



The cascading effects of the Sino-US trade friction on global carbon emissions

Xiaozhe Li^{1,2,3} · Weijing Ma² · Jingwen Kou² · Xiaoya Wang² · Tingting Liang² · Jinhuang Mao³

Received: 14 October 2024 / Accepted: 16 September 2025
© The Author(s), under exclusive licence to Springer Nature B.V. 2025

Abstract

Sino-US trade friction, as a manifestation of anti-globalization trade behavior, is poised to exert a substantial impact on global carbon emissions. However, the underlying mechanisms remain insufficiently understood. This study employs the GTAP-E model to investigate the potential effects of Sino-US trade tensions on global trade flows, energy consumption, and carbon emissions from 2025 to 2050. We consider three tariff scenarios, accounting for both the presence and absence of Non-Tariff Barriers. The key findings are as follows: (1) Sino-US trade friction reduces trade volumes for most countries and regions globally, with the exception of non-US North America, Southeast Asia, and East Asia, where trade volumes increase. (2) The trade friction induces positive structural effects in North America (excluding the US), but negative structural effects in Southeast Asia, alongside a worldwide negative technological effect. (3) Carbon emissions intensify in Europe, Southeast Asia, and the Middle East due to the trade friction, while they significantly decline in North America, Oceania, and China.

Keywords International trade · Energy consumption · Carbon emissions · Cascading effects · Sino-US friction

1 Introduction

While international trade fosters economic growth, it also has significant implications for the global environment. On one hand, trade can help mitigate environmental degradation by promoting technological innovation (Wang et al., 2024a, 2024b) and stimulating economic

✉ Weijing Ma
maweijing@lzu.edu.cn

¹ China Center for Energy Economics Research, School of Economics, Xiamen University, Xiamen 361005, China

² College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China

³ School of Economics, Lanzhou University, Lanzhou 730000, China

development (Xie & Wu, 2021). On the other hand, the expansion of trade and production activities often leads to environmental challenges, including increased energy consumption and emissions (Felbermayr et al., 2025), particularly in developing countries (Wiedmann & Lenzen, 2018). As a form of anti-globalization behavior, Sino-US trade friction has considerable environmental ramifications on a global scale. Studies have shown that trade barriers—exemplified by the Sino-US dispute—negatively impact the economies of various countries (Amiti et al., 2019; Fajgelbaum et al., 2020). At the same time, such barriers affect the environment through a range of direct and indirect channels. These include supply chain reallocation and structural shifts in industry driven by changes in trade patterns (Yuan et al., 2023), which ultimately influence energy use and carbon emissions (Hou et al., 2019). Research further suggests that the continuation of tariffs could result in a 5% reduction in global greenhouse gas emissions (Liu et al., 2020). However, with the rapid pace of global economic development, many countries have achieved growth at the cost of resource overconsumption and environmental degradation, thus jeopardizing the long-term sustainability of that growth (Zhang et al., 2013). Moreover, environmental and social sustainability has been found to significantly influence business practices and decision-making (Ellili, 2024). It is increasingly urgent for countries to explore new development pathways that harmonize growth with ecological sustainability (Schandl et al., 2016). This highlights the importance of thoroughly assessing the environmental consequences of trade barriers—especially in the context of China and the United States, given that China remains a major source of global carbon emissions, largely driven by export-related activities (Ünal et al., 2023).

However, the existing literature still suffers from several notable limitations. First, many studies rely on static GTAP models, which cannot capture the dynamic environmental impacts that evolve over time. By contrast, this paper adopts a dynamic GTAP framework to better reflect temporal changes. Second, prior research rarely engages with the underlying mechanisms from a theoretical perspective, whereas this study draws on the ACT framework to analyze the effects through the channels of scale, technology, and structure. Third, discussions of trade policy have been largely confined to tariff measures, with insufficient attention to the role of Non-Tariff Barriers (NTBs). This paper explicitly incorporates both dimensions. Finally, existing studies seldom address the issue of distributional equity in environmental impacts, thereby limiting their policy relevance. By filling these gaps, this paper not only advances the methodological rigor of GTAP-based analyses but also provides a more comprehensive and policy-oriented understanding of the environmental consequences of Sino-US trade frictions. This paper seeks to investigate the environmental impacts of carbon emissions in the context of trade barriers, with a particular focus on the China-US trade dispute. It aims to make a modest contribution to the existing body of research, provide a foundation for national-level trade policymaking. It also offers theoretical support for building a more sustainable international economic order—an endeavor of both theoretical and practical significance.

Sino-US trade friction can be traced back to the period following China's accession to the World Trade Organization (WTO) in 2001, as China's rapid economic rise increasingly positioned it as a strategic competitor in the eyes of the United States. Tensions escalated significantly after President Trump took office in 2017, with longstanding concerns over trade imbalances and intellectual property rights bringing these issues to the forefront. Between 2018 and 2019, the U.S. imposed tariffs on Chinese steel, aluminum, and a wide range of other goods, citing national security and unfair trade practices, among other rea-

sons. China responded with retaliatory measures. Following intense negotiations, the two countries signed a “phase one agreement” in December 2019, which helped ease tensions but failed to address the underlying structural conflicts. The trade friction had widespread effects across multiple sectors. In manufacturing and supply chains, companies relocated production lines to mitigate tariff impacts. U.S. agriculture suffered from reduced exports to China. High-tech industries, particularly firms like Huawei, were severely affected by U.S. export restrictions on key technologies. The automotive sector revised strategic plans, and the energy industry experienced heightened market volatility. This trade conflict represents not only an economic standoff but also a broader struggle over competing interests in globalization. In the short term, it disrupted various industries, while in the long term, it has the potential to reshape the global supply chain landscape. Although the 2020 “phase one agreement” marked a temporary de-escalation, deep-rooted competition in technology, finance, and global governance rules persists—leaving the future of U.S.-China relations uncertain.

2 Literature review

Most existing studies focus on the economic impacts of Sino-US trade friction. From China’s perspective, the prevailing view is that such trade tensions hinder China’s economic development by suppressing export volumes (Liu & Deng, 2024). Some scholars argue that the friction adversely affects several key industries, significantly curbing export trade. In particular, exports in sectors central to the “Made in China 2025” strategy—such as communications equipment, machinery, and transportation—are disproportionately impacted (Yu & Zhang, 2019), with especially pronounced effects on electronics and related industries (Yang, 2024). Other studies suggest a more complex picture: trade friction has increased domestic employment pressures, reduced China’s trade surplus with the United States, and curtailed capital outflows. At the same time, however, non-tradable sectors in China have seen gains in the form of rising domestic investment and consumption demand (Yang et al., 2023). At the firm level, research indicates that trade friction can spur innovation among exporters through the “export capture effect”, enhancing competitiveness and driving industrial upgrading (Xu et al., 2022). This dynamic has been shown to contribute to the high-quality development of China’s foreign trade (Leihua & Fan, 2024). However, heightened trade policy uncertainty also delays the market entry of exporters and negatively affects trade flows (Handley, 2014), with the adverse effects of U.S. economic policy uncertainty being particularly significant (Bahmani-Oskooee & Xu, 2022). From the U.S. perspective, macro-level studies based on traditional trade and general equilibrium models show that trade friction with China reduces national income and raises prices across a wide range of goods—especially imports—with the burden of tariffs falling entirely on domestic consumers and importers (Amiti et al., 2019; Fajgelbaum & Khandelwal, 2022; Handley, 2014). Beyond economic effects, some scholars highlight both positive and negative impacts on labor markets and social welfare in both countries, though these welfare effects are asymmetrical and not equally distributed between China and the U.S. (Bouët & Laborde, 2018; Li et al., 2018; Qin et al., 2022). At the industry level, Taheripour and Tyner (2018) examine the potential negative consequences for the U.S. agricultural sector. From a global perspective, research shows that Sino-US trade friction disrupts global value chains and the international trade system (Lawrence, 2018; Xing & Yuan, 2025). Using historical

data and a decomposition method based on the total trade accounting framework, Wang and Shi (2022) find that U.S. tariffs on China lead to structural adjustments in value-added trade. In Asia and the Americas, these adjustments manifest as diffusion effects, while in Europe, the impact tends to be positive—highlighting the multilateral implications of a bilateral trade conflict. Moreover, several studies argue that Sino-US trade tensions are reshaping global trade patterns, potentially promoting GDP growth and improving welfare in other countries and regions. As trade flows shift away from China and the U.S., major trading partners—particularly emerging economies—stand to benefit (Carvalho et al., 2019; Li et al., 2020; Rosyadi & Widodo, 2018; Shen et al., 2021). For instance, U.S. imports from China have increasingly shifted to countries such as Mexico, Japan, and Germany, while China has turned to alternative sources including Brazil, Germany, and Japan for its imports from the U.S.

Few studies have examined the environmental impacts of trade barriers, particularly those arising from Sino-US trade friction. However, with the recent rise in trade-restrictive measures, this area has gradually attracted scholarly attention. Wang et al., (2024a, 2024b) investigated the environmental effects of Sino-US trade friction by focusing on agricultural nitrogen loss, using agriculture as the main research sector. Guo et al. (2021) adopted a global perspective and found that trade friction between China and the United States has led to increased trade diversion and longer transportation distances, thereby intensifying global carbon emissions from shipping. Nevertheless, much of the existing literature tends to focus on the heterogeneous effects of trade barriers across different countries and regions. Based on simulations using the GTAP model under various tariff scenarios, Lin et al. (2019) concluded that, compared to trade barriers, free trade results in higher carbon emissions, worsens air pollution, and disproportionately affects developing countries with already high emission levels. Under the context of Sino-US trade friction, Liu et al. (2020) employed a CGE model to assess its potential economic and environmental impacts during the Trump administration. Their findings suggest that while trade friction alters global emission patterns and reduces carbon emissions in both China and the US—thereby improving air quality in most countries—it simultaneously has adverse environmental consequences for less developed regions (Liu et al., 2020) and heightens global climate risks (Yao et al., 2025). Building on this, Du et al. (2020) observed that Sino-US trade friction only marginally reduces emissions in China and the US, but leads to emission reductions in Western Europe, Latin America, and the Caribbean, while increasing emissions in neighboring economies such as Canada, Japan, and South Korea. Nevertheless, existing GTAP-based studies exhibit several important limitations. First, most rely on the conventional GTAP framework and assess environmental impacts only indirectly through changes in economic output, which may obscure the complex pathways through which trade influences environmental outcomes. Second, they tend to focus narrowly on tariff measures, without jointly accounting for the interplay between trade barriers and NTBs, thereby underestimating the full scope of trade frictions. Third, these studies often neglect a theoretical discussion of the underlying mechanisms, which limits their ability to explain how and why trade frictions shape environmental performance. Finally, insufficient attention has been devoted to the unequal distribution of impacts across countries and regions, leaving the policy implications less compelling. By directly addressing these shortcomings, this paper aims to deepen the analytical framework of GTAP-based research and generate conclusions that are not only methodologically robust but also more relevant for real-world policy debates.

In summary, research on the environmental impacts of trade barriers—particularly those exemplified by Sino-US trade friction—has only emerged relatively recently. Early studies primarily focused on the economic and social implications. However, in recent years, with the growing instability of the international landscape, the proliferation of both explicit and implicit trade barriers, and the escalating urgency of global climate change, academic attention to the environmental dimension has gradually increased. Nonetheless, relevant studies remain limited. Most of the existing literature concentrates on the two primary parties involved in the trade friction and provides only broad analyses of carbon emission patterns, with relatively little exploration of the specific mechanisms at play.

To address this gap, this paper takes the Sino-US trade friction as a case study to investigate the actual pathways through which trade barriers affect carbon emissions, disaggregated by industry and region. The aim is to contribute to the theoretical understanding of this issue and offer a potential basis for more coordinated economic and environmental policy-making. To this end, this study employs the GTAP model to simulate and analyze the potential environmental impacts associated with trade friction. First, using graphical presentation and data analysis, the paper examines the overall effects of Sino-US trade friction on global trade volume, energy consumption, carbon emissions, and their structural characteristics. Second, drawing on the ACT model, it analyzes the environmental transmission pathways of trade friction—specifically through trade scale, industrial structure, and technological change—to further explore the mechanisms behind carbon emissions. Finally, the paper investigates the heterogeneity of the environmental effects of trade barriers across different regions and sectors. The main contributions of this paper are as follows: First, it incorporates NTBs into the analysis, thereby reflecting a more realistic trade environment. Second, based on ACT theory, it conducts a detailed examination of the environmental effects of trade barriers using the Sino-US trade conflict as an illustrative case. This enables a more comprehensive understanding of the environmental consequences triggered by significant trade shocks.

3 Material and methods

3.1 GTAP model and scenario setting

3.1.1 GTAP model

Most traditional methodologies used to analyze policy shocks rely on econometric models, such as the Difference-in-Differences (DID) approach. However, these methods are generally grounded in partial equilibrium models, which have a limited scope for incorporating various factors. This limitation often hinders a thorough and nuanced analysis, especially when dealing with complex phenomena. The trade friction between China and the United States, as a major event involving the two largest economies in the world, is likely to produce a wide range of far-reaching and intricate consequences. Conventional econometric models may struggle to accurately capture the full impact of such a complex event. As a result, this study employs the GTAP model, which adopts a general equilibrium framework, to better understand the dynamics of this global economic interaction.

The Global Trade Analysis Project (GTAP), developed by Purdue University, is built upon neoclassical economic theory. At its core, the model is a multi-region, multi-sector Computable General Equilibrium (CGE) framework that evaluates the effects of international trade and policy changes on the global economy through comprehensive simulations. The GTAP system consists of a primary program, RunGTAP, and a database, GTAPAgg, which is based on a series of economic equations that seek to find equilibrium in line with neoclassical economic theory. The program sets up a set of economic equations for equilibrium. The database captures extensive data on the economic activities of countries (or regions) worldwide, including production, consumption, trade, and the use of various factors of production. It reflects the latest trends and status of the global economy, updated and expanded regularly.

The static GTAP model is constrained by its database, with the most recent version using 2017 data. Consequently, data is extrapolated through a dynamic recursive method to meet specific research needs. The dynamic recursive model accounts for factors such as GDP growth, population growth, labor force expansion, and capital accumulation over time. It treats these variables as exogenous and updates the data based on the original database, allowing for more accurate analysis of the potential impacts of current and future economic policies.

In the dynamic GTAP-E framework, the evolution of energy use and emissions is driven by a combination of fixed parameters and endogenous adjustments. First, parameterization of energy-related technological change. GTAP-E models production using a nested CES structure in which energy enters as a separate input alongside capital and labor. Technical change is parameterized through the exogenous projections of GDP, labor, capital, and population from the EconMap database. These projections embody expected improvements in energy efficiency and technological progress, such that energy demand in each sector evolves over time in response to both economic growth and relative price changes. In other words, the model does not assign an arbitrary rate of technological change. Rather, improvements in energy efficiency are indirectly incorporated via the exogenous macroeconomic projections and the model's substitution elasticities. Second, updating of emission coefficients. The link between energy use and emissions is established through fixed carbon emission coefficients by fuel type (coal, oil, gas, refined petroleum products, and electricity), consistent with the IPCC guidelines. These coefficients are not assumed to change over time. However, the activity levels to which they are applied are updated recursively from 2017 to 2025, 2035, and 2050 using EconMap's projections of sectoral energy demand. As a result, total emissions evolve endogenously with changes in energy consumption, even though the underlying coefficients remain constant. Third, treatment of sectoral emission intensities. Sectoral emission intensities are not held constant. Instead, they evolve endogenously as the model simulates substitution between fuels, structural shifts in production, and changes in trade patterns. For example, if manufacturing sectors substitute electricity for coal, the emission intensity of that sector declines even though the emission coefficient of each fuel remains fixed. Thus, while the model preserves a fixed relationship between physical fuel use and emissions, the overall intensity of emissions per unit of output varies across sectors and over time. Finally, it is worth noticing that the current dynamic GTAP-E implementation does not explicitly incorporate feedback effects from environmental degradation to trade or production capacity. That is, while emissions evolve endogenously with changes in energy use, production structure, and trade patterns, the model assumes that

environmental degradation does not directly constrain GDP, labor, or capital accumulation. This approach is consistent with most CGE-based trade-environment analyses, where the primary objective is to assess the impact of trade policy on emissions and structural adjustment, rather than to model potential macroeconomic feedback from environmental shocks. Nevertheless, the findings provide valuable insights into how trade barriers influence energy use and carbon emissions under different scenarios, while recognizing that incorporating explicit environmental feedback effects would require a more complex integrated assessment model.

3.1.2 The setting of GTAP model

The latest version, GTAP11-E, includes data for 160 regions and 65 sectors. For the purposes of this paper, we have reclassified both the regions and sectors in the model to better align with the analytical objectives and the specific context of the study. The regions are grouped into 15 categories, such as China, the United States, and Russia, while the sectors are redefined into 22 categories, including coal, oil, and natural gas, as detailed in Tables 1 and 2. Additionally, the factors of production in the model are classified into four main categories: land, capital, resources, and labor.

3.1.3 Scenario setting for simulation

The benchmark year for the data in the GTAP11 model is 2017. To more accurately assess the potential impact of current and future trade frictions on carbon emissions, a dynamic

Table 1 Codes for regions

Code	Code in Gtap	Region	Describe
1	4	CHN	China
2	29	USA	United states
3	90	RUS	Russia
4	23	IND	India
5	1, 2	Au_New	Australia, New Zealand
6	3	Oceania_else	Rest Oceania
7	5–10	EastAsia	East Asia
8	11–22, 24–27	SEAsia	South and South-east Asia
9	28, 30, 31	NAmerica	North America
10	32–55	LatinAmer	Latin America and Dominican
11	58, 59, 61, 63, 68, 71, 72, 76, 78–80, 87–89, 91, 92, 98	E_EU	East Europe
12	56, 57, 60, 62, 64–67, 69, 70, 73–75, 77, 81–86, 93	W_EU	West Europe
13	99–121	MENA	Middle East Asia and North Africa
14	122–159	SSA	Sub-Saharan Africa
15	160	RestofWorld	Rest of the World

Table 2 Codes for industries

Code	Code in GTAP	Sector	Sub-sector
1	15	Coal	Coal
2	16	Oil	Oil
3	17, 47	Gas	Gas
4	32	Oil_pcts	Oil_pcts
5	46	Electricity	Electricity
6	1, 23	Rice	Paddy rice
7	2, 3	Grains	Cereal grains nec
8	5, 21	Oilp	Oil plants
9	4	Vfn	Vegetables fruits nuts
10	26	Tabacco	Beverages and tobacco products
11	9, 10, 19, 20	Meat	Livestock and meat products
12	14	Water	Fishing
13	11, 22	Dairy	Dairy
14	6–8, 12, 13, 24, 25	Agri_else	Other agriculture products
15	33, 35	Ch_r_p	Chemical rubber plastic product
16	43, 44	Tran	Transportation equipment
17	18, 36–39	Metal	Metals and products
18	40, 41	Elec	Electronic equipment
19	29–31, 34, 42, 45	Indus_else	Other industries
20	27, 28	TextWapp	Textiles and clothing
21	48, 49	Util_Con	Utilities and construction
22	50–65	Serv	Services

recursive approach is applied. In this approach, variables such as GDP, population, labor force, and capital stock are treated as exogenous, and the benchmark year data is extrapolated to the years 2025, 2035, and 2050 using rate-of-change data from the EconMap database, provided by the French Center for Research on the World Economy. The dynamic extrapolation from the 2017 GTAP base year to 2025, 2035, and 2050 relies on EconMap projections for GDP, population, labor, and capital. While these projections provide a consistent and comprehensive set of long-term macroeconomic scenarios, it is important to recognize that they carry inherent uncertainties, particularly when applied to trade-environment modeling over several decades. Future economic growth rates, technological progress, and energy transitions may deviate from these projections, which could affect the quantitative magnitude of simulated emissions and energy use. Nevertheless, the use of EconMap allows for a coherent and comparable framework across countries and sectors, and the main focus of this paper is on relative effects of trade policy scenarios rather than precise prediction of absolute emission levels. In this context, the projections serve as a scenario-based tool to explore structural and environmental implications under different trade frictions.

In defining specific scenarios, this paper first considers the actual situation of Sino-US trade friction in 2018, particularly in terms of the selection of taxed goods and tax rates. Additionally, it accounts for the future trajectory of trade friction, especially the increasing use of new NTBs, such as green trade barriers and technical trade barriers. Specifically, the United States has imposed trade barriers on China in the following sectors: petrochemical

products, transportation equipment, metal products, electronic products, and other industrial goods. Similarly, China has introduced trade barriers against the United States in sectors including petrochemical products, grains, tobacco, meat, and transportation equipment.

The scenarios set up are shown in Table 3. Scenario A is where each side imposes different levels of tariffs on related goods. Scenario B adds 5% NTBs from both sides on top of scenario A. The tariff rates in this paper are set at 5%, 15%, and 25%. These levels are chosen for both empirical and methodological reasons. The 5% rate represents a mild trade friction scenario, consistent with limited disputes that could be resolved under WTO rules. The 15% rate reflects the mid-range of the additional tariffs imposed during the 2018–2019 U.S.–China trade conflict, capturing a realistic escalation of trade tensions. The 25% rate corresponds to the highest tariff level frequently applied by the United States during the same period, which has since become a benchmark in policy discussions. For future projection years (2035 and 2050), these rates are not intended as precise forecasts but rather as scenario-based settings that allow us to explore the potential environmental consequences of different intensities of trade barriers. This approach is consistent with existing studies employing counterfactual scenario analysis. Compared with tariff measures, empirical research on NTBs remains relatively limited, and there is no consensus on their quantitative representation in CGE-based scenario analysis. Existing studies typically rely on stylized assumptions or ad-valorem equivalents derived from specific sectors rather than comprehensive estimates. In this context, the 5% NTB rate adopted in this paper should be understood as a representative benchmark that reflects a moderate degree of trade restrictiveness. The purpose is not to predict the exact magnitude of NTBs in future trade disputes, but to explore their potential structural and environmental implications in comparison with tariff-only scenarios.

3.2 ACT theory

The ACT theory was proposed by Antweiler et al. (2001). It further analyzes the structural effects based on the affirmation of the negative effects of the scale effect and the positive effects of the technology effect. According to ACT theory, international trade affects the environment in three ways: scale, technology, and structure. The scale effect refers to the impact of international trade on the environment through its influence on economic scale, which mostly manifests as harmful to the environment. The technology effect indicates that international trade improves technological levels through the exchange and dissemination of technology, thereby optimizing production and having a positive effect on the environment. The structural effect reflects the influence of international trade on the industrial structure of countries, ultimately impacting the environment, and the direction of this effect is usually uncertain. The theory suggests that the structural effect depends on two motives: the pollution haven hypothesis (PHH) and the factor abundance hypothesis (FAH). The former emphasizes that pollution-intensive industries may relocate to developing countries with

Table 3 Scenario settings

	A	B
Scenario 1 (S1)	5% tariffs	5% NTBs on top of Scenario A
Scenario 2 (S2)	15% tariffs	
Scenario 3 (S3)	25% tariffs	

“tariffs” are modeled in GTAP as TMS (tariff measures), and “NTBs” are modeled as AMS (non-tariff measures)

relatively lax environmental regulations, thereby exacerbating environmental pollution. The latter highlights that countries make trade decisions based on their factor endowment conditions. For instance, developing countries with abundant labor resources are more likely to produce and export labor-intensive products, which tend to be less polluting, thus helping to reduce environmental pollution. The specific direction of the structural effect depends on the relative strength of these two motives.

To more clearly link the ACT framework with our empirical analysis, it is useful to indicate how the three effects can be reflected in the GTAP-E simulation outputs. The scale effect is observed through changes in aggregate trade, production, and emissions, as variations in economic activity directly alter the environmental burden. The technology effect is reflected in shifts in energy efficiency and emission intensities across sectors, since international trade can facilitate the adoption and diffusion of cleaner production methods. The structure effect emerges from the reallocation of production and trade across industries and regions, embodying adjustments in industrial specialization and comparative advantage. To strengthen this connection, we explicitly map these mechanisms to the results section. The scale effect is analyzed in Sects. 4.1, 4.2.1, and 4.3.1. The structure effect is discussed in Sects. 4.2.2–4.2.3, and the technology effect is examined in Sect. 4.2.4. This mapping provides readers with a clear lens through which to connect the theoretical framework of ACT with the empirical evidence generated by the GTAP-E simulations.

3.3 Theil index

The Theil Index was originally applied to study the income disparity between countries, it is commonly used to measure the unevenness, with Theil-T, Theil-L, GE (1) Theil Index, and GE (0) Theil Index in four forms. Among them, Theil-T and Theil-L are calculated based on the multiple weights of GDP and population of each group respectively. Since this paper is based on the prediction of the dynamic recursive model, the GE (1) model, which has been applied more often, is used to minimize the error.

GE is the Generalized Entropy, and the GE index is the index constructed based on General Entropy. The general construction of the GE index is shown as follows:

$$GE_{\alpha}(y) = \frac{1}{n} \frac{1}{\alpha(\alpha-1)} \sum_i \left[\left(\frac{y_i}{\mu} \right)^{\alpha} - 1 \right] \quad (1)$$

where μ is the mean value of y and the GE(1) index when α is 1. The limit of the calculation is:

$$GE_1(y) = \lim_{\alpha \rightarrow 1} \frac{1}{n} \frac{1}{\alpha(\alpha-1)} \sum_i \left[\left(\frac{y_i}{\mu} \right)^{\alpha} - 1 \right] = \frac{1}{n} \sum_i \frac{y_i}{\mu} \log \frac{y_i}{\mu} \quad (2)$$

Thus, the GE(1) Theil index is:

$$T = \frac{1}{n} \sum_i \sum_j \frac{y_{ij}}{\mu} \log \frac{y_{ij}}{\mu} \quad (3)$$

$$T_i = \frac{1}{n_i} \sum_j \frac{y_{ij}}{\mu_i} \log \frac{y_{ij}}{\mu_i} \quad (4)$$

$$T = \sum_i \frac{n_i \mu_i}{n \mu} T_i + \frac{1}{n} \sum_i n_i \frac{\mu_i}{\mu} \log \frac{\mu_i}{\mu} = T_{WR} + T_{BR} \quad (5)$$

where T is the overall Theil Index, T_i is the Theil Index of group i , T_{WR} and T_{BR} are the within-group and between-group differences obtained by first-order decomposition respectively, and the coefficient of T_i in Eq. (5) is the contribution of group i in the overall Theil Index.

3.4 Data sources

The base data for this study are sourced from the GTAP11Agg database, while the data required for dynamic recursion come from the EconMap database. The initial data for each base year (2025, 2035, 2050) are derived by calculating the annual rate of change for GDP, population, labor force, and capital stock using data from the EconMap database, with these variables set as exogenous shocks. The goods selected for tariff imposition and their corresponding tariff levels are based on the \$50 billion and \$200 billion worth of goods that the US and China restricted in 2018 and 2019, respectively, along with the tariffs imposed at rates ranging from 5 to 25%.

4 Results

4.1 The effects of Sino-US trade frictions on global trade

Figure 1 presents the average changes in total trade volume for different countries across various years under different scenarios, along with their sectoral compositions. The countries are ordered in ascending sequence for Scenario 1, Scenario 2, and Scenario 3. As shown in Fig. 1, regardless of the scenario, the trade volume of most countries and regions declines following the onset of trade friction, with the exceptions being the rest of North America (excluding the US), Southeast Asia, and East Asia. China and the United States are the two most significantly affected countries, with their trade volumes decreasing by more than \$150 billion under Scenario 3. In contrast, the countries of Oceania, excluding Australia and New Zealand, experience the smallest reductions.

Looking at specific sectors, industries such as electronics, textiles, chemicals, other manufacturing industries, and transportation products are the most impacted. The severity of the impact grows as trade frictions intensify, although regions without NTBs are relatively more affected. For China and the US, aside from an improvement in China's textile trade, both countries face substantial trade contractions in most sectors. Meanwhile, for the rest of the world, trade increases more than it decreases overall. However, the specific trade changes across regions show notable variations: North America sees a rise in trade, particularly in electronics, which stimulates local trade activities. In contrast, Western European countries experience a decline in trade, especially in services and manufacturing industries like transportation, which negatively impacts trade within the value chain. Ultimately, the

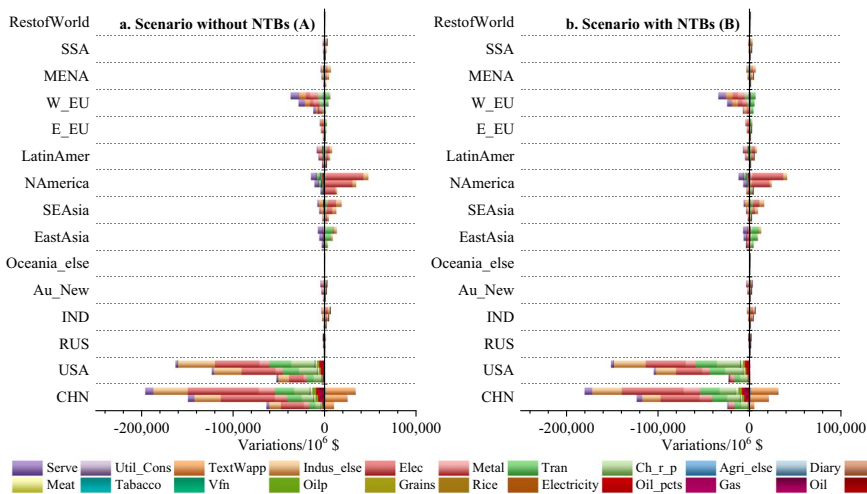


Fig. 1 Change volume in total trade and its sectoral composition

Sino-US trade conflict has a cascading effect, disrupting not only the interests of China and the United States but also those of the global economy.

Shown in Fig. 1, the trade volume in regions excluding the United States, North America, Southeast Asia, and East Asia has increased to some extent. This suggests that Sino-US trade friction has a negative scale effect in these regions—meaning that the expansion of trade leads to higher levels of local production, consumption, and transportation of goods, thereby increasing carbon emissions. In contrast, for the United States and China, the effect is positive: the reduction in trade volume results in lower carbon emissions, helping to mitigate environmental pollution.

4.2 The effects of Sino-US trade frictions on energy consumption

4.2.1 The general effects of Sino-US trade frictions on energy consumption

Figure 2 illustrates the average changes in energy consumption across different countries and years under various scenarios, along with their sectoral compositions. The countries are listed from bottom to top for Scenario 1, Scenario 2, and Scenario 3. In Scenario 3, China shows an increase in the consumption of oil, coal, and electricity, with average changes of 1.95%, 1.17%, and 0.38% respectively under Scenarios A and B. Conversely, consumption of natural gas and petroleum products decreases, with average reductions of -0.81% and -0.71%. The United States exhibits the opposite trend, but the impact is relatively smaller. Among the remaining countries, the largest changes are observed in North America (excluding the US), Oceania, and India. Notably, the rest of North America experiences a sharp decline in natural gas consumption in Scenarios A and B of Scenario 3, with an average decrease of 2.3%. Overall, energy consumption tends to decline, with the exception of East Asia and Eastern Europe. In East Asia, the change in energy consumption mirrors China's pattern, while Eastern Europe shows the opposite trend, with increased consumption of natural gas and petroleum products. Additionally, the magnitude of the change in energy

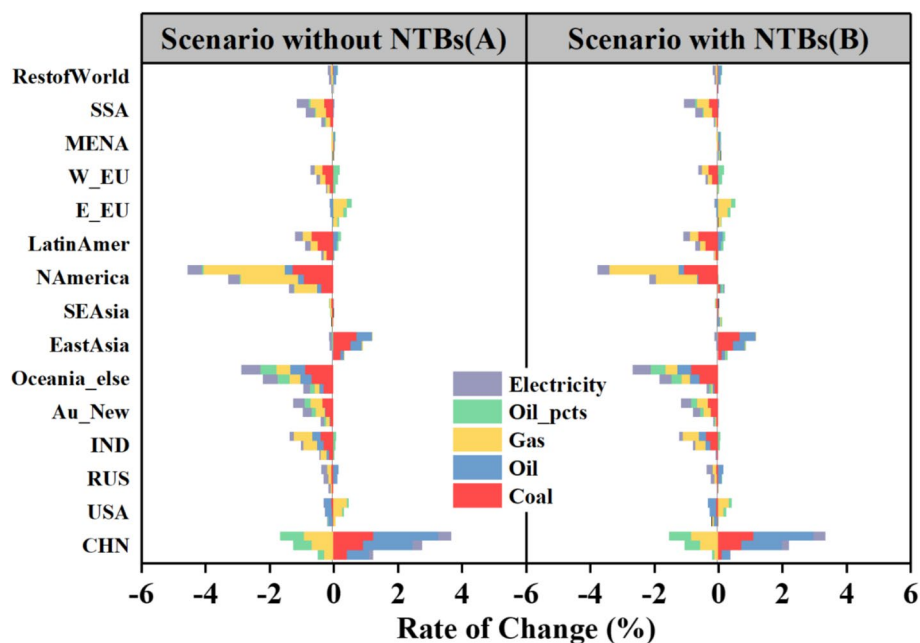


Fig. 2 Change rate in energy consumption and structure

consumption grows as tariff levels rise, though NTBs have a relatively minor impact on the results.

The trend observed in China can be linked to the country's recent energy policies, which prioritize economic growth and energy security. Despite efforts to reduce emissions and promote renewable energy, China remains heavily reliant on coal, as reflected in the rise in coal consumption. This aligns with energy security theory, which suggests that countries prioritize stable energy sources—even at the cost of environmental considerations. In contrast, the situation in the US suggests that wealthier nations, such as the US, are increasingly adopting cleaner and more sustainable energy sources, like natural gas, driven by technological advancements, environmental concerns, and policy interventions.

4.2.2 The effects of Sino-US trade frictions on industry structure

Figure 3 illustrates the rate of change in output across various industries in each region under different scenarios. As shown in the figure, Sino-US trade friction has a noticeable impact on the output structure of both countries. It promotes the growth of China's textile industry, with an average increase of 5.7% in Scenario 3, and boosts the US electronics manufacturing sector by 2.3%. Conversely, it restrains the development of China's public construction industry by -2.3% and the US textile industry by -3.1%. Among the regions outside of the US and China, the most affected is the rest of North America. This is particularly evident in the significant growth of the optics and electronics manufacturing sector (13.1%), alongside sharp declines in the textile industry (-8.3%) and the coal industry (-5.6%). In East Asia, the coal industry also faces a negative impact, with a decrease of -4.1%. Additionally, the textile

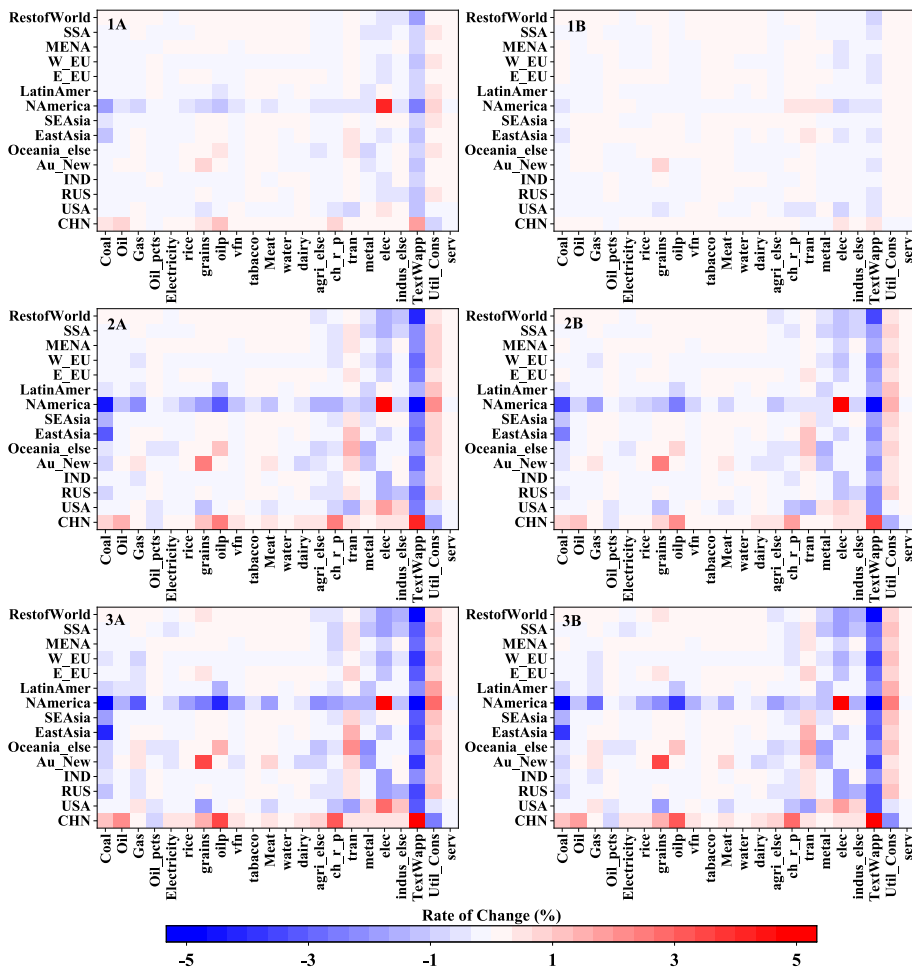


Fig. 3 Change rate in industrial structure by region. (Red indicates higher output value change rate for industries)

industry in all regions, except China, suffers a decline. At the same time, the agriculture sector in Oceania (especially Australia and New Zealand) and the transportation industry in East and Southeast Asia experience substantial growth. From an overall perspective, the global public construction industry has seen some development, and this effect intensifies as tariff levels increase. Notably, industries such as textiles, transportation, and coal are characterized by higher carbon emission intensity, while agriculture tends to have relatively low carbon emissions. Carbon emissions from the optics and electronics manufacturing sectors vary depending on the level of local technological development. In general, the more technologically advanced the region, the lower the carbon emissions in these industries, which are generally considered cleaner. In summary, the Sino-US trade friction appears to have a positive structural effect on regions outside the United States in North America, due to the decrease of the textile and coal industries and the suppression of other polluting sectors. On the other hand, it has a negative structural effect on Southeast Asia, primarily driven by the

expansion of the transportation industry. The structural effects on Oceania and East Asia, however, remain uncertain.

When combined with ACT theory, the structural effects associated with PHH appear more pronounced, while the influence of FAH seems less significant. As shown in Fig. 3, Southeast Asia, with its relatively underdeveloped economic infrastructure, potentially absorbed a large share of pollution-intensive industries during the Sino-US trade friction. These industries, particularly in transportation manufacturing, were relocated to the region in part to take advantage of relatively lower environmental standards and labor costs. This shift in production may have contributed to a concentration in pollution-heavy industries rather than a corresponding expansion of labor-intensive sectors, which could have diversified the industrial base. Consequently, the region could be seen as playing a role similar to PHH, although it is important to note that these changes may also have been influenced by domestic environmental policies, technological progress, and global market dynamics, and should not be interpreted as being entirely caused by PHH. This misalignment between industrial specialization and factor endowments likely exacerbated local pollution levels and related infrastructure pressures, contributing to broader economic and environmental challenges.

4.2.3 The effects of Sino-US trade frictions on energy production structure

Figure 4 illustrates the changes in energy production structures across different countries and regions under various scenarios. Notably, both China and the United States show distinct trends. In China, coal and oil production experience significant increases, with coal production rising by an average of 1.2% and oil production up by 2.0% in Scenario 3 (S3). However, at the same time, China's production of petroleum products declines by 0.7%, suggesting a shift in the composition of its energy mix. In contrast, energy production in the United States remains largely stable, with no significant changes observed in its overall energy output under the same scenario.

For the rest of the world, the most significant changes are observed in regions outside the United States, particularly in North America. In countries like Canada and Mexico, coal production drops dramatically by 5.6%. This sharp decline reflects broader shifts in regional energy policies and market dynamics, possibly driven by environmental regulations, technological advancements, or a gradual transition to cleaner energy sources. These changes underscore the diverse energy strategies adopted by different regions in response to global economic, political, and environmental pressures. Some regions are increasing fossil fuel production, while others are shifting toward decarbonization and greater reliance on renewable energy.

4.2.4 The effects of Sino-US trade frictions on energy use efficiency

Figure 5 shows the efficiency of energy use across different regions under various scenarios. It is evident that Sino-US trade friction reduces energy efficiency in all regions, though its impact varies across different energy sources. China is the most affected, with a notable increase in electricity use efficiency, but a decrease in the efficiency of oil and natural gas usage. Following China, Oceania and Sub-Saharan Africa experience significant reductions in the efficiency of all energy sources. Across regions, the impact on energy efficiency inten-

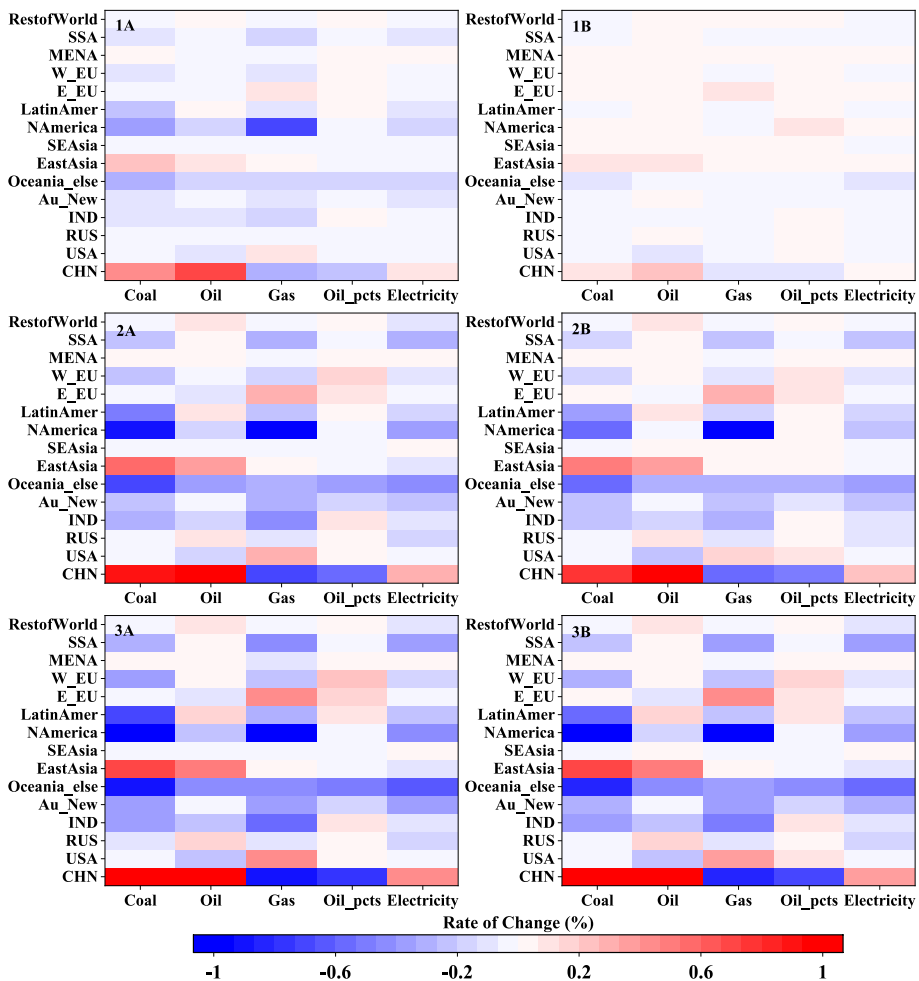


Fig. 4 Change rate in the structure of energy production by region. (Red indicates higher energy output change rate)

sifies as tariff rates rise. Furthermore, an increase in NTBs at the same tariff rate tends to mitigate the negative effect of higher tariffs on energy efficiency.

The results observed here contradict the theoretical analysis of technological effects. One possible explanation is that the restructuring of global trade patterns and the reallocation of industrial resources associated with Sino-US trade friction may disrupt existing supply chains, leading to the reallocation of resources and the search for alternative supply channels. This adjustment process could lead to increased energy use and waste, thereby reducing overall energy efficiency. Additionally, the uncertainty surrounding trade policies may result in market instability and slower economic growth, causing firms to adopt a more cautious approach. As a result, they may be less inclined to invest in technologies or measures to improve energy efficiency, reflecting negative technological effects.

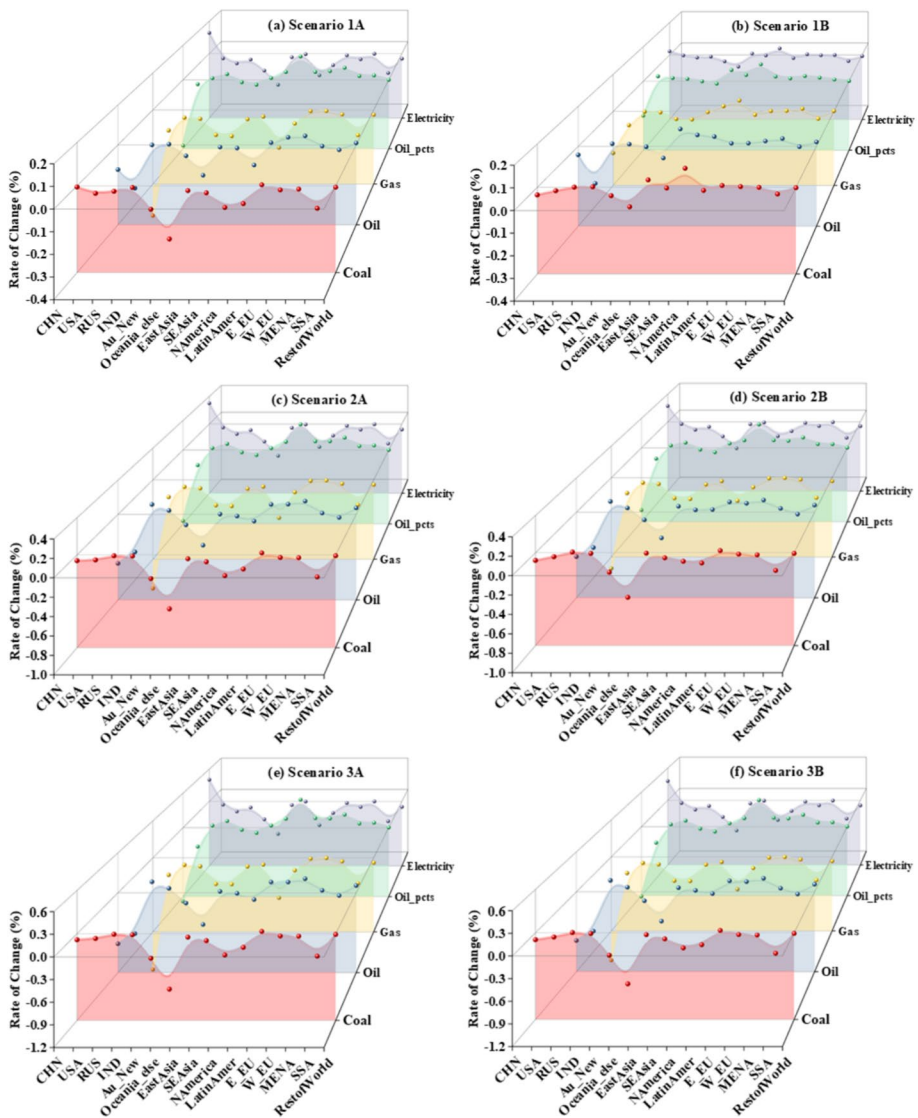


Fig. 5 Change rate in the efficiency of energy use by region

4.3 The effects of Sino-US trade frictions on carbon emissions

4.3.1 Impacts on global carbon emissions and structure

Figure 6 illustrates the changes in carbon emissions across different countries and regions. It is evident that Sino-US trade friction exacerbates local carbon emissions in Europe, Southeast Asia, the Middle East, and Latin America, while significantly reducing carbon emissions in North America, Oceania, Sub-Saharan Africa, China, and the US. Notably, carbon emissions in East Asia are not significantly affected. As tariffs rise, all regions—except

Europe and Latin America—show a downward trend in carbon emissions. North America experiences the most significant reduction, with a -0.2% change by 2050, even exhibiting a notable reverse trend. The increase in NTBs also contributes to a slight rise in carbon emissions, although the results remain relatively stable over time. However, the overall effect is not highly pronounced due to the counteracting forces at play.

4.3.2 The regional heterogeneity in carbon emissions

The 15 regions were further categorized into developed regions (e.g., Australia, New Zealand, Europe), underdeveloped regions (e.g., Southeast Asia, Sub-Saharan Africa), and intermediate regions (e.g., Russia, the rest of North America). The Theil Index was then calculated to measure the distribution of carbon emissions across these groups. The results are shown in Fig. 7, where the shaded portion represents the Theil Index, and the dashed portion reflects the contribution rate under each scenario.

The results indicate that the differences in the rate of change of carbon emissions between regions primarily stem from within-group differences. However, as tariff levels increase,

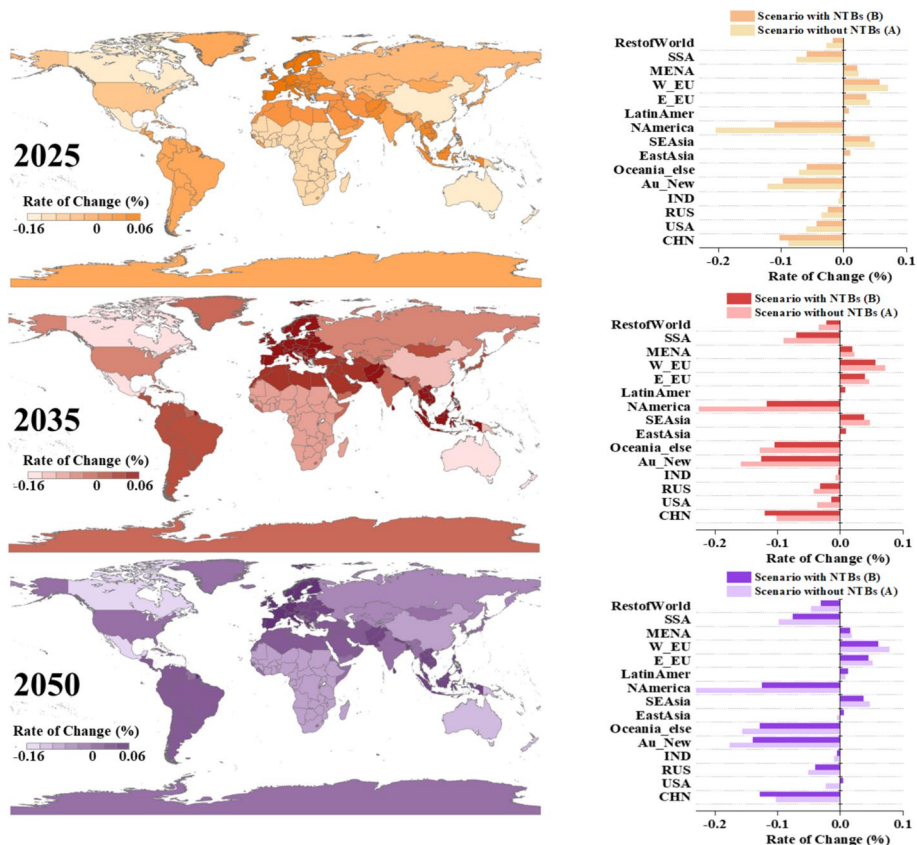


Fig. 6 Change rate in carbon emissions by regions (The left figure provides an overview of the overall situation, while the right figure builds on the left by distinguishing between scenarios with and without NTBs)

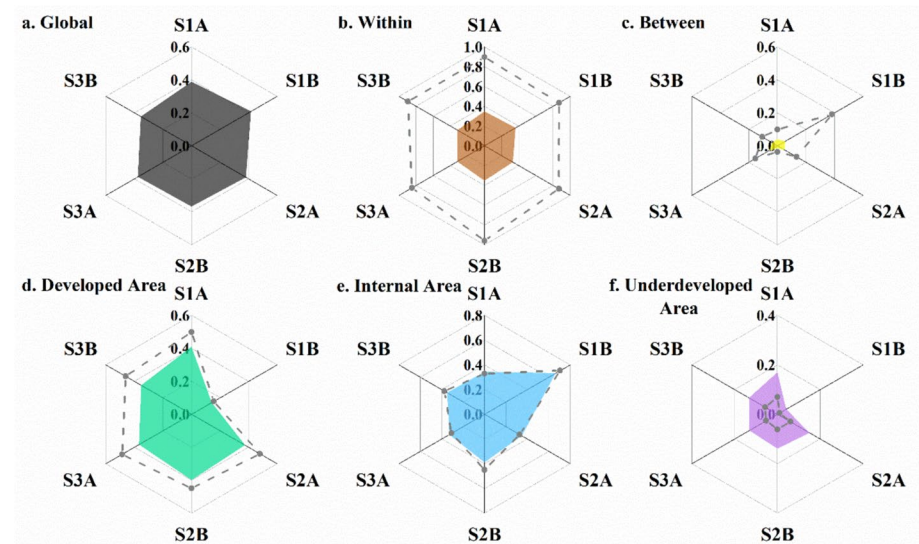


Fig. 7 Theil index and contribution rate by region (global refers to the overall gap, within refers to the within-group gap, and between refers to the between-group gap)

between-group differences become more pronounced. Specifically, when NTBs are not increased, the Theil Index for intermediate regions rises and then falls with increasing tariffs, while the indices for other regions remain relatively stable. When NTBs are introduced, the Theil Index for intermediate regions tends to fall as tariffs increase, while the indices for other regions show a clear downward trend—except in Scenario 1B (with 5% tariffs and NTBs), where the Theil Index experiences a more noticeable decrease. In contrast, in other scenarios, the index remains relatively flat. In the case of double barriers, the Theil Index for intermediate regions is higher than for a single tariff barrier, whereas the reverse is true for the other regions.

Overall, the global Theil Index under each scenario ranges between 0.35 and 0.4. In terms of inter-regional comparison, the developed and intermediate regions have relatively high Theil Index values, above 0.3, while the Theil Index for underdeveloped regions is close to 0. This suggests that the Sino-US trade friction has created significant differences in the rate of change of carbon emissions between developed and intermediate regions, with less impact on underdeveloped regions. As the tariff levels change, the largest shift in the Theil Index occurs in the intermediate regions—especially when 5% tariffs and NTBs are imposed. In this case, the Theil Index rises sharply to 0.7, indicating that the impact of trade friction on carbon emissions in intermediate regions is extremely high. This is likely due to trade diversion effects resulting from the reduction in US imports from China. On one hand, intermediate regions with economic development levels similar to China's will begin producing more of the goods that China had previously exported to the US. On the other hand, while direct imports from China to the US decrease, Chinese companies may find ways to bypass trade barriers and export more indirectly through regions like the rest of North America, which can significantly impact intermediate regions.

4.3.3 Analysis of scale, structure, and technology effects under ACT theory

This study is based on the dynamic GTAP-E model, providing an empirical assessment of the impacts of Sino-US trade frictions on energy consumption, industrial structure, and carbon emissions. While it is not possible to precisely quantify the relative contributions of scale, structure, and technology effects as specified by ACT theory, the results allow for a qualitative assessment of their likely magnitudes and drivers across regions. In China, energy consumption increases across multiple sources, largely reflecting a strong scale effect driven by economic growth, with structural adjustments in industrial output further influencing energy use. Technological effects are temporarily subdued due to trade disruptions and supply chain reallocations. In the United States, changes in energy consumption are smaller and appear to result from a combination of scale and technological effects, with cleaner and more efficient energy adoption mitigating potential increases. In Southeast Asia, structural effects dominate due to the relocation of pollution-intensive industries, while scale and technology effects play smaller roles. Other regions, including North America, Oceania, and East Asia, show mixed patterns, where scale, structure, and technology effects interact to determine energy use and emissions outcomes. It is important to note that these regional patterns may also be influenced by domestic environmental policies, technological progress, and global market dynamics, in addition to the direct effects of Sino-US trade frictions. The long-term projections (2035, 2050), derived from dynamic extrapolations of EconMap data, provide valuable insights but remain subject to uncertainties associated with future policy developments, technological advances, and market shifts.

5 Discussion

5.1 The benefits of no trade barriers to global development

As shown in our empirical analysis, the global trade system responds to trade frictions through complex reallocation effects. The expansion of global value chains and the rise of transnational corporations have led to tighter economic interdependence (Gölgeci et al., 2023), and free trade enhances this by enabling the cross-border flow of goods, capital, and labour, which promotes resource efficiency and accelerates global economic growth (Behrens & Murata, 2012).

First, by promoting the free flow of factors, free trade provides capital, labour and other factors with the potential to earn higher incomes (Marques, 2008). It can also contribute to raising overall income levels. Our results support this view: under lower trade barrier scenarios (S1), most regions maintain or expand trade, especially emerging markets like Southeast Asia and East Asia. These regions benefit from diverted trade, helping to stabilize growth and employment. Second, by participating in the global value chain, enterprises in different countries can make full use of their factor endowments (Dixit & Woodland, 1982), exploit comparative advantages, and engage in the international division of labour. This not only lowers domestic production costs and improves production efficiency but also promotes global total output growth. As seen in our simulation, countries like Canada and Mexico leveraged their proximity and trade linkages to capture displaced demand, expanding their electronics and services exports while reducing emissions, suggesting both eco-

nomic and environmental gains. Third, free trade can achieve economies of scale through the expanded market, further reducing costs and improving production efficiency. Free trade also promotes the diffusion of technology and knowledge, helping developing countries to absorb the advanced technology and management experience of developed countries and achieve their own economic and social leapfrog development by fully exploiting their late-comer advantages. However, our results under scenarios with high trade barriers (e.g., Scenario 3B) show the opposite effect: technological diffusion slows, energy efficiency declines (especially in China and Oceania), and emissions rise in transport-heavy sectors of Southeast Asia. This outcome illustrates that trade restrictions can disrupt technological upgrading, especially where capital and know-how are dependent on international networks. Finally, the liberalization of economic and trade globalization helps break the original monopoly pattern within a country or region, and introduces the competitive mechanism by absorbing new manufacturers into the market, thus realizing the improvement of efficiency.

In conclusion, from the perspective of micro-enterprises, individual countries and regions, and the world economy as a whole, free trade plays a pivotal role in promoting global welfare (Herman & Oliver, 2023). The results of this paper reaffirm the global welfare-enhancing role of trade liberalization. At the same time, they demonstrate that when trade is obstructed, not only does economic output suffer, but environmental inequality may intensify due to carbon leakage and uneven industrial adjustment.

5.2 The far-reaching impact of Sino-US trade frictions on global carbon emissions

As the world's two largest economies, China and the US are affected by their trade frictions in multiple ways: such frictions not only exert complex and far-reaching impacts on bilateral trade and economic development but also influence the local environment. Specifically, changes in trade scale, industrial structure, and technical level lead to fluctuations in energy consumption, which ultimately manifest largely as changes in carbon emissions. This relationship is clearly reflected in the simulation results of this study. According to the model outputs (Fig. 6), the simulation indicates higher carbon emissions in regions such as Europe, Southeast Asia, and the Middle East under the trade friction scenario, while emissions decline significantly in North America, China, Oceania, and Sub-Saharan Africa. These trends follow the classic environmental impact channels predicted by ACT theory, particularly the scale, structure, and technology effects.

The consequences of this event will go beyond the immediate impact on China and the United States. The ripple effect will be felt around the world, with irreversible consequences for the global climate. More specifically, the trade contraction in China and the US results in reduced emissions due to lower production (a negative scale effect), while Southeast Asia experiences an increase in emission-intensive industrial activity (e.g., transportation and textiles), indicating a structural effect caused by PHH.

With international trade, however, countries have reflected on globalization over the years. Although the welfare of all countries has been improved, the degree of improvement is not the same, so there is a difference in the relative gains (Wang et al., 2024a, 2024b). In addition, free trade within a country will also have different effects on different groups, and the income distribution effect of trade (Cateia & Savard, 2025) has given rise to a number of voices against free trade. At the same time, in order to support domestic industries and protect them from the impact of imports, governments also introduced a series of trade-

restrictive policies (Baqae & Farhi, 2024), i.e. in the sense of the “infant industry protection theory”. As a result of the politicisation of globalisation, the influence of globalisation skeptics is increasing (Heggem & Jakobsen, 2016), leading to trade protectionism and a series of trade frictions, of which the Sino-US trade friction is a typical example.

Economically, tariffs exceeding \$360 billion bilaterally have disrupted trade flows, reducing bilateral trade volumes by approximately 12–15% and depressing global GDP growth projections by 0.5–1.2 percentage points annually (Yu & Zhang, 2019). These impacts are amplified through confidence channels, leading to reduced corporate investment, currency volatility, and capital flight from emerging markets. Technologically, the trade war has evolved into a technology Cold War, with export controls on semiconductors, AI, and quantum computing exemplifying efforts to curb technological reciprocity. This has triggered a bifurcation in global technology governance, with U.S. restrictions on Chinese tech firms like Huawei reducing R&D investments in 5G and AI by 20 billion annually, while China accelerates self-reliance through state-funded initiatives. Supply chains have become more resilient but less efficient, with firms adopting “China+1” strategies, incurring 15–20% higher logistics costs and extended lead times (Li et al., 2024). Emerging economies have benefited from export diversification, but their capacity to absorb high-value manufacturing remains constrained. Geopolitically, the trade conflict has catalyzed a reconfiguration of international alliances, with countries like India, Southeast Asian nations, and the EU positioning themselves as strategic intermediaries. This has led to competing visions for global economic governance, with the World Trade Organization (WTO) being sidelined as disputes are increasingly resolved through bilateral negotiations or unilateral sanctions.

5.3 The inequality impact of Sino-US trade frictions on different regions

Mitigating climate change and reducing inequality are both key objectives of sustainable development, and the United Nations Sustainable Development Goals (SDGs) include both urgent action on climate change and reducing inequality (Mishra et al., 2024). Therefore, in addition to examining the impact of the US-China trade dispute on global carbon emissions, this paper also examines carbon inequality using the Theil Index as an indicator.

From the results of this paper, the spillover effects are especially pronounced in middle-income regions—particularly in non-US parts of North America, which manifest in more significant impacts on industrial structure and larger internal differences in carbon emissions. These stem from two concurrent trade diversion mechanisms. On one hand, the US, constrained by its limited domestic manufacturing base, redirected import demand away from China to geographically and economically connected regions such as Canada and Mexico. On the other hand, Chinese firms—seeking to avoid direct trade restrictions—rerouted exports through these same neighboring countries, reinforcing their role as intermediaries in bilateral trade. Furthermore, developed regions such as East Asia also experienced indirect carbon impacts due to overlapping trade reallocation from both the US and China.

These findings suggest that while trade barriers may serve short-term policy goals, they also produce broader and often unintended environmental inequalities across regions—particularly for intermediary economies caught in the restructured value chain.

5.4 Synergies and trade-offs in trade-environment policies

The interplay between trade liberalization and environmental governance remains a central challenge in global economic management. Thoughtfully designed policies can generate synergies that benefit both trade and the environment, yet short-term economic pressures often create trade-offs. WTO Committee on Trade and Environment discussions emphasize the importance of “embedded green rules”, such as harmonized environmental standards and clean energy technology transfer, in achieving these synergies. Pilot Carbon Border Adjustment Mechanisms (CBAM) under the Paris Agreement illustrate this potential. By incorporating carbon costs into imported goods, the EU reduces “carbon leakage” while encouraging exporting countries to adopt greener practices—this creates a positive feedback loop between trade and emissions reduction.

However, implementing these policies faces real-world constraints. Developing countries caution that CBAMs led by advanced economies may act as *de facto* trade barriers, imposing additional costs on nations with slower energy transitions. These challenges reflect structural disparities in environmental capacity, industrial competitiveness, and emission responsibilities. Moreover, unilateral measures risk conflicting with multilateral trade rules—for instance, adjustments considering only direct emissions may ignore indirect ones, potentially generating new trade frictions while weakening global mitigation efforts.

Future policy design must therefore strike a careful balance between ambition and feasibility, addressing global coordination and development equity. Priorities include leveraging WTO platforms to establish development-oriented green trade rules with technical and capacity support, calibrating carbon border adjustments under the principle of “common but differentiated responsibilities” to align emission reductions with development needs, and integrating trade and environmental policies—for example, linking tariff reductions on green goods with carbon trading systems—to maintain a dynamic balance between trade growth and ecological protection.

5.5 Limitations

This study has several important limitations that warrant careful consideration. First, the GTAP-E model employs a relatively coarse industrial classification, which constrains the ability to capture more granular sectoral dynamics, particularly in industries most sensitive to Sino-US trade frictions. As a result, some structural and technological adjustments may be smoothed over, potentially underestimating or overestimating certain environmental impacts. Second, the regional division adopted here relies primarily on economic size and geographic location, which may oversimplify the complex network of trade relationships, political affiliations, and cross-border environmental spillovers. Future research could adopt more systematic, network-based, or functional regional classifications to better reflect global economic interdependencies. Third, the model does not explicitly track embodied emissions in intermediate goods trade, nor does it fully capture the heterogeneity in renewable energy penetration across sectors and regions. While GTAP-E provides a consistent framework for estimating total energy use and emissions, these simplifications mean that certain upstream emissions or region-specific renewable energy dynamics may be represented in an aggregated manner. Future work could explore incorporating more detailed supply-chain accounting and differentiated renewable energy adoption to refine the assessment of scale,

structure, and technology effects. Fourth, although the policy scenarios—including tariffs and NTBs—are designed based on historical precedents and plausible projections, uncertainties remain regarding parameter sensitivity, scenario realism, and alignment with future trade and climate policy developments. Scenario outcomes should therefore be interpreted as indicative rather than predictive. Finally, this study primarily emphasizes environmental outcomes and does not explicitly integrate local economic, social, or cultural factors that may mediate trade-environment interactions. Incorporating such dimensions in future research could offer a more nuanced understanding of how trade frictions interact with local development conditions, capacity constraints, and social priorities.

Overall, while the study provides valuable insights into the potential environmental consequences of Sino-US trade frictions, these limitations highlight the need for cautious interpretation and further empirical and model-based investigation. In future research, we plan to address these limitations by incorporating more detailed sectoral classifications, tracking embodied emissions in intermediate goods trade, and reflecting heterogeneity in renewable energy penetration across regions and sectors. Additionally, dynamic technological spillovers will be explicitly modeled to better capture structural and efficiency adjustments. We also aim to refine regional groupings based on trade networks and functional linkages, and to integrate local economic, social, and cultural factors where relevant. These enhancements will help to improve the realism, robustness, and policy relevance of the simulations. Overall, we acknowledge the necessity of future empirical validation to further assess and strengthen the robustness of these findings, even though such validation may be challenging within the scope of this study.

6 Conclusions

Drawing on the GTAP model, this paper develops multiple scenarios reflecting Sino-US trade friction to simulate and assess its potential environmental impacts. The principal findings are as follows: First, Sino-US trade friction broadly suppresses trade volumes across most countries and regions globally, with notable exceptions including non-US North America, Southeast Asia, and East Asia. Among these, China and the United States emerge as the two most affected nations. Second, the trade friction induces positive structural effects in North America (excluding the US), while Southeast Asia experiences negative structural effects. Moreover, the PHH appears as a more prominent structural driver globally, whereas the FAH is less pronounced. Finally, Sino-US trade friction exacerbates carbon emissions in Europe, Southeast Asia, the Middle East, and Latin America. At the same time, it reduces emissions in North America, Oceania, Sub-Saharan Africa, as well as in China and the United States. Additionally, as tariff levels increase, carbon emissions decline in all regions except Europe and Latin America. The trade friction also intensifies disparities in carbon emission changes between developed and intermediate regions. It particularly accentuates differences within intermediate economies, while its effect on emission disparities among underdeveloped regions remains limited. From a sustainability standpoint, the findings highlight three critical concerns: (1) Carbon emissions are not reduced uniformly. They are reallocated globally in ways that increase environmental inequality. (2) Energy efficiency declines in many regions under friction, contradicting expected technological gains. (3)

Pollution-intensive industries shift to regions with weaker environmental regulation, reinforcing the problem associated with PHH.

Theoretically, these results reinforce the ACT framework, particularly the importance of structural effects in shaping environmental outcomes. Scale reductions in production and trade lower emissions in some regions (e.g., US, China), while structural shifts amplify emissions in others (e.g., Southeast Asia). The expected positive technology effect is undermined by policy uncertainty and broken supply chains. At the policy level, the findings of this study suggest three targeted directions that directly correspond to the identified impacts of Sino-US trade frictions.

First, addressing uneven global carbon emission reallocations is critical. Drawing on our quantitative results, trade frictions reduce emissions in China, the US, and Oceania but increase them in Europe, Southeast Asia, and Latin America, highlighting the uneven distribution of environmental burdens. International cooperation is necessary, with efforts focusing on preventing regions from being locked into high-emission industrial paths. For Southeast Asia, where structural effects are strongly negative, explicit measures are needed to curb the risk of becoming a long-term “pollution haven.” This includes adopting binding regional emission standards, introducing time-bound restrictions on the expansion of coal- and oil-based industries, and prioritizing low-carbon sectors in trade and investment agreements. In Latin America, strengthening green infrastructure financing and environmental impact assessments for foreign investment would help avoid the lock-in of emission-intensive development. In Europe, despite stricter regulation, the rise in emissions as shown in our simulations suggests the importance of coordinated carbon border adjustment mechanisms to reduce regulatory asymmetry with trade partners. While these strategies are sensible from a technical standpoint, their feasibility is constrained by current geopolitical tensions. Diverging trade interests and growing protectionism reduce the likelihood of a fully global approach. Nevertheless, embedding environmental provisions in bilateral and plurilateral trade agreements, forming “climate clubs” among willing economies, and linking carbon pricing mechanisms represent politically feasible intermediate steps that could gradually scale up to broader coordination.

Second, tackling efficiency losses and structural distortions requires region-specific and politically grounded strategies. Our results indicate two regional differences: China sees emission reductions but suffers energy efficiency declines, while Southeast Asia faces strong PHH effects. These findings reinforce the need for tailored policies. In China, policies should focus on accelerating energy system decarbonization and supporting the green upgrading of heavy industries. In Southeast Asia, harmonizing environmental standards within ASEAN and expanding concessional finance for low-carbon infrastructure would help prevent structural deterioration. However, from a political economy perspective, such reforms face domestic resistance from emission-intensive industries and export-oriented business groups that fear competitiveness loss. Conversely, green industry coalitions and civil society actors could provide countervailing pressure, suggesting that the balance of domestic interests will strongly influence the adoption of stricter environmental standards. In advanced economies such as the EU and North America, the fiscal and technological capacity to lead is present, but entrenched fossil-fuel lobbies may delay progress. At the international level, geopolitical rivalries risk politicizing climate-trade linkages—carbon border adjustments, for example, may be perceived as disguised protectionism, undermining trust among partners. These dynamics highlight that feasible policy coordination requires

not only financial and technological support but also credible institutional mechanisms that align domestic interest coalitions with international commitments.

Third, addressing both between-group and within-group carbon emission inequalities is essential for effective global climate governance. The Theil Index results from our simulations demonstrate that Sino-US trade frictions widen disparities in carbon emission changes, particularly among intermediate economies, providing quantitative support for the need for targeted inequality mitigation. From a between-group perspective, disparities across broad development categories (developed, intermediate, and underdeveloped regions) call for differentiated but coordinated international strategies. Advanced economies in North America and Europe should take the lead by integrating climate financing, clean technology transfer, and inclusive trade standards into their policies. This would enable emerging and intermediate economies to decouple growth from emissions. From a within-group perspective, the results suggest that inequalities are particularly pronounced within the intermediate-economy group. Policymakers in these regions should focus on narrowing domestic and regional disparities by adopting regionally harmonized environmental regulations (e.g., within ASEAN) and directing green investments toward pollution-intensive sub-sectors. This would prevent a small set of industries or countries within the group from becoming disproportionate pollution havens, thereby improving fairness and efficiency within the group. These targeted strategies not only respond to the distinct regional impacts identified by the GTAP-E simulations but also offer concrete pathways to reconcile trade policies with global climate mitigation objectives.

Funding This work was supported by the National Natural Science Foundation of China (grant number 42201302) and the "Double First-Class" University Construction Project of Lanzhou University (grant number 561120213).

Data availability Data will be available on reasonable request.

Declarations

Conflict of interest The authors declared that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Amiti, M., Redding, S. J., & Weinstein, D. E. (2019). The impact of the 2018 tariffs on prices and welfare. *Journal of Economic Perspectives*, 33(4), 187–210. <https://doi.org/10.1257/jep.33.4.187>
- Antweiler, W., Copeland, B. R., & Taylor, M. S. (2001). Is free trade good for the environment? *American Economic Review*, 91(4), 877–908. <https://doi.org/10.1257/aer.91.4.877>
- Bahmani-Oskooee, M., & Xu, J. (2022). Whose policy uncertainty matters in the trade between China and the US? *Economic Change and Restructuring*, 55(3), 1497–1542. <https://doi.org/10.1007/s10644-021-09356-2>
- Baqae, D. R., & Farhi, E. (2024). Networks, barriers, and trade. *Econometrica*, 92(2), 505–541. <https://doi.org/10.3982/ECTA17513>
- Behrens, K., & Murata, Y. (2012). Trade, competition, and efficiency. *Journal of International Economics*, 87(1), 1–17. <https://doi.org/10.1016/j.jinteco.2011.11.005>
- Bouët, A., & Laborde, D. (2018). US trade wars in the twenty-first century with emerging countries: Make America and its partners lose again. *The World Economy*, 41(9), 2276–2319. <https://doi.org/10.1111/twec.12719>

- Carvalho, M., Azevedo, A., & Massuquetti, A. (2019). Emerging countries and the effects of the trade war between US and China. *Economies*, 7(2), 45. <https://doi.org/10.3390/economies7020045>
- Cateia, J. V., & Savard, L. (2025). Trade and distribution in Guinea-Bissau: A computable general equilibrium analysis. *International Economics and Economic Policy*, 22(1), 4. <https://doi.org/10.1007/s10368-024-00634-8>
- Dixit, A., & Woodland, A. (1982). The relationship between factor endowments and commodity trade. *Journal of International Economics*, 13(3–4), 201–214. [https://doi.org/10.1016/0022-1996\(82\)90054-X](https://doi.org/10.1016/0022-1996(82)90054-X)
- Du, M., Chen, L., Lin, J., Liu, Y., Feng, K., Liu, Q., Wang, J., Ni, R., Si, W., Li, Y., Kong, H., Weng, H., Liu, M., Adeniran, J. A., & Zhao, Y. (2020). Winners and losers of the Sino-US trade war from economic and environmental perspectives. *Environmental Research Letters*, 15(9), Article 094032. <https://doi.org/10.1088/1748-9326/aba3d5>
- Ellili, N. O. D. (2024). Bibliometric analysis of sustainability papers: Evidence from Environment, Development and sustainability. *Environment, Development and Sustainability*, 26(4), 8183–8209. <https://doi.org/10.1007/s10668-023-03067-6>
- Fajgelbaum, P. D., & Khandelwal, A. K. (2022). The economic impacts of the US–China trade war. *Annual Review of Economics*, 14, 205–228. <https://doi.org/10.1146/annurev-economics-051420-110410>
- Fajgelbaum, P. D., Goldberg, P. K., Kennedy, P. J., & Khandelwal, A. K. (2020). The return to protectionism. *The Quarterly Journal of Economics*, 135(1), 1–55. <https://doi.org/10.1093/qje/qjz036>
- Felbermayr, G., Peterson, S., & Wanner, J. (2025). Trade and the environment, trade policies and environmental policies—How do they interact? *Journal of Economic Surveys*, 39(3), 1148–1184. <https://doi.org/10.1111/joes.12628>
- Gölgeci, I., Gligor, D. M., Bayraktar, E., & Delen, D. (2023). Reimagining global value chains in the face of extreme events and contexts: Recent insights and future research opportunities. *Journal of Business Research*, 160, Article 113721. <https://doi.org/10.1016/j.jbusres.2023.113721>
- Guo, J., Huang, Q., & Cui, L. (2021). The impact of the Sino-US trade conflict on global shipping carbon emissions. *Journal of Cleaner Production*, 316, Article 128381. <https://doi.org/10.1016/j.jclepro.2021.128381>
- Handley, K. (2014). Exporting under trade policy uncertainty: Theory and evidence. *Journal of International Economics*, 94(1), 50–66. <https://doi.org/10.1016/j.jinteco.2014.05.005>
- Heggem, I. Ø., & Jakobsen, T. G. (2016). The challenge of globalisation: A world-wide investigation of public attitudes on individual vs. government responsibility. *World Review of Entrepreneurship, Management and Sustainable Development*, 12(4), 381–398. <https://doi.org/10.1504/WREMSD.2016.079316>
- Herman, P. R., & Oliver, S. (2023). Trade, policy, and economic development in the digital economy. *Journal of Development Economics*, 164, 103135. <https://doi.org/10.1016/j.jdeveco.2023.103135>
- Hou, D., O'Connor, D., Sonne, C., & Ok, Y. S. (2019). Trade war threatens sustainability. *Science*, 364(6447), 1242–1243. <https://doi.org/10.1126/science.aay3596>
- Lawrence, R. Z. (2018). Can the trading system survive us—china trade friction? *China & World Economy*, 26(5), 62–82. <https://doi.org/10.1111/cwe.12256>
- Leihua, H., & Fan, S. (2024). Empirical evidence on the impact of the “new round” of Sino-US trade frictions on China’s foreign trade industrial policy and high-quality development. *PLoS ONE*, 19(10), e0309458. <https://doi.org/10.1371/journal.pone.0309458>
- Li, C., He, C., & Lin, C. (2018). Economic impacts of the possible China–US trade war. *Emerging Markets Finance and Trade*, 54(7), 1557–1577. <https://doi.org/10.1080/1540496X.2018.1446131>
- Li, M., Balistreri, E. J., & Zhang, W. (2020). The US–China trade war: Tariff data and general equilibrium analysis. *Journal of Asian Economics*, 69, Article 101216. <https://doi.org/10.1016/j.asieco.2020.101216>
- Li, K. X., Zhang, X., Yuen, K. F., Xu, Q., Zhu, Y., & Xiao, Y. (2024). Who carries the great trade? Logistics links between China and the world. *Maritime Policy & Management*, 51(6), 1277–1294. <https://doi.org/10.1080/03088839.2023.2249900>
- Lin, J., Du, M., Chen, L., Feng, K., Liu, Y., Martin, R. V., & Kong, H. (2019). Carbon and health implications of trade restrictions. *Nature Communications*, 10(1), Article 4947. <https://doi.org/10.1038/s41467-019-12890-3>
- Liu, Z., & Deng, Y. (2024). Does Sino-US trade friction hurt corporate resilience? Evidence from Chinese enterprises. *The Journal of International Trade & Economic Development*. <https://doi.org/10.1080/09638199.2024.2378953>
- Liu, L.-J., Creutzig, F., Yao, Y.-F., Wei, Y.-M., & Liang, Q.-M. (2020). Environmental and economic impacts of trade barriers: The example of China–US trade friction. *Resource and Energy Economics*, 59, Article 101144. <https://doi.org/10.1016/j.reseneeco.2019.101144>
- Marques, H. (2008). Trade and factor flows in a diverse EU: What lessons for the eastern enlargement (s)? *Journal of Economic Surveys*, 22(2), 364–408. <https://doi.org/10.1111/j.1467-6419.2007.00540.x>

- Mishra, M., Desul, S., Santos, C. A. G., Mishra, S. K., Kamal, A. H. M., Goswami, S., ... Dos Santos, C. A. C. (2024). A bibliometric analysis of sustainable development goals (SDGs): a review of progress, challenges, and opportunities. *Environment, development and sustainability*, 26(5), 11101–11143. <https://doi.org/10.1007/s10668-023-03225-w>
- Qin, M., Fan, Z., & Zhong, Y. (2022). The global value chain and welfare effects of tariffs—Counterfactual analysis of Sino–US economic and trade frictions. *Sustainability*, 14(14), 8280. <https://doi.org/10.3390/su14148280>
- Rosyadi, S. A., & Widodo, T. (2018). Impact of Donald Trump's tariff increase against Chinese imports on global economy: Global Trade Analysis Project (GTAP) model. *Journal of Chinese Economic and Business Studies*, 16(2), 125–145. <https://doi.org/10.1080/14765284.2018.1427930>
- Schandl, H., Hatfield-Dodds, S., Wiedmann, T., Geschke, A., Cai, Y., West, J., Newth, D., Baynes, T., Lenzen, M., & Owen, A. (2016). Decoupling global environmental pressure and economic growth: Scenarios for energy use, materials use and carbon emissions. *Journal of Cleaner Production*, 132, 45–56. <https://doi.org/10.1016/j.jclepro.2015.06.100>
- Shen, G., Wang, P., & Xu, Y. (2021). Trade destruction and deflection effects of US-China trade frictions on China's tariff-targeted products. *World Economy*, 44(7), 2076–2106. <https://doi.org/10.1111/twec.13067>
- Taheripour, F., & Tyner, W. E. (2018). Impacts of possible Chinese 25% tariff on U.S. soybeans and other agricultural commodities. *Choices*, 33(2), 1–7.
- Ünal, E., Lin, B., & Managi, S. (2023). CO2 emissions embodied in bilateral trade in China: An input-output analysis. *Environmental Impact Assessment Review*, 103, Article 107218. <https://doi.org/10.1016/j.eiar.2023.107218>
- Wang, X., & Shi, B. (2022). Transmission and diffusion effect of Sino-US trade friction along global value chains. *Finance Research Letters*, 46, Article 102057. <https://doi.org/10.1016/j.frl.2021.102057>
- Wang, J., Yu, S., Elbakidze, L., Xin, Y., Song, S., & Ma, Y. (2024a). US-China trade friction and agricultural nitrogen loss in China. *Environmental Impact Assessment Review*, 106, Article 107507. <https://doi.org/10.1016/j.eiar.2024.107507>
- Wang, Q., Zhang, F., & Li, R. (2024b). Free trade and carbon emissions revisited: The asymmetric impacts of trade diversification and trade openness. *Sustainable Development*, 32(1), 876–901. <https://doi.org/10.1002/sd.2703>
- Wiedmann, T., & Lenzen, M. (2018). Environmental and social footprints of international trade. *Nature Geoscience*, 11(5), 314–321. <https://doi.org/10.1038/s41561-018-0113-9>
- Xie, Q., & Wu, H. (2021). How does trade development affect environmental performance? New assessment from partially linear additive panel analysis. *Environmental Impact Assessment Review*, 89, Article 106584. <https://doi.org/10.1016/j.eiar.2021.106584>
- Xing, K., & Yuan, Y. (2025). Will sino–U.S. trade friction affect the resilience of the global backbone industry network? *Economic Analysis and Policy*, 87, 893–908. <https://doi.org/10.1016/j.eap.2025.06.033>
- Xu, Z., Zhong, X., & Zhang, Z. (2022). Does the Sino–US trade friction promote firm innovation? The role of the export grab effect. *Sustainability*, 14(5), 2709. <https://doi.org/10.3390/su14052709>
- Yang, S., Shi, B., & Yang, F. (2023). Macroeconomic impact of the Sino–US trade frictions: Based on a two-country, two-sector DSGE model. *Research in International Business and Finance*, 65, Article 101956. <https://doi.org/10.1016/j.ribaf.2023.101956>
- Yang, X. (2024). A review on the shock of Sino-US trade friction on semiconductor industry in China. Paper presented at the proceedings of the 2023 international conference on economic management, financial innovation and public service (EMFIPS 2023). https://doi.org/10.2991/978-94-6463-441-9_47
- Yao, C.-L., Huang, P.-C., Su, C.-W., Lobont, O.-R., & Qin, M. (2025). A barometer of climate change: Does the US–China tension exacerbate its risks? *Emerging Markets Finance and Trade*, 61(13), 4124–4137. <https://doi.org/10.1080/1540496X.2025.2501231>
- Yu, M., & Zhang, R. (2019). Understanding the recent Sino-US trade conflict. *China Economic Journal*, 12(2), 160–174. <https://doi.org/10.1080/17538963.2019.1605678>
- Yuan, R., Rodrigues, J. F. D., Wang, J., & Behrens, P. (2023). The short-term impact of US-China trade war on global GHG emissions from the perspective of supply chain reallocation. *Environmental Impact Assessment Review*, 98, Article 106980. <https://doi.org/10.1016/j.eiar.2022.106980>
- Zhang, X., Wu, L., Zhang, R., Deng, S., Zhang, Y., Wu, J., Li, Y., Lin, L., Li, Li., Wang, L., & Wang, Y. (2013). Evaluating the relationships among economic growth, energy consumption, air emissions and air environmental protection investment in China. *Renewable and Sustainable Energy Reviews*, 18, 259–270. <https://doi.org/10.1016/j.rser.2012.10.029>

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.