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Impact of International Trade on the Carbon Intensity of Human Well-Being

Shaojian Wang, Jieyu Wang, Xiangjie Chen, Chuanglin Fang, Klaus Hubacek, Xiaoping Liu, Chunshan Zhou, Kuishuang Feng, and Zhu Liu

1. INTRODUCTION

International trade is one of the major drivers of the global economy. According to the United Nations Conference on Trade and Development, international trade increased by more than 757% from 1980 to 2020. There has been a longstanding debate about the impact of international trade on the environment and human well-being, yet there is little known about such environmental and human well-being trade-off. Here, we explore the effect of international trade on the carbon intensity of human well-being (CIWB) globally under the current global trade system and a hypothetical no-trade scenario. We found that between 1995 and 2015, CIWB of 41% of countries declined and 59% of countries increased, caused by international trade, and this resulted in a reduction of the global CIWB and a decline in CIWB inequality between countries. International trade decreased CIWB for high- and upper-middle-income countries and increased CIWB for lower- and middle-income countries. In addition, our results also show that decreases in emission intensity are the most important driver of lower CIWB and the percentage contribution of emission intensity to the improvement in CIWB increases with income. The reduction of emission intensity, population growth, and increases in life expectancy all contribute to CIWB reduction, while the consumption level is the primary factor driving CIWB growth. Our results underscore the importance of studying the impact of international trade on the CIWB of countries at different stages of development.

KEYWORDS: carbon intensity of human well-being, international trade, drivers, global courtiers
of environmental and human well-being. Carbon intensity of human well-being (CIWB) reflects a basic notion of sustainability. Its underlying logic is consistent with the idea of increasing human well-being while reducing the pressure of human behavior on the environment. Research on CIWB reflects a shift in focus from traditional affluence (such as GDP) to a more direct and objective measure of well-being. The CIWB indicator combines environmental and human components into one measure. Therefore, exploring the relationship between CIWB and international trade can provide a deeper and more integrated understanding of the impact of international trade on the environment and human well-being.

International trade has far-reaching impacts, and many studies have explored the effects of international trade on climate, environmental space, equity, and well-being. However, the importance of international trade as a driver of CIWB is poorly understood. The relevant discussions have centered around the relationship between economic growth and CIWB. Few literature studies the impact of international trade on CIWB. For example, Givens explores the relationship between trade integration and the structure of trade relationships on CIWB for 81 countries from 1990 to 2011. However, several studies use the volume of a country’s exports to represent global trade. Export volumes do not reflect the intricate global trade channels and trade relations. Moreover, as international trade expands rapidly around the world, different virtual resources can flow with traded commodities, with the consequent transfer of environmental burdens, which can greatly affect the environment and people’s quality of life in each country. But previous studies on the impact of trade on CIWB do not take these aspects into account. A systematic examination of how international trade alters CIWB is yet lacking.

The aim of this paper is to fill these knowledge gaps, and the contribution of this paper includes the following: first, we evaluate the effects of trade on CIWB at the global and national levels and explore how these effects have changed over time. To estimate the impact of international trade on CIWB, we set up a no-trade scenario. A multi-regional input–output (MRIO) model is used in this context. Input–output tables provide a comprehensive view of economic linkages between sectors in each country, and MRIO models can track environmental impacts in complex international supply chains by capturing the end-users of goods and services in the supply chain. Using this approach provides a more comprehensive and in-depth view of the impacts of global trade than is possible with export volumes. Second, based on the argument that trade has different environmental impacts in different countries, we investigate how the impact of international trade differs across different income countries, which is of great significance to the realization of environmental equity. Third, we examine the drivers of CIWB change, in particular, the impact of changes in trade structure on CIWB. Fourth, the results of this study can provide valuable information for global efforts to achieve environmental protection and promote human well-being goals across spatial scales. Contributing to a shift in attention from a singular focus on GDP per capita growth to the promotion of human well-being with less stress on the environment may open the way to a more sustainable, healthier, and equitable future.

Here, we perform detailed analyses on the CIWB of 158 countries from 1995 to 2015 under the current global trade system and a hypothetical no-trade scenario. This no-trade scenario assumes that there are no embodied CO₂ imports or exports between countries. It is calculated by subtracting a country’s real-world (or production-based) CO₂ emissions from its embodied carbon exports to get the CO₂ emissions in the no-trade scenario and then calculating each country’s CIWB performance in the no-trade scenario (details of the hypothetical no-trade scenario approach are provided in Section 2). We then compare the differential impact of international trade on CIWB across countries. We further investigate the drivers of CIWB change using structural decomposition analysis (SDA), in particular, the impact of changes in trade structure on CIWB. Our findings indicate that although international trade could reduce the overall global CIWB and the CIWB gap between countries, high-income countries are the main beneficiaries of international trade in decreasing their respective CIWB. Moreover, the ability to achieve a decrease in CIWB boils down to a competition between growth in total consumption (especially domestic consumption level) and a decrease in emission intensity.

2. MATERIALS AND METHODS

2.1. Data. The global MRIO data by sectors are obtained from the Eora26 Database (v199.82, https://www.worldmrio.com/eora26/). The Eora26 database is the most detailed (in terms of the number of countries) global MRIO database to date, with a harmonized classification of 26 sectors for 190 countries, spanning from 1990 to 2015. Based on data availability and quality of data for each country, we selected 158 countries studied (see Supplementary Table 1 for the whole list of the countries and regions used in this study). Due to the instability of the data in the Eora database from 1990 to 1994 and the large variation in the number of sovereign states due to the dissolution of the Soviet Union, the time period we selected for the study is from 1995 to 2015. To avoid price variation and to make MRIO tables comparable across years, we convert the original MRIO tables with current year prices to constant 2015 prices using the USD GDP deflator. T CO₂ emission data for each country from 1995 to 2015 were derived from a satellite account in Eora called “Total CO₂ Emissions (Gg) from Emissions Database for Global Atmospheric Research (EDGAR)”. For accuracy, we have adjusted the total emissions from the original satellite account for each country to the latest EDGAR CO₂ emission data set (see Supplementary Figure 3 for the CO₂ emissions statistical description). Country-level data on population, GDP, and life expectancy at birth from 1990 to 2015 were obtained from the World Development Indicators (WDI) database.

The 158 countries studied were grouped into 49 high-income countries/regions, 42 upper-middle-income countries/regions, 41 lower-middle-income countries/regions, and 26 low-income countries/regions based on the World Bank’s income classification (see Supplementary Figure 2 for the distribution of different income countries and regions). We then calculated the CIWB for each country in each group for the average with and without trade scenario.

2.2. Measurement of CIWB. CIWB is used to measure the carbon stress placed on human well-being. We use the methodology introduced by Jorgenson to calculate CIWB. Specifically, since greenhouse gas emissions are a key stressor on the environment, CO₂ emissions are used as the numerator to characterize the impact of human activities on the environment. We use the per capita CO₂ emissions of the real-world and the per capita CO₂ emissions of the no-trade scenario as the numerator of the CIWB for the with-trade and no-trade scenarios, respectively. We chose life expectancy at birth as a
measure of human well-being. Life expectancy is a direct indicator of health and longevity and closely linked to equity. Life expectancy is widely regarded as a goal of social development and reflects social equality to some extent. And most countries have valid data on life expectancy at multiple points in time, making life expectancy a common indicator of well-being in cross-national social science research. In addition, life expectancy as a measure of well-being has some technical advantages and is available for most countries. Along with GDP per capita and education, it is one of the three components of the Human Development Index and, as such, has achieved broad international consensus. We do not use the HDI itself because the other two components—education and affluence—are often seen as resources that produce well-being.

2.3. Measurement of CIWB Inequality. Here, we used the Gini coefficient and Theil index to measure the inequality of CIWB. Gini coefficient is derived from Lorenz curves, which Lorenz initially developed in 1905 to study the inequality of wealth distribution among the population. The original Lorenz curve ranks all people in society in ascending income order and then calculates what percent of society’s total income is earned by the top X% cumulatively, with the 45° line of the Lorenz curve indicating perfect equality. The area below the curve is defined as the Gini coefficient and ranges from 0 to 1, with 0 indicating perfect equality and 1 indicating perfect inequality. Now, the Lorenz curve and Gini coefficient are widely used to measure inequality in climate change. The Gini coefficient for CIWB can be calculated using the following equation.

\[ G = 1 - \sum_{i=1}^{n} \left( \frac{x_{i+1} - x_i}{y_{i+1} + y_i} \right) \]

where \( x_i \) represents the accumulative proportion of life expectancy at birth when coming to country \( i \), and \( y_i \) is the accumulative proportion of \( CO_2 \) emissions per capita when coming to country \( i \).

The Theil index was proposed as a generalized entropy index to measure inequality. Following Theil’s research in the area of income inequality, a large literature of environmental inequality research emerged. The Theil index is now widely used to measure inequality in carbon emissions, pollution exposure, or health inequality. In this paper, we use this index to measure inequalities in the CIWB. The Theil indexes correspond to the following formulation:

\[ T = \sum_{i} p_i \log \left( \frac{CIWB_i}{CIWB} \right) \]

where \( p_i \) is the product of population and life expectancy of country \( i \) as a share of the world, CIWB represents the average CIWB of the world, and CIWB\(_i\) stands for the CIWB of country \( i \).

2.4. Hypothetical No-Trade Scenario for Estimating the Impacts of Trade on CIWB. According to the procedure used by Xu et al., we build a hypothetical no-trade scenario to estimate the impact of international trade on the CIWB. This no-trade scenario assumes no embodied \( CO_2 \) imports or exports between countries. It is calculated by adding back the \( CO_2 \) trade balance (\( CO_2 \) exports minus imports, i.e., net \( CO_2 \) exports) to the exporting country and then calculating the CIWB performance of each country in the no-trade scenario. CIWB under the trade and hypothetical no-trade scenarios (CIWB\(_n\)) can be calculated using the following equation.

\[ CIWB = \frac{CE}{P \times LE} \]

\[ CIWB_n = \frac{CE - NEVE}{P \times LE} \]

where CE is \( CO_2 \) emissions in the real-world, \( P \) is population, and LE is average life expectancy at birth. And eq 1 represents a country’s CIWB under the trade scenario. In eq 3, NEVE denotes the net exported \( CO_2 \) embodied in trade. Since there will be no \( CO_2 \) imports or exports in the no-trade scenario, a country’s \( CO_2 \) emissions will be the difference between CE and NEVE, equal to the consumption-based emission. Since adjusting the coefficient of variation would make the two CIWBs incomparable, we did not adjust the coefficient of variation in order not to change the comparability between countries within the indicator and between indicators for the same country, which would not change the meaning of the indicator either.

We acknowledge that in the no-trade scenario, a country’s carbon emissions may differ from our estimate due to differences in carbon emission intensity, i.e., a country with a lower carbon emission intensity than its carbon importing country may emit less carbon emissions than we estimate in the no-trade scenario. In addition, it is possible that a country’s consumption patterns would change under a no-trade scenario. This approach must be considered an approximation given the complex economic dynamics that can occur in the absence of trade. We believe that this approach provides a useful approximation because of the multiple complexities that may arise in the no-trade scenario and it is almost impossible to find the ideal method for accurate prediction.

2.5. MRIO Model for Quantifying \( CO_2 \) Embodied in International Trade. We conduct the MRIO to trace \( CO_2 \) emissions embodied in the international trade in this study (see Supplementary Figure 4 for the \( CO_2 \) emissions embodied in trade). MRIO, which comprehensively captures the economic linkages among industries in each country/region, is well utilized to explore international resource allocation and is often used to assess human-induced regional and global long-range energy and environmental problems.

The basic framework of MRIO can be written as:

\[ x = (I - A)^{-1} Y = BYI \]

where \( x \) is the total output of sector \( i \) in region \( s \). The technical coefficient sub-matrix is calculated by \( a_{ij} = \frac{x_{ij}}{s} \), where \( x_{ij} \) denotes the inter-sector monetary flows from sector \( i \) in region \( r \) to sector \( j \) in region \( s \) and \( s \) is the total output of sector \( j \) in region \( s \). \( I \) stands for the identity matrix, and \( B \) is the Leontief inverse matrix. The final demand matrix \( Y = (y_{is}) \) represents trade in final products, specifically, its calculation of the final demand of region \( s \) for sector \( i \) in the region \( r \). And \( I \) is a unit vector with all elements equal to 1.
We apply an environmental extension to MRIO using CO₂ emissions as an environmental indicator to track the amount of CO₂ emissions embodied in international trade. The environmental extended MRIO can be mathematically written as:

\[ CE = \hat{J} BYI \]  
\[ CE = NEVE = i\hat{J} BY \]  

where \( \hat{J} \) is a diagonal matrix of carbon intensity (i.e., CO₂ emissions per unit of economic output) for all economic sectors in all countries/regions. CE represents the CO₂ emissions under the trade scenario, and CE – NEVE represents the CO₂ emissions under the no-trade scenario.

2.6. Structural Decomposition Model for Changes in CIWB. Based on eqs 2 and 5, the CIWB under trade scenario can be represented as

\[ \text{CIWB} = \frac{CE}{P \times LE} = \frac{\hat{J} BYI}{P \times LE} = \frac{\hat{J} (B_D + B_F) (S_D + M_D + S_F + M_F)}{P \times LE} \]  

Referring to Xu and Dietzenbacher and Hubacek et al. in the MRIO model, the Leontief inverse matrix can be decomposed into the sum of domestic (\( B_D \)) and foreign parts (\( B_F \)). Similarly, the final demand matrix can be split into four components: domestic demand level (\( M_D \)), domestic demand patterns (\( S_D \)), foreign demand level (\( M_F \)), and foreign demand patterns (\( S_F \)). In this way, we can test the effect of factors of different geographical origins. When combined with the domestic carbon intensity, population, and life expectancy, the CIWB under the trade scenario is influenced by nine factors.

We employ the structural decomposition model (SDA) to examine the driving factors of temporal changes of CIWB under trade scenario (i.e., the actual scenario). It should be noted that there are multiple forms in SDA decomposition. The first is the choice between chaining and non-chaining decomposition, where chaining decomposition refers to year-by-year decomposition followed by summation to obtain the total effect in the long run. In contrast, non-chaining decomposition directly compares the base and end cases. Su and Ang indicated that chaining decomposition is superior to non-chaining decomposition for the factor decomposition of long-term changes. The second is the choice of decomposition formula. The two popular decomposition formulas are the average polarization decomposition and the average of all possible first-order decompositions. Hubacek et al. found that the decomposition results of both are basically consistent. In this paper, we use the average polarization decomposition method to reveal the driving factors of changes in CIWB under trade scenario from 1995 to 2015.

3. RESULTS

3.1. Global Trend and Spatial Pattern of CIWB. The global CIWB increased before 2006 and then showed a noticeable decrease around 2009 and maintained stability after that (Figure 1). The global CIWB increased by 16.87%, from 64.89 in 1995 to 75.84 in 2006. The sharpest drop in CIWB was in 2009, after which it remained stable. The countries with higher CIWB are mainly developed regions, mainly in North America, Australia, North Asia, and Europe. While developing countries in Africa, South America, and most of Asia have significantly lower CIWB than other regions (Supplementary Figure 1c). 59% of the countries (94) show an increase in CIWB during 1995−2009, after which it remained stable. The countries with higher CIWB are mainly developed regions, mainly in North America, Australia, North Asia, and Europe. While developing countries in Africa, South America, and most of Asia have significantly lower CIWB than other regions (Supplementary Figure 1a,b).

3.2. Impact of Trade on CIWB across Global to National Levels. Overall, the CIWB with trade is significantly lower than the hypothetical CIWB without trade (Figure 1), which indicates that international trade improves the carbon footprint followed by summation to obtain the total effect in the long run. In contrast, non-chaining decomposition directly compares the base and end cases. Su and Ang indicated that chaining decomposition is superior to non-chaining decomposition for the factor decomposition of long-term changes. The second is the choice of decomposition formula. The two popular decomposition formulas are the average polarization decomposition and the average of all possible first-order decompositions. Hubacek et al. found that the decomposition results of both are basically consistent. In this paper, we use the average polarization decomposition method to reveal the driving factors of changes in CIWB under trade scenario from 1995 to 2015.

Figure 1. Temporal change in CIWB at the global level. The shading indicates the 95% confidence band of the prediction using the fitted curve.
intensity of human welfare. And the CIWB difference between the two scenarios with and without trade is gradually increasing during the period 1995–2007, while it has been gradually decreasing since 2008. This indicates that the impact of trade on CIWB was growing until the great recession and the associated decline of trade in 2008 and the weak recovery in subsequent years, resulting in a shrinking impact of trade on CIWB.

Figure 2 shows the Gini coefficient and Theil index for CIWB from 1995 to 2015. It can be seen from Figure 2 that the CIWB inequality index shows two similar patterns under trade and no-trade scenarios: the level of inequality increases slowly in the first years and shows a clear downward trend thereafter. The Gini coefficient and Theil index with trade were consistently lower than the Gini and Theil without the trade scenario, which means that trade reduces the CIWB gap between countries. This impact on reducing CIWB inequality strengthened and then gradually weakened over the study period.

In addition, there is a big difference between the CIWB changes in different countries under trade and no-trade scenarios (Figure 3 and Supplementary Figure S). Most high-income countries (including European countries, the United States, Japan, and Singapore) were the main beneficiaries of international trade in terms of decreasing their respective CIWB. However, international trade also increased the CIWB of 59% of countries, mainly upper-middle-income and lower-middle-income countries (including most countries in Asia and most countries in Eastern Europe) (Figure 3c). This finding is similar to that of previous studies on the impact of international trade on carbon emissions. The finding also supports the theory of ecologically unequal exchange, that is, international trade contributes to an unequal distribution of environmental hazards and human development. In terms of improving CIWB, developed countries are the beneficiaries of international trade because they are well positioned in global trade networks to take unfair advantage of global natural resources and ecosystem services and to externalize negative environmental costs. In developing countries, especially emerging economies, CIWB is increasing, which means that they tend to pay higher environmental costs through international trade and are forced to accept negative environmental consequences transferred from advantaged countries.

3.3. Impact of Trade on CIWB of Countries. The CIWB increases with income. In the presence of trade, the mean CIWB value for high-income countries is about 1.5 times that of upper-middle-income countries, seven times that of lower-income countries and low-income countries. This is consistent with previous studies that have shown that high affluence is associated with high CIWB. This is because high-income countries tend to consume more energy and emit more CO2, but their “overconsumption” of energy does not generate additional welfare above a specific threshold. In addition, the high CIWB in high-income countries may also be related to income inequality. A study of the effect of income inequality on CIWB in OECD and non-OECD countries shows that income inequality increases CIWB and that the effect is greater in OECD countries than in non-OECD countries. A study of the 50 U.S. states shows that CIWB is positively associated with income concentration and poverty headcount.

The trend of CIWB change is significantly different for countries at different income levels. In the period concerned, the CIWB value of high-income countries increased first and then decreased. The CIWB of upper-middle-income countries continued to rise, while the CIWB of low-income countries shows a downward trend. The CIWB of lower-middle-income countries shows two different patterns under trade and no-trade scenarios: in the no-trade scenario, the CIWB of upper-middle-income countries changes with insignificant regularity, while in the with-trade scenario, their CIWB values consistently increased (Figure 4a). Note that under the trade scenario, the CIWB of upper-middle-income countries shows a very flat development trend with only a slight increase after 2008, while the growth rate of CIWB in lower-middle-income countries has increased significantly. This result reflects the accelerated fragmentation of global supply chains since the 2008 global financial crisis. The early stages of production in many industries have shifted from upper-middle-income economies to developing economies with even lower wages.

We found that trade does reduce CIWB in high-income countries, which is consistent with Givens’ finding that global integration reduces CIWB in more developed countries. In addition, we found that the impact of international trade on CIWB increases with income. International trade had the largest impact on CIWB for high-income countries and the least impact on CIWB for low-income countries (Figure 4c). Most countries experienced a decline in CIWB in the situation with international trade versus in the hypothetical situation without trade and producing all imports domestically. However, not all countries experienced decreases in their CIWB from international trade. There are still about 12% of high-income countries, 30% of upper-middle-income countries, 24% of lower-middle-income countries, and 12% of low-income countries whose CIWB was higher due to the impact of international trade, especially high carbon intensive countries such as Australia, China, India, and Russia (Figure 4b). Ecologically unequal exchange theory describes the mechanism by which this occurs, with uneven flows of energy and natural resources across borders, exacerbating the gap between production and material consumption, and further affecting human well-being. Countries that are better positioned in the global trading system are therefore able to use trade as a force to reduce their CIWB through ecologically unequal exchange relationships (i.e., uneven distribution of environmental benefits and burdens).

3.4. Drivers of CIWB. We investigate the potential drivers of CIWB changes for countries with different income types through SDA. We decompose each country’s CIWB under the trade scenario into nine factors (sectoral emission intensity, intermediate structure at home, intermediate trade, consumption patterns at home, consumption patterns abroad, consumption levels at home, consumption levels abroad, population, and life expectancy) to quantify the effects of
structural change of trade, improvement of emission intensity, population change, and life expectancy growth on a country's CIWB. Figure 5 shows the average contribution of the drivers in the four income categories.

Sectorial emission intensity improves CIWB for all four income groups, suggesting that decreases in emission intensity (increases in production and energy use efficiency) prove to be the most important driver of lower CIWB. Notably, the
percentage contribution of sectoral emission intensity to the improvement in CIWB increases with income, contributing 687% (47.31) for the reduction in CIWB in high-income countries, 430% (38.68) in upper-middle-income countries, 338% (8.49) in lower-middle-income countries, and 129% (10.51) in low-income countries. Population and life expectancy are the second and third largest drivers of CIWB reduction in all four income groups, respectively.

In terms of increasing CIWB drivers, increasing the consumption level for domestic products is the most significant factor in increasing CIWB, especially in high-income countries (adding 887% to the increase of CIWB).

Different contributions of the same drivers have been found for different income country groups. We found that changes in domestic consumption patterns resulted in a 9.0 and 3.7% decrease in CIWB in high-income and upper-middle-income economies and a 9.6 and 5.3% increase in CIWB in lower-middle-income and low-income groups, respectively. In addition, only in upper-middle-income countries, the contribution of consumption structure abroad to the change in CIWB is greater than that of the domestic consumption structure.

Country-level results are presented in Figure 6, with each map representing the contribution of one driver as a percentage of the total CIWB change in a country. Changes in domestic

Figure 4. Impact of international trade on CIWB differs between income groups. (a) Temporal change in CIWB for different income groups under the trade and no-trade scenarios (the dot represents the value of CIWB, and the shading indicates the 95% confidence band of the prediction using the fitted curve). (b) Impact of trade on CIWB between different income groups. The solid lines represent the positive impact of trade on CIWB, the dashed lines represent the negative impact of trade on CIWB, and the percentages in parentheses represent the proportion of countries involved in the positive or negative impact. (c) Differences in CIWB between different income groups under the trade and no-trade scenarios over 21 years. The error bars indicate the standard errors in CIWB (n = 21).
consumption levels and consumption levels abroad led to an increase of CIWB across almost all countries in the world. Changes in life expectancy resulted in a decrease of CIWB for all countries studied, with the highest relative contributions found in Africa.

It can be seen that results are more heterogeneous in terms of consumption patterns abroad and domestic consumption patterns. Changes in domestic consumption patterns tend to increase CIWB in about 57% of countries, including most Asian countries (including China and India), some European countries, Canada, and some African countries. Conversely, changes in domestic consumption patterns decreased CIWB in the United States, Russia, Australia, most Eastern-European countries, and several Asian countries (including Japan and South Korea). As for consumption patterns abroad, changes in consumption patterns abroad tend to increase CIWB in about 60% of studied countries, including Southeast Asian countries, some European countries, Canada, Russia, and most West African countries.

The change in emission intensity reduces the CIWB for most countries (72%), except for Myanmar, Vietnam, and some African and South American countries, which implies that those countries’ emission intensity has increased during the study period. This may be because the less technologically efficient, carbon-intensive fuel mix of these countries has kept their energy intensity at a high level or even further increased it. The change in intermediate trade caused an increase in CIWB in 70% of countries but reduced CIWB in some high-income developed countries, including the United States, Japan, and some European countries. On the other hand, change in intermediate at home has increased CIWB for 57% countries and reduced CIWB for 43% countries.

4. DISCUSSION

There has been a longstanding theoretical and policy interest in the potential impacts of international trade on environmental and human well-being. This study quantitatively evaluates the impacts of international trade on CIWB (an important indicator that measures carbon intensity associated with human well-being). Our results show that international trade can reduce the overall global CIWB and the CIWB inequality between countries.

The rapid growth of international trade reflects the fragmentation and complexity of global supply chains. The early production stages of many industries have shifted from developed countries such as Europe and the United States to emerging economies such as China and India. Since the 2008 global economic crisis, the focus of the trade has further shifted to other lower-wage economies, such as Vietnam and between such lower-income countries, referred to as South–South trade. These changes in international trade have an important impact on the development and pattern of the global economy and affect the scale and regional distribution of global CO₂ emissions. International trade brings about a net carbon emission transfer; if a country or region has a net carbon emission inflow, the carbon emission intensity on human well-being in that country or region will increase, pushing up the CIWB of that country or region. Conversely, if a country or region has a net carbon emission export, it will lower the CIWB of that country or region.

The Gini coefficients and Theil index show that international trade reduces the CIWB inequality between countries. But this does not mean that international trade contributes to global environmental equality. The value of CIWB increases with income and is much greater in high-income countries than in other countries. The decrease in CIWB inequality results from a reduction in CIWB in high-income countries and an increase in CIWB in developing countries. This is mainly caused by the transfer of carbon emissions from high-income countries to lower-income countries, and the decrease of CIWB in high-income countries comes at the cost of the increase of CIWB in lower-income countries. This can be explained by the ecologically unequal exchange theory. Specifically, asymmetric trade relationships promote vertical flows of material values from low-income to high-income countries, while negative
environmental benefits such as carbon emissions are transferred to low-income countries, and this unequal exchange also affects human well-being. Studies have shown that vertical flows of material values can inhibit resource consumption by populations in low-income countries. In turn, this underconsumption can further lead to negative health outcomes that reduce well-being, such as increased maternal mortality and chronic lack of development in low-income countries, with detrimental effects on well-being. Suppose we remove the effect caused by trade and return to the hypothetical no-trade scenario, in that case, our environmental inequality situation is actually worse. This does not bode well for humans or the environment. If this trend of environmental inequality continues, then the CIWB, which has declined throughout the study period, may begin to rise in the future.

Our results show that the effect of international trade on CIWB differs across countries and the effect changes over time. We found that developed countries, including most European countries, the United States, Japan, and Singapore, were the main beneficiaries of international trade in terms of decreasing their respective CIWB, while international trade also increased the CIWB of 20% of the countries, mainly including most countries in Asia and most counties in Eastern Europe. This is consistent with the finding that global integration has reduced CIWB in the more developed countries. Our results provide support for the ecologically unequal exchange theory.
Ecologically unequal exchange theory posits that ecologically unequal exchange refers to the increasingly disproportionate use of ecosystems by core countries and the externalization of negative environmental costs, which leads to increased environmental burdens and suppression of consumption and human well-being in peripheral countries.\textsuperscript{27,28} For example, the net emissions transferred from developed countries to developing countries through international trade increased by 1.2 Gt CO\textsubscript{2} between 1990 and 2018.\textsuperscript{19} This has led to a gradual stabilization or even reduction of emissions in developed countries,\textsuperscript{22} while emissions in developing countries, especially emerging economies (Brazil, Russia, India, Indonesia, and China), have increased significantly.\textsuperscript{29,30} It has been argued that this is the result of energy-intensive and highly polluting activities moving from developed countries to developing countries.\textsuperscript{31}

Our results also show that under the trade scenario, the CIWB for upper-middle-income countries showed a very flat development trend with only a slight increase after 2008, while the growth rate of CIWB in lower-middle-income countries has increased significantly. This reflects a new stage of globalization after the global economic crisis. As a result of rising labor and resource costs, raw material extraction and production of energy-intensive intermediate goods have been shifting from developing countries in upper-middle-income countries to lower-income developing countries with lenient environmental policies and relatively cheap labor and raw materials. For example, emissions embodied in China’s exports have declined, but the CO\textsubscript{2} emissions reflected by exports from other Asian countries and the Pacific are increasing.\textsuperscript{53} For example, from 2004 to 2011, emissions embodied in textile exports from Bangladesh and Vietnam increased by 175 and 236%, respectively.\textsuperscript{52} In other words, labor-intensive and resource-intensive textile and clothing production has begun to move from China to other Asian countries (such as Bangladesh and Vietnam).\textsuperscript{52}

The results also show that decreases in emission intensity are the most important driver of lower CIWB and the percentage contribution of emission intensity to the improvement in CIWB increases with income. This is mainly because as technology continues to advance in higher-income countries, there is a significant reduction in their emission intensity. For example, the increasing penetration of renewable energy in Europe and the structural shift from coal to gas power in the United States have played an important role in reducing the country’s emission intensity.\textsuperscript{56} In terms of increasing CIWB drivers, increasing consumption level for domestic products is the biggest factor increasing CIWB. We also found that changes in consumption patterns at home resulted in a decrease in CIWB in high-income and upper-middle-income economies and an increase in CIWB in lower-middle-income and low-income groups. This is due to the different consumption structures of different income economies. In general, higher-income countries have less carbon-intensive lifestyles. Their spending on services accounts for a higher proportion of total consumption. In comparison, the consumption structure of lower-income countries remains dominated by meeting basic needs and a higher proportion of spending on goods.\textsuperscript{65} In addition, only in upper-middle-income countries, the contribution of consumption structure abroad to the change in CIWB is greater than that of the domestic consumption structure. This is because as global trade and supply chains diverge, upper-middle-income countries are shouldering an increasing share of exports. For example, from 1996 to 2011, Asian exports in monetary terms increased by 136% and their share in global exports increased from 27 to 48%.\textsuperscript{56} These countries are playing an increasingly important role in global trade, and thus the impact of foreign consumption patterns on their CIWB changes even exceeds the impact of domestic consumption patterns. These findings underscore the importance of improving the CIWB through international cooperation.

This study assumes a scenario where there is no global trade. Future studies could set-up scenarios where partial trade exists, such as a country trading only with developed countries or emerging economies, and it would be an interesting topic to explore the impact of different trading partners on CIWB. In addition, the economic sectors and types of goods traded may also have different effects on CIWB, which is also a topic that future researchers could explore. The time span of this paper is from 1995 to 2015, and the impact of international trade may be more apparent if a longer time span is analyzed. Researchers could also explore country-specific situations in detail.\textsuperscript{56}

\section*{ASSOCIATED CONTENT}

\subsection*{Supporting Information}

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c07582.

Additional description of countries and regions used for study, all CO\textsubscript{2} emission and embodied CO\textsubscript{2} emission data for the analysis of results, and additional CIWB results figures (PDF)

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Notes
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