evidence reveals that this dynamic is strongly moderated by institutional quality, financial conditions, and technological capacity. In contexts with stronger governance and greater access to capital, both foreign and domestic firms are more likely to undertake green investment and emissions reduction, fostering industrial upgrading rather than simple relocation (Zhang & Sun, 2023). Recent cross-country and regional studies using multi-regional input–output (MRIO) and computable general equilibrium models and firm-level panel data highlight a dual-track dynamic: in the short term, carbon-intensive industries may shift to less regulated regions, but in the long term, regions with stronger innovation capacity may leverage GTBs to capture upgrading opportunities (C. Zhang & Jin, 2025).

Firm-level studies on green investment, innovation, and competitiveness provide further nuance. On the one hand, stricter environmental regulations and green investments tend to raise compliance and operational costs in the short run (Falcone, 2020). On the other hand, they stimulate green research and development, process improvement, and higher product value-added, which enhance export sophistication and long-term competitiveness (Chen et al., 2025). This conditional validity of the Porter hypothesis has been widely observed (Hu et al., 2021). In addition, digital transformation has emerged as an important driver of green innovation, although its effectiveness depends heavily on financing constraints. For firms with limited financial resources, digital investment may increase pressure rather than alleviate costs (Wang & Zhong, 2024). Moreover, recent studies show that green finance and institutional investors significantly boost corporate green innovation, underlining the importance of financial instruments in helping firms adapt to new international GTBs (Zhu & Liu, 2025).

Methodologically, recent research combines macro- and micro-level approaches. At the macro level, MRIO and computable general equilibrium models are widely used to evaluate the distributive impacts and transmission channels of the CBAM and similar policies. At the micro level, firm-level panel data and quasi-experimental designs (e.g., difference-in-differences, regression discontinuity, instrumental variables) reveal the mechanisms linking regulation, innovation, and competitiveness. The integration of these two approaches—using firm-level cost and emissions data to calibrate MRIO parameters—has been identified as a promising frontier. However, several research gaps remain, particularly regarding the long-term behavioral responses of firms under the CBAM's phased implementation, the adaptive capacity of developing economies in the absence of strong financial and technological support, and the challenge of reconciling firm-level emissions accounting with trade and customs data at the industry level (Amendola, 2025; Clòra et al., 2023).

DATA AND METHODS

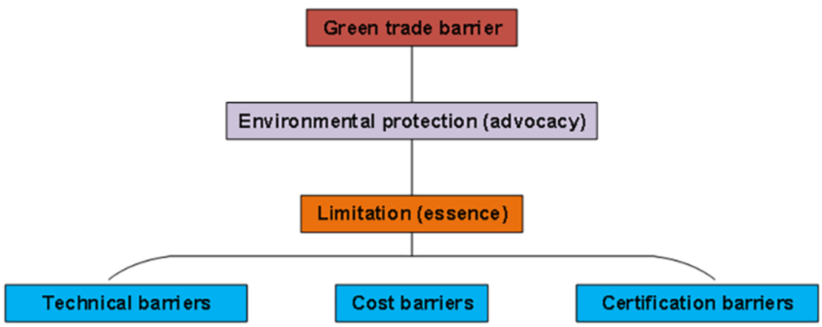
Definition and Classification of GTBs

The emergence of GTBs is essentially the product of intertwined environmental protection demands and trade interest competition (Olasehinde-Williams & Folorunsho, 2025). They are not merely simple trade restrictions but rather policy instruments that, under the guise of ecological protection, exert substantive impacts on cross-border trade by establishing specific standards, regulations, or procedures. Their core characteristic lies in a combination of apparent legitimacy and concealed protectionism—while aligning with the global consensus on sustainable development, they can indirectly restrict foreign competition and protect domestic industries by imposing differentiated market access requirements (Xu et al., 2024). GTBs refer to trade-related environmental measures—including technical standards, certification requirements, carbon tariffs, and eco-labeling schemes—that create compliance burdens for exporters and may function as non-tariff barriers. These differ from general environmental regulations in that they are directly tied to cross-border market access and often reflect strategic industrial or geopolitical objectives. Industrial relocation, in this context, denotes the geographic repositioning of production activities—particularly in carbon- or pollution-intensive sectors—driven by shifts in regulatory costs, market access conditions, or competitive pressures. It encompasses both offshoring (to lower-regulation jurisdictions) and reshoring (driven by green competitiveness). Environmental compliance cost refers to the sum of expenditures firms incur to meet foreign environmental standards, including technology upgrading, certification, monitoring, and administrative procedures. These definitions anchor the analytical framework and ensure consistency in interpretation across case studies.

Unlike traditional tariff barriers, GTBs typically do not directly raise the prices of imported goods. Instead, they increase exporters' compliance costs—or even deny them market access—by setting environmental technical requirements, inspection standards, or certification procedures (Mao & Lu, 2024). This shift from price-based to standards-based regulation marks a fundamental transformation in the architecture of global trade governance, reflecting the growing integration of environmental objectives into economic policy. The effectiveness of such barriers often hinges not on outright prohibition but on the asymmetric distribution of technological and financial capacity across countries. For instance, while large multinational corporations may absorb additional compliance costs through vertical integration or R&D investment, small and medium-sized enterprises (SMEs) in developing economies frequently lack the resources to adapt, leading to market exclusion and unequal competitive outcomes.

From the perspective of implementation methods and impact pathways, GTBs can be broadly categorized into three types, as shown in Figure 1.

Figure 1. Overview of Green Trade Barriers (GTBs)



Technical barriers are the most common form, primarily restricting the inflow of non-compliant goods by establishing stringent environmental technical standards (Zhao & Gao, 2025). These standards are often directly linked to production processes, raw material composition, or pollutant emissions and are frequently upgraded in line with technological advancements. For instance, Germany's strict requirements on automobile exhaust emissions not only affect the import of complete vehicles, but also compel component suppliers to enhance their environmental technologies (Crippa et al., 2016). The defining features of such barriers are their high technical specificity and rapid pace of evolution, posing significant challenges to SMEs in developing countries, which often lack sufficient technological capacity and financial resources to meet these standards.

Cost-based barriers influence industrial location by directly or indirectly increasing trade costs (McCormick et al., 2018), with the CBAM being a typical example. The European Union's carbon tariff, piloted since 2023, requires exporters of imported products such as steel and cement to pay additional fees based on the carbon emission intensity of these products during their production process—an arrangement that effectively incorporates carbon costs into the trade accounting system. The core mechanism of such barriers uses price signals to impose higher cross-border transaction costs on high-carbon industries, thereby incentivizing industrial relocation toward low-carbon regions (Chakraborty & Dey, 2024). Early data from the CBAM pilot phase show that Turkish steel exporters faced a 12–18% cost increase on average, prompting several firms to accelerate investments in electric arc furnaces or consider relocating partial operations to European Union member states. In addition, environmental surcharges and waste disposal fees imposed by some countries on imported goods also fall under cost-based barriers, with direct impacts on corporate profit margins. Japan's container and packaging recycling law, for example, requires foreign producers to pay recycling fees proportional to packaging volume, affecting exporters from Thailand, Indonesia, and India. These cost mechanisms not only alter trade flows, but also reshape investment decisions, as firms seek to internalize environmental costs within lower-risk jurisdictions.

Certification-based barriers center on a qualification review, controlling market access through the establishment of specific environmental certification systems (Galvin, 2011). The internationally recognized 2015 Environmental Management Systems — Requirements with Guidance for Use Certification (ISO 14,000 Environmental Management System certification), while not mandatory, has become a de facto threshold in many international procurement processes (Murray, 1997). The key challenge of such barriers lies in the complexity and regional variation of certification procedures—differences in standards across countries often require firms to undergo repetitive certification processes, increasing both time costs and market entry barriers (Boström et al., 2015). For export-dependent small and medium-sized agricultural enterprises, obtaining green certifications from developed countries often becomes a major obstacle to market expansion. For example, in Kenya's tea industry, for instance, compliance with the European Union's Global Good Agricultural Practice (Global G.A.P.) and rainforest alliance certifications has enabled some large estates to maintain market access, while smallholder farmers remain excluded due to high audit costs and complex documentation. Similarly, Indonesian palm oil producers face repeated certification demands from the European Union's deforestation regulation, requiring geospatial traceability down to the plantation level—a requirement that many smallholders cannot meet. These cases illustrate how certification systems, while promoting sustainability in principle, can function as exclusionary mechanisms in practice, reinforcing structural inequalities in GVCs.

Static Impact Mechanisms of GTBs on Regional Industrial Transfer

The static impact of GTBs on regional industrial transfer essentially reshapes the driving forces behind industrial spatial distribution by altering the cost structure and market environment for industries (Altenburg & Rodrik, 2017). This influence is immediate and based on policy constraints and market responses at a specific point in time, without involving dynamic feedback or adjustment over time.

The cost transmission mechanism constitutes the most direct pathway of influence. When GTBs take the form of technical standards or environmental investment requirements, firms must bear additional compliance costs—ranging from upgrading environmental equipment and replacing raw materials in production to third-party certification fees in testing processes. These expenditures directly squeeze profit margins (Gao et al., 2024). For highly polluting and energy-intensive industries, this cost pressure is particularly significant. For example, the European Union's REACH(Registration, Evaluation, Authorization and Restriction of Chemicals) regulation for chemical products requires companies to register and conduct safety assessments for thousands of chemicals, with testing costs alone potentially exceeding 10% of annual revenue for SMEs. When domestic compliance costs rise to a critical threshold, firms are naturally incentivized to relocate to regions with lower environmental standards and reduced compliance burdens. The cost differential created by such relatively lenient emission standards makes certain regions attractive for industries such as dye processing and electronic waste treatment.

The market access mechanism forces industrial relocation by directly restricting trading opportunities. When importing countries set green barriers high enough to block product entry, "local production" becomes a practical strategy to circumvent these restrictions. After China's photovoltaic industry faced anti-dumping and countervailing duties along with environmental standard restrictions from the European Union and the United States in 2012, its exports plummeted by 60%. This compelled Chinese firms to invest in and build factories in countries like Malaysia and Vietnam, leveraging local origin status to bypass trade barriers. Such relocation is not driven by differences in production costs but rather by the need to overcome physical market access barriers. Similarly, America's formaldehyde emission standards for imported furniture are far stricter than international norms. As a result, many Chinese furniture manufacturers have established plants in Mexico, utilizing the rules of origin under the North American free trade framework to enter the United States market as "locally produced" goods—effectively neutralizing the exclusionary effect of trade barriers through geographical relocation.

The policy signal mechanism guides industrial relocation by shaping market expectations (Zheng et al., 2025). The introduction of GTBs often sends a clear policy signal: high-barrier regions are transitioning toward low-carbon, environmentally friendly industries, while regions with lower standards may become "safe havens" for traditional industries. This signal influences long-term capital allocation decisions. When Germany introduced its New Federal Emission Control Act, significantly tightening automotive emission standards, it not only accelerated the electrification transformation of domestic automakers, but also prompted some traditional internal combustion engine component suppliers to shift production capacity to Eastern European countries. These destinations offer policy signals more favorable to manufacturing investment, as opposed to stringent environmental regulations.

These three mechanisms do not operate in isolation; rather, they interact and reinforce each other. Cost pressures push firms to seek alternative locations, market access restrictions eliminate fallback options, and policy signals indicate viable destinations. Together, they drive a static reallocation of industries across regions with varying levels of GTB stringency.

Dynamic Effect Mechanisms of GTBs on Regional Industrial Transfer

The impact of GTBs on regional industrial transfer is not a fixed, static outcome but rather exhibits multi-layered dynamic evolution over time. This dynamic effect arises from firms' adaptive responses to policy changes, the gradual restructuring of industrial ecosystems, and the interaction between barrier intensity and market reactions at different stages, ultimately forming distinct impact pathways across the short and long term.

In the short term, the imposition of barriers often triggers a dual response of "reactive relocation" and "wait-and-see adjustments." When a new green barrier is suddenly implemented, some firms lacking technological reserves and compliance capacity opt to quickly relocate production capacity to regions with lower barriers to mitigate risks. For instance, after the European Union abruptly tightened recycling standards for plastic packaging in 2019, approximately 30% of small and medium-sized plastic processing enterprises in Europe relocated their production lines to Turkey and North African countries within a year. This type of relocation is clearly emergency-driven, relying heavily on geographic proximity and policy arbitrage. However, another group of firms—particularly those with stronger technological foundations or greater financial capacity—may choose to temporarily absorb the increased costs while observing the policy trajectory rather than immediately relocating. This divergence leads to a "pulsed" pattern of industrial transfer in the short run, where the scale of relocation is positively correlated with the suddenness of barrier implementation.

In the long term, the dynamic effect manifests as sustained "path dependence" and "ecological lock-in." When green barriers persist and gradually intensify over time, industrial relocation shifts from an emergency response to strategic, systemic repositioning. The formation of Mexico's electronics cluster serves as a typical case: (1) Policy Context: The United States, as Mexico's core trade partner, gradually upgraded GTBs targeting the electronics industry. In 2003, the United States's Electronic Waste Recycling Act introduced technical barriers, mandating that imported electronics meet raw material harmlessness standards (e.g., heavy metal content $<$100ppm) and recyclability requirements (dis-assemblable ratio $\geq$85%). By 2007, the United States expanded to cost-based barriers via the Energy Independence and Security Act, imposing carbon footprint tracing and a 3–5% carbon tariff on high-emission electronic products. By 2015, the Untitled States's ERS index for electronics reached 6.8 (vs. 4.5 in Mexico), increasing compliance costs for non-domestic assemblers by 25–30% (per IEA 2016 data). In terms of industrial response, firms like Intel and Foxconn initially relocated assembly operations to Mexico post-2000 to bypass American technical barriers. From 2005 to

2010, Mexico's electronics FDI inflows surged by 120% (UNCTAD data), with assembly plants concentrated in border regions (e.g., Baja California). By 2015, supporting industries (packaging, logistics, component manufacturing) followed—local packaging suppliers increased by 80%, and logistics costs dropped by 15% due to agglomeration. For the long-term trend, by 2022, Mexico's electronics cluster accounted for 18% of its manufacturing GDP (up from 5% in 2000), with 70% of output exported to the United States. Even as American barrier tightening slowed after 2018, agglomeration effects sustained relocation: 2018–2022 saw 45 new electronics firms enter Mexico, driven by existing supply chain networks. Meanwhile, the United States (high-barrier region) retained high-value R&D and chip design, deepening "green lock-in" and widening the industrial gap with Mexico. This case illustrates how technical and cost-based GTBs first drive initial relocation, then agglomeration of supporting industries, and finally path-dependent further relocation—validating the long-term dynamic mechanism of GTBs.

The heterogeneity of dynamic effects is further evident in the interaction between barrier types and industry characteristics. The long-term impact of technical barriers follows a "stepwise" upgrading pattern: the European Union's REACH regulation updates its list of restricted chemicals every three years, compelling chemical firms to reassess their production locations after each revision, thus generating recurring pressure for relocation. Firms with strong R&D capabilities may remain in Europe through continuous innovation, while small and medium enterprises are pushed toward Southeast Asian countries with lower technological thresholds. In contrast, cost-based barriers (such as carbon tariffs) produce a "cumulative amplification" effect over time: as carbon prices rise from €30 to €90 per ton, the relocation elasticity of steel firms increases from 0.3 to 1.2 because initial cost increases can be absorbed through energy efficiency improvements, but long-term cumulative carbon costs eventually exceed the threshold of cost-effective retrofitting.

This dynamic evolution reveals that the influence of GTBs on industrial transfer is fundamentally a prolonged process of strategic interaction between policy pressure and market adaptation—neither an instantaneous static adjustment nor a simple linear transformation.

RESULTS

Empirical Analysis

This paper constructs a dynamic panel model to capture the dynamic effects of GTBs on regional industrial transfer. The model is specified as Eq. (1):

$$Y_{it} = \alpha Y_{it-1} + \beta_1 G_{it} + \beta_2 G_{it-1} + \beta_3 G_{it-2} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where Y_{it} represents the intensity of industrial transfer in region i in year t, measured by the ratio of manufacturing foreign direct investment inflows to GDP in that region; G_{it} denotes the intensity of GTBs, proxied by the Environmental Regulation Stringency index, which ranges from zero to 10, with higher values indicating stricter barriers; Y_{it-1} is the lagged dependent variable, capturing the dynamic inertia of industrial transfer; G_{it-1} and G_{it-2} are the first- and second-period lags of the core explanatory variable, respectively, included to examine short-term dynamic effects; X_{it} represents a vector of control variables, including GDP per capita (market size), unit labor cost, R&D expenditure as a share of GDP (technological level), and trade openness; and μ_i is the individual fixed effect, λ_t is the time fixed effect, and ε_{it} is the random error term. The data are drawn from a panel dataset of 50 major economies worldwide from 2005 to 2022, covering both OECD economies (e.g., the United States, Germany, Japan) and emerging market countries (e.g., China, India, Brazil); the sample is selected to ensure representativeness across different income levels, geographical regions, and industrial structures, thereby avoiding selection bias.

The baseline regression is estimated using the system GMM method, and the results are presented in Table 1 below. The coefficient of the core explanatory variable G_{it} is 0.032, significant at the 1% level, indicating that a one-unit increase in the intensity of GTBs is associated with an average increase of 0.032 units in the current period's industrial transfer intensity. This suggests an immediate promoting effect of GTBs on industrial relocation. The coefficient of the lagged dependent variable Y_{it-1} is 0.615, significant at the 1% level, confirming the presence of strong dynamic inertia in industrial transfer—past relocation levels have a significant positive influence on current relocation. Among the control variables, the coefficient for GDP per capita is 0.028 ($p < 0.05$), indicating that larger market size attracts more industrial transfer. The coefficient for unit labor cost is -0.017 ($p < 0.01$), suggesting that rising labor costs inhibit industrial relocation, which is consistent with theoretical expectations. Figure 2 shows the benchmark regression results.

Figure 2. Benchmark Regression Results: Coefficients and Significance of Each Variable

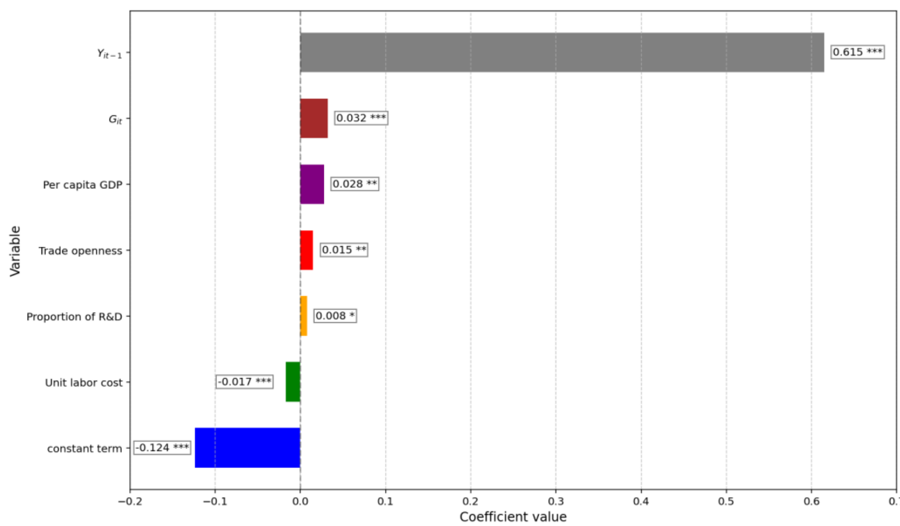


Table 1. Benchmark Regression Results

Variable	Coefficient	Standard Error	T-Value	P-Value
Y_{it-1}	0.615	0.052	11.83	0.000
G_{it}	0.032	0.009	3.56	0.000
Per capita GDP	0.028	0.012	2.33	0.020
Unit labor cost	-0.017	0.005	-3.40	0.001
R&D expenditure ratio	0.008	0.004	2.00	0.045
Trade openness	0.015	0.007	2.14	0.032
Constant	-0.124	0.041	-3.02	0.003

Note. * p<0.01, ** p<0.05, and *** p<0.1; the validity test of instrumental variables passed the Sargan test (p=0.231).

After introducing the lagged terms of the core explanatory variable, the regression results are shown in Table 2 below. The coefficient G_{it} is 0.025 (p<0.01), indicating a significant short-term immediate effect; the coefficient $G_{it\text{-}1}$ is 0.018 (p<0.05), and the coefficient $G_{it\text{-}2}$ is 0.011 (p<0.1), with absolute values of the coefficients decreasing over time, suggesting that the dynamic effect of GTBs weakens over time; and the long-term cumulative effect is mainly concentrated within one to two years after policy implementation. This finding is consistent with the theoretical analysis conclusion that "short-term reactive responses are stronger than long-term adjustments." For example, after the European Union upgraded its recycling standards for plastic packaging, the scale of industrial relocation surged in the short term, but as enterprises adapted technologically and markets adjusted, the pace of relocation slowed in later periods. Table 2 shows the results of the dynamic effect decomposition.

Table 2. Results of Dynamic Effect Decomposition

Variable	Coefficient	Standard Error	T-Value	P-Value
$Y_{it\text{-}1}$	0.582	0.056	10.39	0.000
G_{it}	0.025	0.008	3.13	0.002
$G_{it\text{-}1}$	0.018	0.007	2.57	0.010
$G_{it\text{-}2}$	0.011	0.006	1.83	0.067
Control variables	Controlled			

Note. * p<0.01, ** p<0.05, and *** p<0.1.

The sample is divided into highly polluting industries and green industries for subgroup regression, and the results are shown in Table 3 below. In the highly polluting industries group, the coefficient G_{it} is 0.047 (p<0.01), significantly higher than the full-sample level; in contrast, the coefficient G_{it} for the green industries group is 0.012 (p<0.05), indicating that highly polluting industries are more sensitive to GTBs and have stronger relocation intentions, thus corroborating the "pollution haven hypothesis." This is because highly polluting industries face higher compliance costs and are more inclined to relocate to regions with lower environmental standards when confronted with such barriers, as evidenced by the more pronounced shift of industries such as textiles and chemicals to Southeast Asia under the European Union's stringent regulations. In contrast, green industries exhibit lower relocation elasticity due to dependence on technological infrastructure and local market demand. Table 3 shows the regression results by industry group.

Table 3. Regression Results by Industry Group

Variable	Highly Polluting Industries	Green Industries
G_{it}	0.047***	0.012**
	(0.011)	(0.005)
$Y_{it\text{-}1}$	0.523***	0.685***
	(0.063)	(0.071)
Control variables	Controlled	Controlled

Note. *** p<0.01 and ** p<0.05; standard errors are in parentheses.

Figure 3. Trends in Green Train Barrier (GTB) Intensity and Industrial Relocation Intensity Over the Years

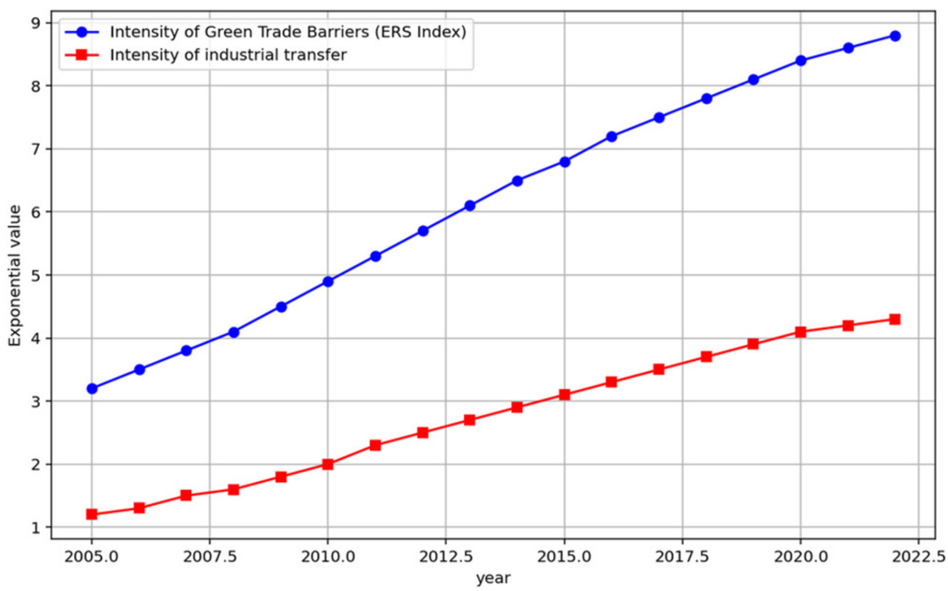


Figure 3 shows the trends in global GTB intensity (ERS index) and industrial relocation intensity from 2005 to 2022. As can be seen from the figure, the two indicators exhibit a generally synchronized upward trend. In particular, after 2012, the ERS index rose from 5.3 to 8.8, while industrial relocation intensity increased from 2.3 to 4.3, with roughly consistent slopes, visually confirming the positive association between GTBs and industrial relocation. During 2008–2009, industrial relocation intensity briefly declined due to the global financial crisis, but the ERS index continued to rise, indicating that the impact of green barriers is relatively rigid and not severely disrupted by short-term economic fluctuations.

Overall, the empirical results indicate that GTBs have a significant dynamic effect on regional industrial relocation, with both immediate and lagged effects present. Moreover, there is notable heterogeneity across different industries, with highly polluting industries being more sensitive to barrier intensity. Additionally, industrial relocation exhibits strong dynamic inertia, as the scale of prior relocation significantly influences current relocation decisions. These findings are consistent with the theoretical analysis and provide empirical evidence for understanding the relationship between GTBs and regional industrial relocation.

DISCUSSION

The division of labor within GVCs exerts a significant mediating effect in the process through which GTBs influence regional industrial relocation, offering a complementary explanation for the heterogeneity in dynamic responses observed across countries and industries. While the static cost transmission, market access restriction, and policy signal mechanisms operate at the national or firm level, their real-world impact is filtered through the structure of global production networks, where final goods are assembled from components produced across multiple jurisdictions. As GTBs—particularly those based on carbon accounting or lifecycle assessments—target not only final products but also upstream inputs, they generate regulatory spillovers that cascade backward along supply chains. This means that even firms located in countries with relatively lax domestic environmental regulations may face de facto compliance pressures if their products are integrated into exports destined for high-barrier markets such as the European Union or the United States. In this context, GVC integration does not merely facilitate trade; it becomes a channel through which environmental standards are enforced transnationally, reshaping the incentives for industrial location.

The nature of GVC participation thus conditions how firms respond to GTBs. For lead firms headquartered in high-regulation economies, relocating only final assembly stages may no longer suffice to circumvent carbon tariffs or technical standards, as these now cover embodied emissions from raw material extraction and intermediate production. As a result, there is growing pressure to reconfigure entire supply chains toward lower-carbon configurations, either through vertical integration or selective delocalization. In contrast, suppliers embedded in fragmented, arm's-length relationships—particularly SMEs in developing economies—are more likely to face abrupt exclusion unless they upgrade their processes, often lacking the financial or technological capacity to do so. This asymmetry reinforces a dualistic pattern: while some firms undertake strategic relocation to maintain market access, others are simply displaced, leading to uneven industrial adjustment across regions. Moreover, regions with established GVC hubs—such as East Asia in electronics or Central Europe in automotive manufacturing—exhibit stronger path dependence due to agglomeration economies and sunk investments in specialized infrastructure, making them less sensitive to short-term regulatory shocks despite rising green barriers. This suggests that the impact of GTBs is not uniform but is moderated by the depth and configuration of GVC integration.

From a policy perspective, the findings of this study can provide practical guidance for governments in balancing environmental regulation with industrial competitiveness. Policymakers should design environmental laws that gradually raise standards while avoiding excessive compliance costs that could accelerate industrial hollowing-out. At the same time, GTBs can be leveraged as tools for industrial upgrading by coupling them with targeted support policies such as green transition funds, subsidies for cleaner production technologies, or capacity-building programs for SMEs. Such policy packages would not only reduce the risk of relocation, but also enhance long-term competitiveness by stimulating green innovation and process efficiency. Importantly, the balance between environmental objectives and industrial resilience requires differentiated approaches across industries and development stages, ensuring that policy intensity matches the adaptive capacity of domestic firms.

Furthermore, incorporating more up-to-date data and emerging trends will enrich the analysis and ensure policy relevance. For example, the phased implementation of the CBAM, the expansion of carbon pricing schemes in East Asia, and the increasing role of green finance instruments are reshaping the trade–environment nexus. These developments underscore the need for the continuous monitoring of global regulatory trends and the integration of dynamic empirical data to refine both academic research and policy design.

Finally, the socioeconomic effects of industrial relocation under GTBs should not be overlooked. On the one hand, relocation may generate employment opportunities and investment inflows in host regions, particularly in developing economies. On the other hand, it can also produce negative externalities, such as environmental degradation, labor market segmentation, and social inequality, if relocated industries remain highly polluting or exploitative. For origin countries, the rapid outflow of industries may weaken domestic industrial bases and exacerbate regional disparities. Policymakers should therefore adopt complementary measures—such as social safety nets, workforce reskilling programs, and regional development strategies—to mitigate adverse impacts and ensure that the green transition is both environmentally effective and socially equitable.

In sum, the evolving interplay between GTBs and regional industrial transfer cannot be fully understood without accounting for the mediating role of GVCs, the practical considerations of policy design, the integration of current global trends, and the socioeconomic consequences of relocation. Only by adopting a comprehensive and forward-looking approach can policymakers and firms turn the challenges of GTBs into opportunities for sustainable and inclusive growth.

CONCLUSION

The study shows that GTBs have a significant and multidimensional dynamic impact on regional industrial relocation. In terms of mechanisms, technological, cost-based, and certification barriers affect industrial layout through technological thresholds, cost leverage, and access restrictions, respectively. At the static level, cost transmission, market access, and policy signaling mechanisms lead to immediate spatial restructuring. At the dynamic level, this manifests as the combined effect of short-term reactive relocation and long-term path dependency. Empirical results confirm the positive association between barrier intensity and industrial relocation, with dynamic effects diminishing over time. Highly polluting industries exhibit greater relocation elasticity due to higher compliance costs, while green industries show lower relocation willingness due to technological and market dependencies. Moreover, the mediating effect of GVCs is significant: manufacturing segments tend to relocate to low-barrier regions, whereas core technology segments experience a "standard lock-in" effect in high-barrier regions.

In the future, countries need to respond strategically to the impacts of GTBs, and developing countries—given their divergent industrial structures and development stages—require differentiated policy frameworks tailored to their unique challenges. For labor-intensive dominant developing countries, the core constraint lies in excessive green certification costs rather than technological R&D gaps. These countries should prioritize reducing certification burdens: they can establish regional mutual recognition agreements for green certifications and advocate for international organizations (such as the United Nations' Conference on Trade and Development) to provide targeted subsidies for SMEs covering certification fees. Additionally, building public inspection and testing platforms can lower the per-unit cost of compliance, helping labor-intensive industries maintain market access without sacrificing cost competitiveness. For high-pollution industry transitioning developing countries, the key challenge is balancing the avoidance of "low-end lock-in" and "industrial hollowing out." These countries should adopt a "restructure while retaining" strategy: first, they should implement phased environmental standards for high-pollution industries to prevent the hasty relocation of core manufacturing capacity. Second, they should establish green transition funds to support process innovation—for example, subsidizing steel enterprises to adopt electric arc furnace technology or cement plants to deploy carbon capture systems—reducing compliance costs while preserving industrial value chains. Third, they should restrict the relocation of only the most pollution-intensive links while retaining high-value segments to avoid deindustrialization. For green industry cultivating developing countries, the focus should be on leveraging GTBs as a catalyst for industrial upgrading. These countries can prioritize building technological ecosystems for emerging green sectors: for instance, establishing industrial parks for solar photovoltaic manufacturing that integrate upstream raw material supply, midstream module production, and downstream installation services to form agglomeration effects. They can also strengthen partnerships with high-barrier economies in green technology co-development—participating in joint R&D on low-carbon technologies to align local standards with international benchmarks, thereby avoiding "standard isolation" and enabling their green industries to compete in high-value global markets. Developed countries, in turn, can facilitate global coordination by promoting the harmonization of green standards through technical cooperation and providing targeted technology transfer to developing countries—particularly in areas like pollution control and carbon accounting—to reduce trade friction arising from standard discrepancies. Policymakers worldwide should monitor the dynamic evolution of GTBs, design interventions based on industry and national heterogeneity, and guide polluting industries toward green transformation rather than simple offshoring. Future research could expand sample coverage by incorporating more firm-level data from developing countries and explore the interactions between GTBs and factors such as digital trade and green finance, providing more refined theoretical support for the green restructuring of GVCs.

COMPETING INTERESTS STATEMENT

The authors of this publication declare there are no competing interests.

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All authors contributed to the study conception and design. Wenjie Zhang was primarily responsible for data collection, empirical analysis, and initial manuscript drafting. Li Chen contributed to the theoretical framework development, model design, and critical revision of the manuscript. Both authors collaborated on the interpretation of results and approved the final version of the article.

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REFERENCES

Altenburg, T., & Rodrik, D. (2017). Green industrial policy: Accelerating structural change towards wealthy green economies. *Green Industrial Policy*, *1*, 2–20.

Amendola, M. (2025). Winners and losers of the EU carbon border adjustment mechanism. An intra-EU issue? *Energy Economics*, *142*, 108139. DOI: 10.1016/j.eneco.2024.108139

Bao, X., & Jin, Y. (2025). Insight into border carbon adjustment: A visual bibliometric analysis from 2009 to 2024. *Humanities & Social Sciences Communications*, *12*(1), 1114. DOI: 10.1057/s41599-025-05401-x

Bellora, C., & Fontagné, L. (2023). EU in search of a carbon border adjustment mechanism. *Energy Economics*, *123*, 106673. DOI: 10.1016/j.eneco.2023.106673

Boström, M., Jönsson, A. M., Lockie, S., Mol, A. P. J., & Oosterveer, P. (2015). Sustainable and responsible supply chain governance: Challenges and opportunities. *Journal of Cleaner Production*, *107*, 1–7. DOI: 10.1016/j.jclepro.2014.11.050

Cao, B., & Wang, S. (2017). Opening up, international trade, and green technology progress. *Journal of Cleaner Production*, *142*, 1002–1012. DOI: 10.1016/j.jclepro.2016.08.145

Chakraborty, D., & Dey, O. (2024). Trade policy and price-based barriers. In Chakraborty, D., & Dey, O. (Eds.), *Influence of WTO and global dynamics on trade flows: A machine-generated literature overview* (pp. 183–244). Springer Nature Singapore. DOI: 10.1007/978-981-99-7375-0_2

Chen, Y., Li, W., Zeng, L., & Chen, M. (2025). Quality or quantity? The impact of voluntary environmental regulation on firm's green technological innovation: Evidence from green factory certification in China. *Sustainability (Basel)*, *17*(6), 2498. DOI: 10.3390/su17062498

Clora, F., Yu, W., & Corong, E. (2023). Alternative carbon border adjustment mechanisms in the European Union and international responses: Aggregate and within-coalition results. *Energy Policy*, *174*, 113454. DOI: 10.1016/j.enpol.2023.113454

Crippa, M., Janssens-Maenhout, G., Guizzardi, D., & Galmarini, S. (2016). EU effect: Exporting emission standards for vehicles through the global market economy. *Journal of Environmental Management*, *183*, 959–971. DOI: 10.1016/j.jenvman.2016.09.068 PMID: 27681872

Dobranschi, M., Nerudová, D., Solilová, V., & Stadler, K. (2024). Carbon border adjustment mechanism challenges and implications: The case of Visegrád countries. *Heliyon*, *10*(10), e30976. Advance online publication. DOI: 10.1016/j.heliyon.2024.e30976 PMID: 38770295

Falcone, P. M. (2020). Environmental regulation and green investments: The role of green finance. *International Journal of Green Economics*, *14*(2), 159–173. DOI: 10.1504/IJGE.2020.109735

Galvin, S. S. (2011). Nature's market? A review of organic certification. *Environment and Society*, *2*(1), 48. DOI: 10.3167/ares.2011.020104

Gao, J., Hua, G., & Huo, B. (2024). Digital technology, green innovation, and high-quality economic development: Mechanism analysis and empirical evidence. *Journal of the Knowledge Economy*, *16*(3), 12011–12047. Advance online publication. DOI: 10.1007/s13132-024-02355-4

Grácová, K. (2024). *Union carbon border adjustment mechanism*. Central European University.

Guo, Y. (2024). Green trade barriers under the developing country perspective. *Future Human Image*, *21*, 4–15. DOI: 10.29202/fhi/21/1

Hsu, C. C., Choon Tan, K., Hanim Mohamad Zailani, S., & Jayaraman, V. (2013). Supply chain drivers that foster the development of green initiatives in an emerging economy. *International Journal of Operations & Production Management*, *33*(6), 656–688. DOI: 10.1108/IJOPM-10-2011-0401

Hu, Y., Sun, S., & Dai, Y. (2021). Environmental regulation, green innovation, and international competitiveness of manufacturing enterprises in China: From the perspective of heterogeneous regulatory tools. *PLoS One*, *16*(3), e0249169. DOI: 10.1371/journal.pone.0249169 PMID: 33784363

Mao, Y., & Lu, S. (2024). Intelligent analysis of import and export in green trade barrier based on big data analysis. *Ecological Chemistry and Engineering. S*, *31*(1), 117–126. DOI: 10.2478/eces-2024-0009

McCormick, R., Cohen, S., Hunter, A. P., & Sanders, G. (2018). *National technology and industrial base integration: How to overcome barriers and capitalize on cooperation*. Rowman & Littlefield.

Murray, P. C. (1997). International environmental management standard, ISO 14000: A non-tariff barrier or a step to an emerging global environmental policy. *U. Pa. J. Int'l Econ. L., 18*, 577. https://scholarship.law.upenn.edu/jil/vol18/iss2/7

Niu, G., & Yang, Y. (2024). Research on the carbon reduction effect of regional industrial transfer in China—Based on the perspective of factor flow. *Heliyon*, *10*(14), e33771. Advance online publication. DOI: 10.1016/j.heliyon.2024.e33771 PMID: 39100439

Olasehinde-Williams, G., & Folorunsho, A. (2025). Environmental policy, green trade and sustainable development in Europe: New perspective on the Porter hypothesis. *Energy & Environment*, *36*(3), 1443–1461. DOI: 10.1177/0958305X231193870

Sarangi, U. (2019). Green economy, environment and international trade for global sustainable development. *Journal of International Economics*, *10*(2), 44–60.

Wang, X., & Zhong, X. (2024). Digital transformation and green innovation: firm-level evidence from China [Original Research]. *Frontiers in Environmental Science, 12*. DOI: 10.3389/fenvs.2024.1389255

Xu, P., Jin, Z., & Wu, X. (2024). Effect of green trade barriers on export enterprise green technological innovation from the perspective of the low-carbon city pilot policy [Original Research]. *Frontiers in Environmental Science, 12*. DOI: 10.3389/fenvs.2024.1486855

Zhang, C., & Jin, L. (2025). Weakly binding carbon policy, FDI evolution, and the pollution haven hypothesis: A difference-in-differences analysis of China's low-carbon pilot cities [Original Research]. *Frontiers in Environmental Science, 13*. DOI: 10.3389/fenvs.2025.1554728

Zhang, W., & Sun, C. (2023). How does outward foreign direct investment affect enterprise green transition? Evidence from China. *Journal of Cleaner Production*, *428*, 139331. DOI: 10.1016/j.jclepro.2023.139331

Zhao, P., & Gao, S. (2025). Green trade barriers, financial support and agricultural exports. *International Review of Economics & Finance*, *97*, 103758. DOI: 10.1016/j.iref.2024.103758

Zheng, X., Huang, J., & Yuan, Z. (2025). Move to innovation: Place-based industrial relocation policy and firm innovation in China. *International Journal of Emerging Markets*, *20*(1), 157–186. DOI: 10.1108/IJOEM-08-2022-1299

Zhu, S., & Liu, L. (2025). Green institutional investors and corporate green innovation: Evidence from Chinese listed companies. *International Review of Economics & Finance*, *103*, 104476. DOI: 10.1016/j.iref.2025.104476

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