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G-2 and the climate crisis: How global exports to China and the U.S. drive carbon emissions, 2000–2022

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Abstract

In recent decades, China has risen to become the second-largest national economy and the world's top national carbon emitter, while the United States (U.S.) has retained its status as the largest national economy and a top emitter among nations. The trade war between the two nations has heightened geopolitical and world-economic tensions, underscoring the need to examine its implications for the climate crisis. Although prior research identifies global trade expansion as a key driver of nations' greenhouse gas emissions, the specific influence of exports to these two world-economic powerhouses on emissions remains greatly understudied. To help remedy this gap, we investigate how export flows to the U.S. and China have shaped carbon emissions from 2000 to 2022, using fixed effects models across 181 nations and territories. Focusing on both export volumes and export shares to the U.S. and China, we find that exports to China increase carbon emissions in both the short run and long run, highlighting China's outsized carbon impacts on exporting nations. In contrast, exports to the U.S. do not consistently contribute to national carbon emissions.

Introduction

Previous research on international trade and carbon emissions largely focuses on the broader Global North-South divide. Many studies suggest that in Global North nations, trade openness and carbon emissions exhibit an inverted U-shaped relationship, supporting the Environmental Kuznets Curve hypothesis [1,2], whereas in Global South nations, trade openness is more consistently associated with rising emissions [3–6]. These patterns are partly explained by the outsourcing of pollution-intensive production from developed nations to developing nations [7–9], as well as an increase in South-South trade in carbon-intensive intermediate goods [10–12]. Some researchers further argue that these trade–emissions dynamics are shaped by cross-national differences in economic conditions and trade strategies. The impacts of trade on carbon emissions are heterogeneous depending on factors such as a country's comparative advantage and capital intensity in production [13,14], as well as the degree of trade diversification and technological advancement within its industrial structure [15].

However, the world-economic landscape has shifted dramatically over the past few decades. China has risen to become the world's second-largest national economy, while the U.S. has retained its position as the largest. Although the U.S. has a much greater historical contribution to cumulative carbon emissions, these two economic superpowers are also currently leading national contributors to global carbon emissions and the climate crisis. In terms of production-based CO_2 emissions, the U.S. emitted 5,928.97 Mt of CO_2 in 2000, accounting for 23.1% of global emissions, while China emitted 3,666.95 Mt (14.3% of global emissions). By 2022, their emissions trajectories had diverged sharply. China's emissions surged to 12,526.83 Mt (32.8% of global emissions), whereas U.S. emissions declined modestly to 4,786.63 Mt (12.5% of global emissions). Combined, their share of annual global emissions increased from 37.4% in 2000 to 45.3% in 2022. This shift has unfolded alongside rising geopolitical tensions, including the current trade war between China and the U.S. that began in 2018 under the Trump administration's tariff policies. These transitions have reshaped global trade flows, raising important questions about the climate-related consequences of trade with both nations.

We suggest a need for greater understanding of the role of the U.S. and China in shaping the global climate crisis, especially in the context of international trade. According to the UN Comtrade database [16], global exports of goods totaled approximately USD 6.15 trillion in 2000, with 18% destined for the U.S. and 3.3% for China. By 2022, total exports of goods had grown to USD 23.5 trillion, with the U.S. and China accounting for 13.3% and 8.6%, respectively. Together, these "G-2" economies received nearly 22% of global goods exports in 2022. Their central roles in global trade raise important climate-related questions. In particular, to what extent do exports to these two nations influence an exporting nation's CO_2 emissions in the short term? And, do exports to either the U.S. or China shape a nation's long-term emissions trajectory?

Without question, strands of prior research shed some light on the CO_2 emissions embodied in trade with the U.S. or China. For example, Weber and Matthews [17] analyzed emissions embodied in U.S. international trade with the nation's seven largest trading partners (Canada, China, Mexico, Japan, Germany, South Korea, and the U.K.) from 1997 to 2004. Their findings show that the amount of CO_2 emissions embedded in U.S. imports increased substantially, rising from 500–800 Mt of CO_2 in 1997 to 800–1,800 Mt in 2004. These embedded emissions in imports accounted for approximately 9–14% of total U.S. CO_2 emissions in 1997, and 13–30% in 2004. Stretesky and Lynch [18] examined the effect of exports to the U.S. on per capita CO_2 emissions for a large sample of nations from 1989 to 2003. They found that exports to the U.S. are positively associated with a nation's per capita emissions, particularly in carbon-intensive industries including chemicals, oil and gas, and re-imports.

Furthermore, Huang [19] showed that from 2000 to 2010, exports to the U.S. from developing countries remained significantly associated with increases in per capita CO2 emissions, even during the economic recessions in 2001 and 2008.

Turning to China, Lin and Sun [20] estimated that in 2005, Chinese exports embodied approximately 3,357 Mt of CO_2, while its imports externalized around 2,333 Mt of CO_2 to sending nations. Yunfeng and Laike [21] analyzed trade-embodied emissions of China from 1997 to 2007, finding that import-related emissions grew from 4.4% (137.82 Mt) in 1997 to 9.05% (587.87 Mt) in 2007 of China's production-based CO_2 emissions, while export-related emissions surged from 10.03% (314.24 Mt) to 26.54% (1,725.02 Mt) of China's production-based CO_2 emissions. Their analysis also suggested that outsourcing to China allowed other countries to avoid emitting 150.18 Mt of CO_2 in 1997 and 593 Mt in 2007. Extending these findings, Qi et al. [22] employed multi-regional input-output (MRIO) analysis to show that in 2007, China exported 1,722 Mt and imported 545 Mt of embodied CO_2, remaining a net exporter of emissions to all regions except Taiwan, with imports from Taiwan, South Asia, Korea, and Japan each externalizing between 50 and 100 Mt of CO_2.

Despite these important contributions, existing research has yet to fully examine how trade with the U.S. and China affects the emissions of exporting nations in both the short run and long run. Whereas considerable attention has been given to the emissions associated with exports from these two superpowers, less focus has been given to how their demand shapes emissions in exporting nations. Analyzing such export-emissions dynamics offers a complementary perspective by highlighting the climate burden shouldered by producers and the broader role of exporting nations in driving global emissions, particularly within a trade structure that is largely shaped by the U.S. and China. Moreover, much of the existing research predates recent global disruptions, including the 2008 Great Recession, the U.S.–China trade war beginning in 2018, and the COVID-19 pandemic starting in 2020.

To address these gaps, we examine the impact of goods exports to the U.S. and China on production-based national CO_2 emissions from 2000 to 2022. Utilizing dynamic fixed-effects panel regression models across 181 nations and territories, we analyze two key metrics: export volumes to the U.S. and China and export shares to these two nations. Each metric provides unique insights. On the one hand, export volumes capture the scale of transactions, offering a direct measure of how exports influence emissions. On the other hand, export shares reflect the relative importance of each receiving market to the exporting country, shedding light on market dependency and its implications for carbon emissions.

Our findings reveal that exports to China lead to significant increases in CO_2 emissions for exporting nations in both the short run and long run. This underscores China's outsized climate impact, not only as a major emitter itself but also through its demand for goods that increase emissions beyond its own borders. In contrast, exports to the U.S. show no consistent link to national emissions, suggesting distinct emissions patterns tied to these trade relationships. By focusing on the post-2000 era, this study provides new insights into global trade's environmental consequences and emphasizes the need for targeted climate strategies in an interconnected world. As nations grapple with the challenges of economic growth, geopolitics, and climate mitigation, understanding how exports to these economic superpowers influence national emissions throughout the world is crucial for designing effective and equitable climate policies.

Methods

Data

We maximize the use of available data. The overall panel dataset consists of 3,578 observations for 181 nations and territories between 2000 and 2022, with each nation contributing an average of 21.2 observations (ranging from 4 to 23 annual observations per nation). Due to missing data across measures, the sample size differs across models depending on the independent variables included. Hong Kong and Macao are treated as independent units from mainland China in line with their separate reporting in World Bank and UN Comtrade data. Results remain robust when these two territories are excluded from the analysis. S1 Table provides a full list of nations included in the study. As a robustness check, we also estimate models using a dataset restricted to nations with no missing data, resulting in a balanced panel of 2,169 annual observations from 103 nations (the 103 nations are flagged in S1 Table). We also estimate models using a dataset that is extended from 1990 to 2022, which consists of 3,488 observations from 162 nations (average of 21.5 observations per nation, ranging from 1 to 33).

Dependent variables

We use production-based total CO_2 emissions as the primary dependent variable, obtained from the World Bank [23]. These emissions reflect a country's annual CO_2 output from the agriculture, energy, waste, and industrial sectors, excluding land use, land-use change, and forestry (LULUCF). Measured in megatonnes of CO_2 equivalent (Mt CO_2e), total CO_2 emissions quantify the absolute volume released, assessing each nation's contribution to atmospheric CO_2 accumulation.

Primary independent variables

The primary independent variables in this study are export volumes and export shares to the U.S. and China, derived from the UN Comtrade database [16]. Export volumes, measured in current US dollars, represent the value of exported goods, encompassing transaction costs and services required to reach the exporting country's border. Export shares, expressed as percentages, are calculated by dividing a country's annual exports of goods to the U.S. or China by its total annual exports of goods. While export volumes reflect the absolute scale of exports and its association with a country's carbon emissions, export shares represent relational dynamics of exports, highlighting how a country's world-economic alignment with the U.S. or China shapes its overall emissions profile.

Additional variables

The reported models include additional control variables commonly used in prior research on anthropogenic drivers of national emissions (e.g., ref. [24,25]). All models include gross domestic product (GDP) per capita, measured in constant 2015 U.S. dollars, total population and urban population as a percentage of the total population, the age dependency ratio, trade as a percentage of GDP, and manufacturing as a percentage of GDP. The age dependency ratio represents the proportion of individuals younger than 15 or older than 64 to the working-age population (ages 15–64). All data for the additional variables were obtained from the World Bank [23]. As we estimate dynamic models, the lagged dependent variable (t-1) is included in each model. Descriptive statistics for the variables used in this study are provided in S2 Table.

Model estimation techniques

We use Stata 18 for all statistical analysis and transform non-binary variables into natural logarithmic form to yield elasticity coefficients—each representing the percentage change in emissions per 1% increase in an independent variable.

We apply fixed-effects panel regression with Driscoll-Kraay standard errors [26], implemented using the *xtscc* command, to address potential cross-sectional dependence indicated by CD tests [27]. The Driscoll-Kraay estimator corrects for cross-sectional dependence, autocorrelation, and heteroskedasticity [28], which are critical concerns given the interconnected nature of trade and emissions. The lag structure in *xtscc* models specifies the maximum lag length for correcting autocorrelation. Following standard econometric guidance, we applied the rule-of-thumb bandwidth $m(T) = floor[4(\frac{T}{100})^{2/9}]$, which yields m = 2 for our data [28,29]. We also tested lag lengths from two to twelve to ensure robustness. Coefficient estimates remained stable across specifications. A three-lag structure was selected as optimal, as it produced the lowest standard errors while preserving statistical efficiency and model robustness.

To address autocorrelation and reduce omitted variable bias [30], we include the lagged dependent variable as a control. This addition also enables estimation of both short-run and long-run effects of the independent variables. The equation for Model 3 in S3 Table is outlined below:

$$CO_2\ Emissions_{i,t} = \lambda_1 CO_2\ Emissions_{i,t-1} + \beta_1 Exports\ to\ US_{i,t} + \beta_2 Exports\ to\ China_{i,t} + \beta_3 GDP\ Per\ Capita_{i,t} + \beta_4 Total\ Population_{i,t} + \beta_5 Age\ Dependency\ Ratio_{i,t} + \beta_6 Urban\ Population + \beta_7 Manufacturing_{i,t} + \beta_8 Trade_{i,t} + \alpha_i + u_t + \varepsilon_{i,t}.$$

$CO_2\ Emissions_{i,t}$ refers to the annual national CO_2 emissions for country *i* in year *t*. α_i captures nation-specific fixed effects, u_t represents year-specific fixed effects, and $\varepsilon_{i,t}$ denotes the error term. The short-run effects are estimated by β_1–β_8, while the long-run effects are obtained by dividing each short-run estimate by $1 - \lambda_1$ [31]. Long-run effects are computed using Stata's community-contributed *lreff* command [32], which acts as a wrapper for the *nlcom* command, applying the delta method to estimate standard errors. The short-run estimates capture the immediate change in emissions, whereas the long-run effects measure the cumulative change over time. For robustness checks, we apply the same models used in our main analysis to both the extended sample and the balanced sample.

Results

The structure of the global economy has shifted its center from the U.S. to China

Fig 1a illustrates bilateral export volumes to the U.S. and China, along with national production-based CO_2 emissions for the years 2000 and 2020. In 2000, the U.S. had the highest CO_2 emissions globally, and export volumes to the U.S. exceeded those to China. Canada, Mexico, and Japan were major exporters to the U.S. at the time. By 2020, however, China had emerged as the world's largest carbon emitter and the largest exporter to the U.S. Although the U.S. continues to import substantial volumes from around the world, exports to China have grown significantly from South Korea, Japan, Germany, Australia, Brazil, and the U.S.

Turning to Fig 1b, the global distribution of export shares to the U.S. and China reflects shifting patterns of countries' economic orientation toward these two major powers. On average, the share of national exports directed to the U.S. declined from 15.7% in 2000 ($P_{10} = 0.64\%,\ P_{50} = 7.74\%,\ P_{90} = 47.4\%$) to 11.3% in 2020 ($P_{10} = 0.39\%,\ P_{50} = 4.97\%,\ P_{90} = 30.1\%$). In contrast, the average share of national exports to China increased from 2.43% in 2000 ($P_{10} = 0.023\%,\ P_{50} = 0.37\%,\ P_{90} = 5.09\%$) to 8.89% in 2020 ($P_{10} = 0.24\%,\ P_{50} = 3.18\%,\ P_{90} = 27.58\%$). In 2000, countries in the Americas, Africa, South and Southeast Asia, and parts of Europe exhibited relatively greater export dependence on the U.S., whereas nations in the Middle East, Oceania, and Northern Europe displayed higher export shares to China. By 2020, however, export shares to China had increased across most regions, with pronounced increases especially observed in countries in Southern Africa, the Middle East, and Oceania.

Export growth toward China increases global CO_2 emissions

Models are estimated using the xtscc command in Stata 18 with a three-lag structure to account for autocorrelation. All models include the lagged dependent variable, country-specific fixed effects via the within estimator, and year-specific fixed effects as intercepts. See Methods for additional details on the methodology and models. Full results are in S3 Table.

We estimated the extent to which a country's total production-based CO_2 emissions are influenced by exports to the U.S. and China, using a dynamic fixed-effects panel regression. Fig 2 summarizes the results for the export-related metrics (see S3 Table for full results). For both volumes and shares, exports to China exhibit statistically significant positive effects on national CO_2 emissions in both the short run and long run. In contrast, exports to the U.S. show positive but statistically nonsignificant effects. Specifically, a 1% increase in export volumes to China by an average country is associated with a 0.0078% increase in national CO_2 emissions in the short run (95% CI: 0.0041 to 0.012) and a 0.018% increase in the long run (95% CI: 0.0085 to 0.027). Similarly, a 1% increase in export share to China by an average country leads to a 0.0064% increase in emissions in the short run (95% CI: 0.0025 to 0.010) and a 0.014% increase in the long run (95% CI: 0.0049 to 0.024).

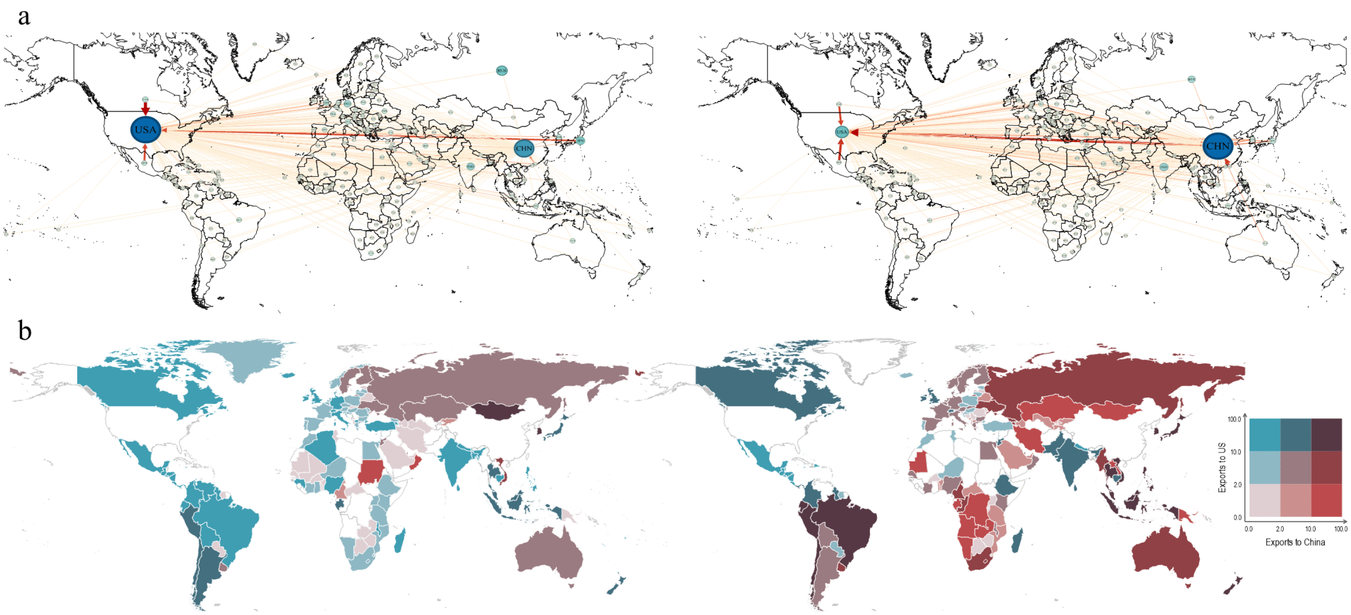

Fig 1. Maps of Global Exports to the U.S. and China in 2000 (Left) and 2020 (Right). a. Export volumes from countries to the U.S. and China, alongside their relative total CO_2 emissions in 2000 and 2020. Node size is scaled by each country's total CO_2 emissions in the respective year, with node color transitioning from light to dark blue to reflect increasing emissions levels. Edge thickness represents the export volume from the source country to the target country (U.S. or China), with edge color varying from light orange to dark red to indicate higher export volumes. The maps were generated using the map of countries plugin in Gephi (https://gephi.org/desktop/plugins/mapofcountries/). **b.** Bivariate maps of export shares to the U.S. and China in 2000 and 2020, categorized into three groups: less than 2%, 2%–10%, and greater than or equal to 10%. The maps were generated in Stata version 18 using a shapefile from the dataset "World Administrative Boundaries – Countries," accessible at: https://public.opendatasoft.com/explore/assets/world-administrative-boundaries-countries/. Due to missing data in 2022, we primarily use 2020 data in the main analysis to present geopolitical information on total national emissions and export volumes to the U.S. and China. The maps for the year 2022 are included in S1 Fig.

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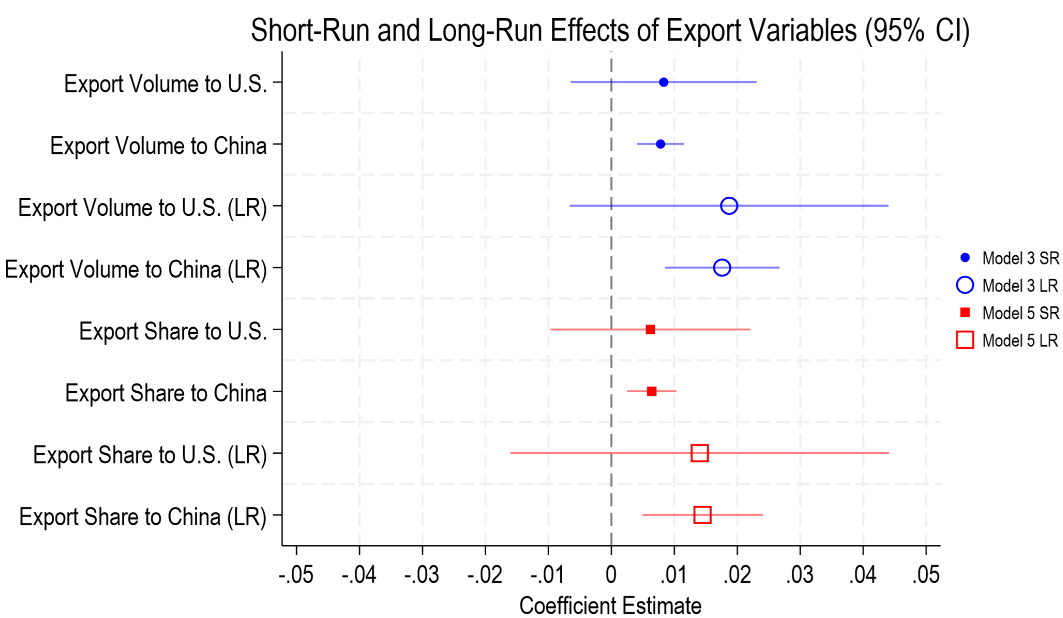

Fig 2. Coefficient plots of Short-Run and Long-Run Elasticities of Export Volumes and Shares to the U.S. and China on Total CO_2 Emissions, 2000–2022.

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The estimated effects of export metrics on emissions are far from trivial. Total CO_2 emissions excluding the U.S. and China were 20933.16 Mt (54.7% of total global emissions) in 2022. Based on our analysis, and using the emissions data for 2022, a 1% increase in global export volumes to China (excluding the U.S.) in 2022 is estimated to increase their combined CO_2 emissions by approximately 1.63 Mt in the short run and 3.77 Mt in the long run if other conditions remain stable. For just the five countries with the highest total emissions in 2022 when excluding the U.S. and China (India, Russia, Japan, Iran, Germany), with combined emissions of 5654.79 Mt, a 1% increase in export volumes to China in 2022 is estimated to increase their total CO_2 emissions by approximately 0.44 Mt in the short run and 1.02 Mt in the long run.

To assess the robustness of these findings, we conducted additional analyses using both an extended sample and a balanced sample. The extended sample includes data from 1990 to 2022 (N = 3,488; 162 nations), while the balanced sample is restricted to countries with complete data across all variables used in the main analysis (N = 2,169; 103 nations). Results from the extended sample (S4 Table) confirm that the observed effects of exports to China and the United States persist when extending coverage back to the 1990s. Similarly, findings from the balanced sample (S5 Table) are consistent with the main results, reinforcing the robustness of the identified relationships.

Discussion and conclusion

In this study, we demonstrate how exports to two economic superpowers—China and the U.S.—shape the production-based CO_2 emissions of exporting nations. Using data for a global sample of nations between 2000 and 2022, our findings suggest that the worldwide landscape of exports of goods has experienced substantial shifts. In bilateral terms, the global export structure transformed from being U.S. centric in the early 2000s to the extension of Chinese influence across the world in the 2020s. Furthermore, our analysis shows that exports to China are associated with increases in CO_2 emissions for exporting nations in both the short run and long run, whereas exports to the U.S. are not significantly associated with emissions for exporting nations. This divergence highlights the complex and uneven environmental outcomes of global trade and underscores the broader implications for national emissions trajectories and the global climate crisis.

We primarily aim to reconceptualize our analytical framework of the global political economy by shifting the focus from traditional Global North-South divisions to the evolving trade dynamics between these two major superpowers and their trading partners. This perspective highlights the disproportionate influence of China and the U.S. in global trade networks and their central roles in the climate crisis. Our analysis of the effects of exports to China on exporting nations' emissions reveals the presence of a spillover effect stemming from China's carbon-intensive trade structure. Although China launched extensive environmental reforms under its 2014 "war against pollution" initiative [33] and energy policies to achieve the peaking target for the Paris commitment [34], our findings indicate that it remains heavily reliant on carbon-intensive trade while continuing to be the largest emitter which limits the overall effectiveness of these policies.

In contrast to studies that find pollution offshoring hypothesis, or carbon leakage, which posits the relocation of pollution-intensive production to nations with lower environmental costs [35], our findings suggest that global exports to the U.S. appear less associated with the offshoring of emissions to exporting countries. This finding aligns with previous research showing that the composition of U.S. imports shifted towards relatively clean goods from 1972 to 2001, and this green shift is even larger than the corresponding green shift of U.S. domestic manufacturing [36]. Nonetheless, because our analysis focuses on the structural dynamics of global trade and emissions, further narrowing of scope will be needed to unpack the mechanisms underlying these patterns.

The analysis can be deepened by examining exports at the sectoral level to better understand why exports to China are more carbon-intensive than those to the U.S. To address this, we further analyzed global exports to China and the U.S. by sector.

Fig 3a shows the export composition by sectoral share toward China and the U.S. in 2000 and 2022. Fig 3b presents the export composition by export volume for each sector toward China and the U.S. Sectors are classified according to the HS codes. Further details on the HS code classification are provided in S6 Table.

Fig 3 illustrates the disaggregated global exports to China and the U.S. by sector. Fig 3a shows that the composition of exports to China has changed markedly: the share of the energy and minerals sector increased from 7.6% to 17.5%, and the agriculture sector from 4.3% to 8.8%, while the shares of the wood and paper sector and the textiles and light manufacturing sector declined from 6.3% to 2% and from 11.1% to 1.6%, respectively. Exports to the U.S., by contrast, show an increase in the chemicals and plastics sector from 8.2% to 15% and in the agriculture sector from 4.6% to 7.9%, while the machinery and transport sector declined from 57.8% to 49.1%.

Focusing only on the proportional changes across sectors might suggest that the emissions impact of exports to China is driven by the growing shares of the energy and minerals and agriculture sectors, which are environmentally demanding industries. However, Fig 3b reveals that a more nuanced interpretation is required. When comparing export volumes by sector between China and the U.S. in 2022, the export volume of the energy and minerals sector is not substantially different between the two countries, and overall export volumes for most sectors are higher toward the U.S. This reinforces our argument that exports to China are more environmentally demanding, suggesting that the carbon burden stems not merely from trade volume but from the underlying production and supply chain structures linked to Chinese demand. Future research should further investigate why exports to China impose greater carbon burdens on exporting nations by examining sector-specific trade patterns and their impacts on emissions in greater depth.

Like all research, our study has limitations. We primarily focused on the export of goods to highlight production-based CO_2 emissions and international trade flows, which may lead to an underestimation of the impact of service exports on emissions. Our analysis, grounded in bilateral trade data, does not account for the impact of imports from these two countries on national emissions. Future research should address these gaps by incorporating service exports (e.g., ref. [37]), employing consumption-based accounting (e.g., ref. [38]), and focusing on carbon-intensive industries—for example, fossil fuels [39], trade via international shipping [40], and sector-specific carbon intensities of exports [41].

In addition, our methodological approach does not fully capture the causal relationships or determine whether a reduction in exports to China would result in a proportional decrease in national emissions. Establishing causality between global trade and emissions would require more sophisticated research designs capable of addressing potential endogeneity arising from unobserved factors or reverse causality. Moreover, given the path dependency of industrialization and

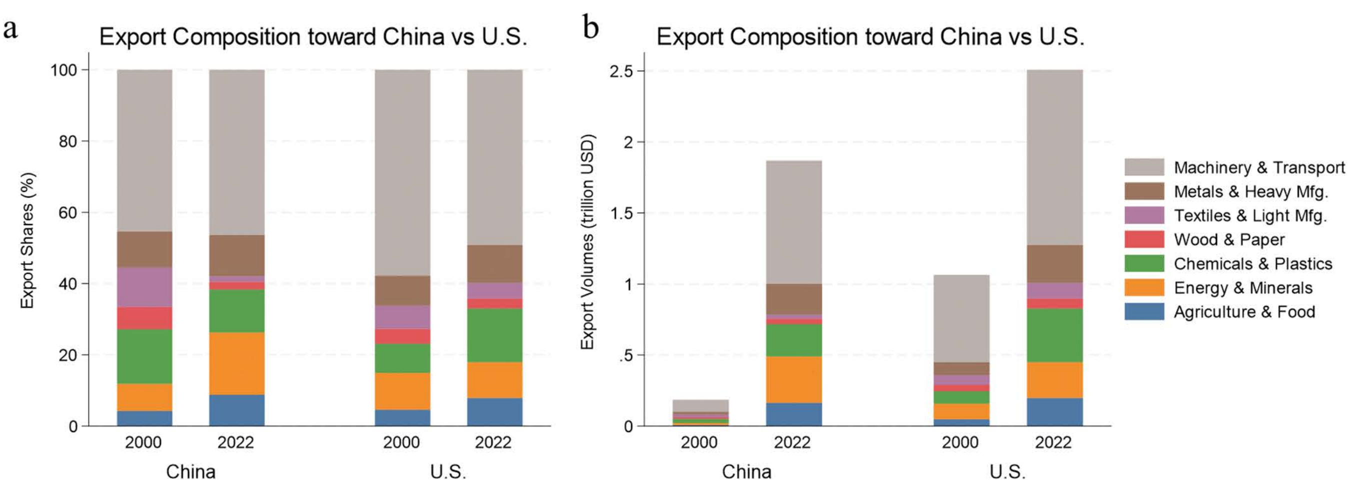

Fig 3. Export Shares and Volumes to China and the U.S. by Sector in 2000 and 2022.

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institutionalization, efforts to diversify export portfolios or green production processes may have a limited impact on reducing CO_2 emissions compared to emissions growth driven by economic development. To derive more targeted policy implications, future studies could employ asymmetry-focused statistical modeling to assess whether increases and decreases in exports to the U.S. and China have symmetric effects on national emissions.

While recognizing these limitations, our analysis, centered on bilateral export relationships, reveals the carbon implications of export structures oriented toward China and the U.S. Understanding these trade-emission dynamics is particularly critical for nations closely tied to Chinese markets, as it underscores the need to foster environmental responsibility and emissions reduction in production. Furthermore, our results raise important considerations for climate justice: nations that expand exports to meet Chinese demand bear the environmental costs of the resulting carbon-intensive trade. Mechanisms such as carbon border adjustment measures (CBAMs), green trade agreements, or supply chain decarbonization standards could play complementary roles in ensuring that the carbon intensity of global trade is more equitably accounted for across partners. Strengthening such linkages between trade policy and climate responsibility would promote fairer and more sustainable global trade practices, advancing both emissions reduction and climate justice goals.

Supporting information

S1 Table. List of nations and territories in the full dataset.
(DOCX)

S2 Table. Descriptive analysis of variables.
(DOCX)

S3 Table. Fixed-effects regression of total CO_2 emissions.
(DOCX)

S4 Table. Fixed-effects regression of total CO_2 emissions using the extended panel, 1990–2022.
(DOCX)

S5 Table. Dynamic fixed-effects regression of total CO_2 emissions using balanced panel, 2000–2022.
(DOCX)

S6 Table. Sectoral classification of HS codes.
(DOCX)

S1 Fig. Global maps of exports to the U.S. and China in 2022.
(DOCX)

S1 Data. Dataset and do files.
(ZIP)

Author contributions

Conceptualization: Taekyeong Goh, Andrew Jorgenson.

Data curation: Taekyeong Goh.

Formal analysis: Taekyeong Goh.

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Visualization: Taekyeong Goh.

Writing – original draft: Taekyeong Goh, Andrew Jorgenson.

Writing – review & editing: Taekyeong Goh, Andrew Jorgenson.

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