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CO_2 Emissions Embodied in International Migration from 1995 to 2015

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ABSTRACT

Whilst present international CO_2 mitigation agreements account for the impact of population composition and structure on emissions, the impact of international migration is overlooked. This study quantifies the CO_2 footprint of international immigrants and reveals their non-negligible impacts on global CO_2 emissions. Results show that the CO_2 footprint of international immigrants has increased from 1.8 Gigatonnes (Gt) in 1995 to 2.9 Gt in 2015. In 2015, the U.S. had the largest total and per capita CO_2 emissions caused by international immigrants. Oceania and the Middle East are highlighted for their large portions of immigrant-caused CO_2 emissions in total CO_2 emissions (around 20%). Changes in the population and structure of global migration have kept increasing global CO_2 emissions during 1995–2015, while the reduction of CO_2 emission intensity helped offset global CO_2 emissions. The global CO_2 mitigation targets must consider the effects of global migration and demand-side measures need to concern major immigrant influx nations.

Keywords: international migration, immigrant, climate change, CO_2 emissions, trade, consumption.

Synopsis: This study links the population mobility with global CO_2 mitigation, which evaluates the contribution of international immigrants to global CO_2 emissions.

INTRODUCTION

International migration is a phenomenon accompanying the process of human civilization and globalization. In recent decades, the number of international immigrants has proliferated and the destinations of immigrants have become increasingly diversified. International migration has a variety of implications on the place of destination including politics, economy, culture and welfare security issues.[1-3]

Migration can be a critical demographic factor affecting the environment.[4] Previous studies have investigated the environmental impacts of regional migration (including interregional migration, rural-rural migration, and rural-urban migration) on land use,[5, 6] forest cover,[7, 8] air pollutant emissions,[9, 10] and carbon emissions.[11-13] Population migration has implications for carbon emissions mainly because migration flows affect population size and structure both at the origin and destination. Not only does migration-induced population growth translates into higher energy consumption, migration process can bring about lifestyle change which influences consumption pattern and consequently CO_2 emissions[14]. This line of argument has been put forward to campaign for restriction of immigration for example in the US because population growth induced by migration coupled with the American lifestyle adopted by immigrants will have consequential environmental impact[15, 16].

The evidence on the impact of migration on the environment however is inconclusive. On the one hand, rural to urban migration within a country is typically found to be associated with an increase in CO_2 emissions given a rise in the demand for residential energy in the urban area and lifestyle change thanks to increased income level[13, 17]. On the other hand, studies on the environmental impact of immigration measured by air quality and air pollutant emissions focusing on the US do not find evidence that immigration contribute to heightened air pollution levels[18, 19]. Ma and Hofmann even find that the presence of immigrant population is associated with better overall air quality[20] possibly because migrants express greater environmental concerns and have lower energy consumption than the US native born. The inconclusive nature of the evidence calls for further research using different indicators of environmental impact[20] as well as cross-national comparisons between sending countries with high and low emissions[18].

Indeed, more accurate and objective studies about the migration–environment relationship are needed since they have relevant policy implications. However, little attention is paid to the impacts of international migration on environmental emissions at the global scale. In the context of enormous challenges of global climate change, the international community formulates active CO_2 mitigation agreements to keep the temperature arisen within 2 degrees at the end of this century. However, these agreements do not account for changing population structure and distribution which can shift the global patterns of CO_2 emissions. A study of population mobility finds a significant contribution of tourism on global CO_2 emission growth, especially in the sectors such as transportation, food, and accommodations.[21] If a short-term population movement like tourism has a substantial impact on CO_2 emissions, this raises an important question how migration as a long-term population movement will impact the global emissions.[22-24]. Longer term population mobility involves comprehensive consumption sectors (e.g., housing, infrastructure, energy use, health care, and education) which would lead to long-term environmental impacts. Given the current trends that international migration will continue to play a role in global population dynamics coupled with the intensity of globalization and labor transfer, global CO_2 emissions caused by international migration are no doubt worthy of critical attention. However, the impacts of international migration on global CO_2 emissions are not well evaluated.

To that end, this study fulfills the above knowledge gap by analzing the impacts of international migration on global CO_2 emissions. We construct a set of international migration matrixes to uncover the sources, destinations, and quantities of the migrant population. Then we evaluate the CO_2 footprint of the international immigrants and the impacts of international migration on global CO_2 emissions. Findings of this study can contribute to the formulation of CO_2 mitigation strategies in different nations with the consideration of future immigrants.

MATERIALS AND METHODS

Constructing International Migration Matrixes. This study constructs the migration matrixes in 1995, 2000, 2005, 2010, and 2015 to describe the international migrant stock by destination and origin. Each row of the matrixes represents emigrants from a country of origin, while each column denotes the immigrants to a country of destination. Thus, the sum of each row equals the original population of a nation, while the sum of each column equals the current population of a nation. The diagonal elements of the matrixes represent the population which do not emigrate. The migration matrixes are constructed with the international migration data and national population data. The international migration data are from the dataset of the United Nations Department of Economic and Social Affairs (UN DESA)[25]. This dataset presents the estimates of international immigrants by ages, sexes, and origins, based on official statistics on the foreign-born or foreign population. The national population data are from the World Bank[26].

CO_2 Footprint of Immigrants. We use a global environmentally extended multi-regional input-output (EE-MRIO) model to evaluate the CO_2 footprint of nations and their immigrants. The EE-MRIO model has been widely used to investigate environmental issues related to socioeconomic activities, such as CO_2 emissions,[27-29] mercury emissions,[30, 31] resource extraction and scarcity,[32-34] and health risks[35, 36]. We construct a global EE-MRIO model by treating global CO_2 emissions as the satellite account of the global MRIO table. We use the global MRIO tables from the Eora database[37, 38], mainly due to two reasons: (1) Eora covers 190 nations/regions, which is more than other global MRIO databases. Thus, it is suitable for investigating the issue of international migration. (2) Eora has a complete time series for 1990-2015, which covers all the time points in this study.[37, 38] This study groups all the nations into 13 sub-regions considering geographical factors and their significance for migration, including the U.S., Canada, Mexico, China, India, South America, European Union (EU), Russia and CIS (Commonwealth of Independent States) regions, Southeast Asia, Middle East, Africa, Oceania, and the Rest of the World (RoW). The list of nations and corresponding sub-regions are shown in SI Data S4. Data for the satellite account of global CO_2 emissions are also from the Eora database. We use the satellite account of CO_2 emissions generated from the PRIMAP-HIST dataset, as recommended by the Eora database. The selected satellite account is the National Total (CAT0) CO_2 emissions. It covers all the sources of CO_2 emissions, including the Total Energy, Industrial Processes, Land Use, Land Use Change, and Forestry (LULUCF), etc.

The CO_2 footprints of nations are calculated by the Leontief MRIO model, as shown in equation (1).

$$cf_n = q(\mathbf{I} - \mathrm{A})^{-1} y_n \qquad (1)$$

The notation cf_n represents the CO_2 footprint of nation *n*. The row vector q indicates the CO_2 emission intensity, where each element q_i represents the CO_2 emissions for unitary output of nation sector *i*. The matrix **A** is the direct input coefficient matrix, where the element a_{ij} equals to the direct input from nation sector *i* to nation sector *j* divided by the total output of nation sector *j*. The matrix **I** is an identify matrix. The matrix $(\mathbf{I}-\mathbf{A})^{-1}$ is the *Leontief Inverse* matrix, where the element l_{ij} indicates both direct and indirect inputs from nation sector *i* to satisfy unitary final demand of sector *j*. The vector y_n represents the final demand of nation *n*.

The CO_2 footprint of immigrants in a nation is calculated with the CO_2 footprint of this nation and the proportion of immigrants in the current population of this nation, as shown in equation (2).

$$cf_{m,n}^{immi} = cf_n \times \frac{p_{m,n}^{immi}}{p_n^{total}} \tag{2}$$

The notation $cf_{m,n}^{immi}$ indicates the CO_2 footprint in nation *n* caused by the immigrants from nation *m* ($m \neq n$). The notation $p_{m,n}^{immi}$ represents the population of immigrants from nation *m* to nation *n*, and the notation p_n^{total} denotes the total current population of nation *n*. Consequently, the CO_2 footprint of immigrants to nation *n* (cf_n^{immi}) and that of the world (cf^{immi}) are calculated by equations (3) and (4), respectively.

$$cf_n^{immi} = \sum_m cf_{m,n}^{immi} \tag{3}$$

$$cf^{immi} = \sum_n cf_n^{immi} \tag{4}$$

Structural Decomposition Analysis. We combine the structural decomposition analysis (SDA) with the EE-MRIO model to investigate the relative contribution of the international migration to global CO_2 emissions during 1995–2015. In this study, we decompose global CO_2 emission changes into the relative contributions of the changes in CO_2 emission intensity, production structure, final demand structure, per capita final demand level of the current population, migration structure, and original population.

Global CO_2 emissions can be expressed with the global EE-MRIO model, as shown in equation (5)

$$t = q \times (\mathbf{I} - \mathrm{A})^{-1} \times y \tag{5}$$

The notation t denotes global CO_2 emissions, and q is a vector of CO_2 emission intensity of nation sectors. The matrix $(\mathbf{I} - \mathrm{A})^{-1}$ is the *Leontief Inverse* matrix, and y is a vector of the final demand.

The final demand vector y can be further decomposed into the final demand structure, per capita final demand level, and population, as shown in equation (6).

$$y = y_s \times \widehat{y_v} \times p \tag{6}$$

The notation y_s represents the final demand structure, which is the proportion of the nation sectors in the total final demand. The notation y_v denotes the per capita final demand level, and p represents the current population of nations. The hat notation ^ denotes the diagonalization of a vector.

To investigate the relative contribution of the international migration, we further decompose the population into vector e, migration structure matrix $\mathbf{B}$, and original population m, as shown in equation (7).

$$p = (e \times \hat{m} \times \mathbf{B})^T \tag{7}$$

The elements of the row vector e are all 1. The notation m represents a vector of the original population of nations. The matrix **B** indicates the migration structure, where the element b_{ij} equals to the number of immigrants from nation i to nation j divided by the original population of nation i. The hat notation ^ and the notation T denote the diagonalization and transposition of a vector, respectively. Consequently, global CO_2 emissions can be expressed by equation (8).

$$t = q \times (\mathbf{I} - \mathrm{A})^{-1} \times y_s \times \widehat{y_v} \times \mathbf{B}^T \times \hat{m}^T \times e^T \tag{8}$$

We use **L** to represent the *Leontief Inverse* matrix $(\mathbf{I} - \mathrm{A})^{-1}$. The changes in global CO_2 emissions can be expressed by equation (9). Items in the right-hand side of equation (9) represent the relative contributions of the changes in CO_2 emission intensity Δq, production structure $\Delta \boldsymbol{L}$, final demand structure Δy_s, per capita final demand level of the current population $\Delta \widehat{y_v}$, migration structure $\Delta \boldsymbol{B}^T$, and the original population $\Delta \hat{m}^T$ to global CO_2 emission changes Δt.

$$\begin{aligned} \Delta t = {} & \Delta q \times \boldsymbol{L} \times y_s \times \widehat{y_v} \times \mathbf{B}^T \times \hat{m}^T \times e^T \\ & + q \times \Delta \boldsymbol{L} \times y_s \times \widehat{y_v} \times \mathbf{B}^T \times \hat{m}^T \times e^T \\ & + q \times \boldsymbol{L} \times \Delta y_s \times \widehat{y_v} \times \mathbf{B}^T \times \hat{m}^T \times e^T \\ & + q \times \boldsymbol{L} \times y_s \times \Delta \widehat{y_v} \times \mathbf{B}^T \times \hat{m}^T \times e^T \\ & + q \times \boldsymbol{L} \times y_s \times \widehat{y_v} \times \Delta \boldsymbol{B}^T \times \hat{m}^T \times e^T \\ & + q \times \boldsymbol{L} \times y_s \times \widehat{y_v} \times \boldsymbol{B}^T \times \Delta \hat{m}^T \times e^T \end{aligned} \tag{9}$$

We have 6 decomposition forms, and we average all the 6 decompositions to calculate the relative contributions of the decomposed factors. Moreover, to make the indicators in different time points comparable, we convert the current-price global MRIO tables (in U.S. dollars) to ones in 1995 constant prices (in U.S. dollars) using methods of previous studies[39, 40]. Such a conversion can eliminate the effects of price changes caused by inflation or deflation. Producer Price Index (PPI) is an economic index reflecting the price changes during a time period. It is typically used to convert comparable prices. The PPIs used for the conversion in this study are from the United States Bureau of Labor Statistics[41].

RESULTS

International Migration During 1995–2015. The number of international immigrants are 161 million (2.8% of the total global population) in 1995. This percentage has shown an upward trend from 1995 to 2015 with slight fluctuations. International immigrants reach 248 million (3.4% of the total global population) in 2015. The quantity of international immigrants has increased by 54% during 1995–2015 (more results in SI Data S1).

Figure 1a shows that, in 2015, the most significant international migration corridors are from Mexico to the U.S., from Africa to the European Union (EU), and from India to the Middle East. The migration corridors highlighted in Figure 1a can be generally classified into three types: from developing regions to developed nations (e.g., from Mexico to the U.S., from South America to EU countries,), labour exports (e.g., from India and Southeast Asia to the Middle East, and from Southeast Asia to the U.S.), and refugee flows (e.g., from Africa and Middle East to the EU). The U.S. is a primary destination for migrants from Mexico, India, and China (including Chinese Mainland, Hongkong, Macao, and Taiwan). The number of immigrants in the U.S. exceed 320 million in 2015 (SI Figure S1).

Figure 1b shows the changes in the migration population from 1995 to 2015. Migration to the U.S. expanded the most. During 1995–2015, immigrants from Mexico, Southeast Asia, South America, India, and China to the U.S. increased dramatically. Meanwhile, immigrants from India to the Middle East presented the most substantial increments. In contrast, the migrant population in Russia, Ukraine, and India decreased remarkably. In Asia, the number of migrants from India in United Arab Emirates (labour exports) increased substantially, while the number of migrants from Iraq in Iran decreased (SI Figure S1).

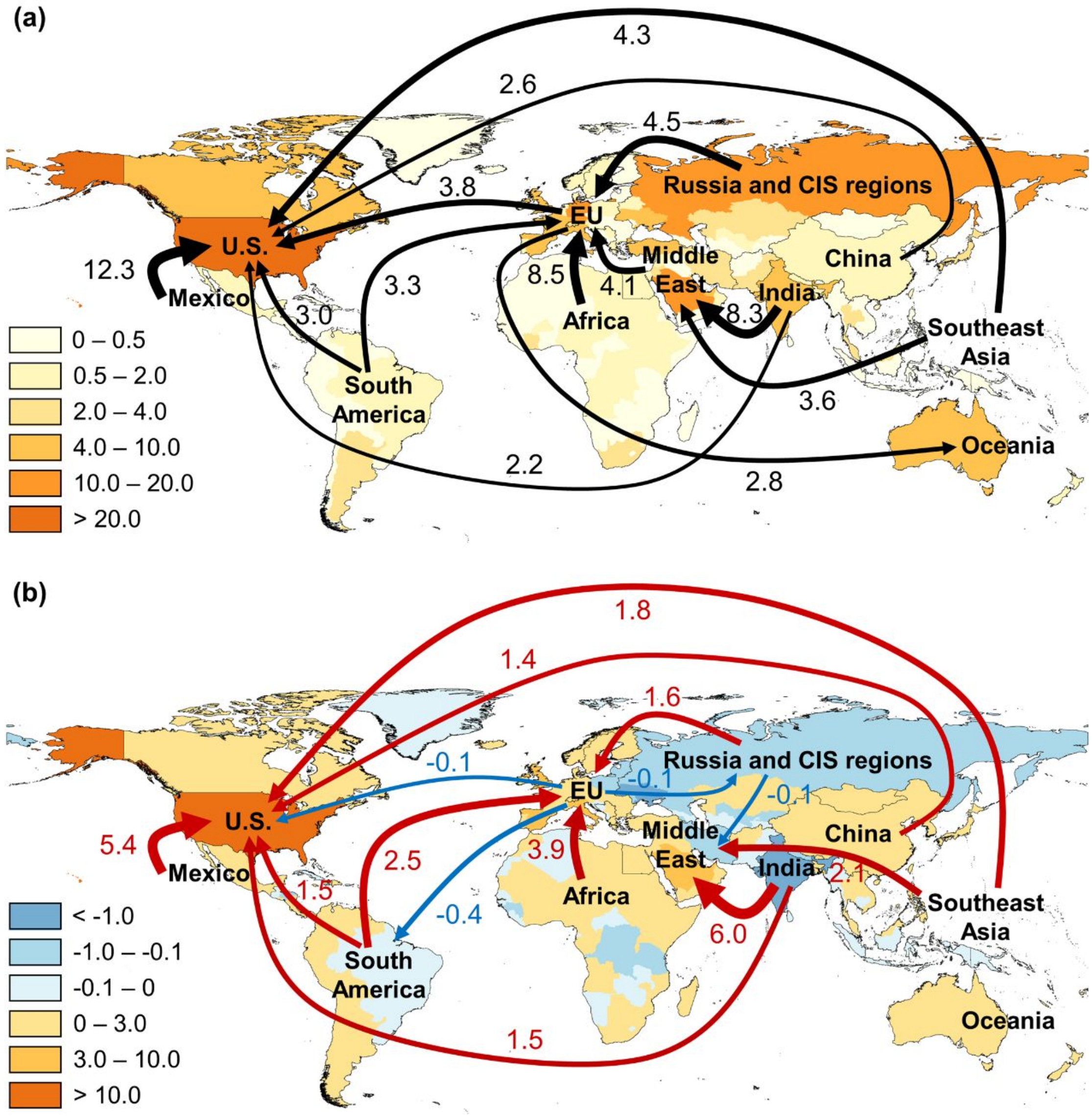


Figure 1. Global migration population in 2015 and migration changes during 1995–2015. Panel (a) shows global migration in 2015 (million), and panel (b) shows changes in the number of global migration during 1995–2015 (million). The colour of nations in the world maps shows the number of migrant population (a) and changes in migrant population (b). The arrows start from the origins of immigrants and end at their destinations (at the sub-regional scale). The red arrows indicate an increased population of immigrants, while the blue ones represent a decrease. The numbers and

width of the arrows indicate the migrant population (a) and the migrant population changes (b).

CO_2 Footprint of International Immigrants. The CO_2 footprint of international immigrants is 1.8 Gigatonnes (Gt), occupying 6% of the global total CO_2 emissions in 1995. It has shown an upward trend during 1995–2015 with slight fluctuations, and reaches 2.9 Gt (8%) in 2015. The CO_2 footprint of international immigrants has increased by 65% during 1995–2015 (more results in SI Data S2).

Figure 2a shows global CO_2 emissions caused by international migration (hereinafter called immiCO_2, which is part of the CO_2 footprint of the migrants receiving nation) in 2015. The developing regions are generally net exporter of immiCO_2, while the developed regions mostly act as net importers of immiCO2.

The U.S. has the highest immiCO_2 in 2015 (947 million ton, Mt). The immigrants from Mexico contribute the most (25% of the immiCO_2 in the U.S.), followed by Southeast Asia (9%), the EU (8%), and South America (6%). The immiCO_2 flows are in consistent with typical migration corridors such as corridors from developing regions to developed regions and labour export corridors. For instance, Mexico, a developing economy, has been one of the largest origins of immigrant population in the U.S. The immigrants from Mexico move to the U.S. for job opportunities and better living conditions (e.g., better healthcare and education). The improvement of personal income and living conditions promote the consumption of immigrants. This can drive larger CO_2 emissions from the upstream regions/sectors in the supply chains, and hence increases CO_2 footprint of the U.S. The U.S. is the primary migration destination with a diverse migrant composition, which leads to enormous effects of the immigrants on global CO_2 emissions.

The immiCO_2 of the Middle East (513 Mt) rank second, mainly induced by immigrants from India (leading to 38% of the immiCO_2 in the Middle East) and Southeast Asia (13%). In particular, immigrants from India to the United Arab Emirates and Qatar are the most critical causes of immiCO_2 in the Middle East (SI Figure S2). The United Arab Emirates and Qatar have small populations, with immigrant populations accounting for the majority (SI Data S1). Their prosperous economic development requires large amounts of labour forces. These nations attract overseas labour forces, especially immigrants from India. This reveals that labour export to the Middle East results in large amounts of global CO_2 emissions. For the EU, the immiCO_2 reaches 274 Mt, with Africa, South America, and Russia and CIS (Commonwealth of Independent States) contributing significantly. The refugee flows from Africa to EU lead to large amounts of immiCO_2. The political unrest and severe natural disaster in Africa bring about lots of refugees, and EU becomes the main destination of African refugees. CO_2 emissions driven by immigrant refugees cannot be neglected.

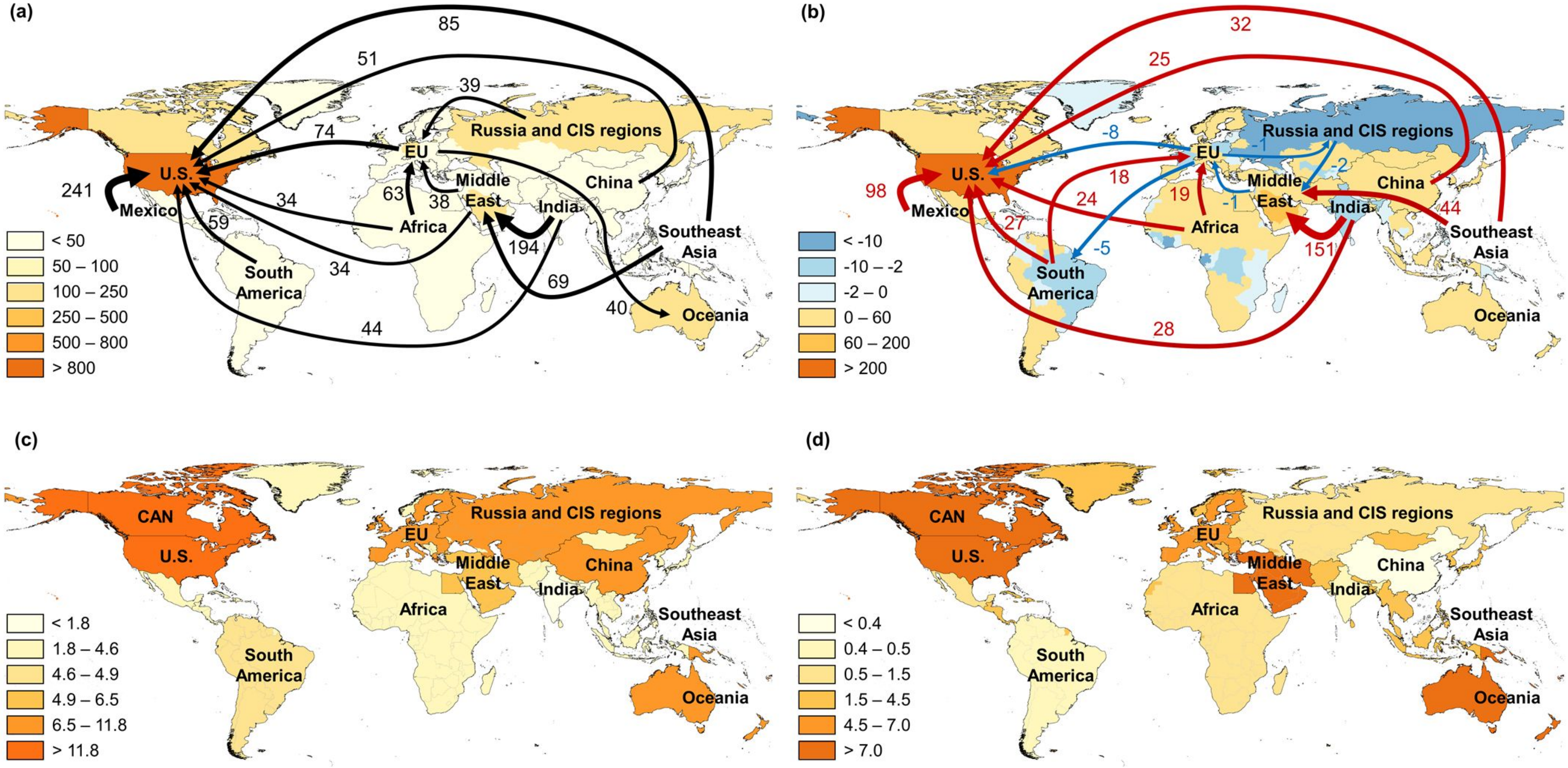
From 1995 to 2015, the migration flows from India to the Middle East lead to the most massive global CO_2 emissions (Figure 2b). Notably, the immiCO_2 flows from

India to Qatar and the United Arab Emirates significantly increased immiCO_2 of the Middle East (SI Figure S2). The immiCO_2 of the U.S. has increased and then declined slightly during 1995–2015, while its portion in total CO_2 emissions of the U.S. steadily has increased from 11% in 1995 to 15% in 2015 (more results in SI Data S3). Figure 2b also shows that all the immiCO_2 flows from Mexico, Southeast Asia, India, China, South America, and Africa to the U.S. have increased. This finding is in accordance with the changes in migration trends. On the other hand, immiCO_2 flows from the EU to the U.S., South America, and Russia and CIS have shown a small decrease.

In 2015, the per capita immiCO_2 of the U.S. reached 20 ton/capita, followed by Oceania (12 ton/capita) and the EU (8 ton/capita). Although the U.S. and the EU are both major destinations of immigrants, they are evidently different in terms of per capita immiCO_2. The value of the U.S. is approximately 2.5 times as that of the EU (Figure 2c). In Africa and India, the per capita immiCO_2 is the lowest. At the national level, nations with the highest per capita immiCO_2 include Qatar (48 ton/capita) and San Marino (41 ton/capita), which have small populations. Moreover, the immiCO_2 in Luxembourg, United Arab Emirates, and Singapore all exceeded 30 ton/capita (SI Figure S2).

Oceania and the Middle East are highlighted for their large portions of immiCO_2 in their total CO_2 emissions, with the percentages of 22% and 20%, respectively. The immiCO_2 in the U.S. and EU, which are major migration destinations, account for

15% and 7% of their total CO_2 emissions, respectively (Figure 2d). At the national level, the percentages in the United Arab Emirates, Kuwait, and Qatar all exceeded 65%, which were the highest in 2015 (SI Figure S2). CO_2 emissions of the emphasized areas are more greatly influenced by international migration. Prospect CO_2 reduction strategies in these areas are suggested to take the quantity and structure of population movement into account.


(a)
85
51
39
74
Russia and CIS regions
EU
U.S.
241
Mexico
Middle East
China
63
38
34
59
Africa
India
194
Southeast Asia
34
South America
69
40
Oceania
44
< 50
50 – 100
100 – 250
250 – 500
500 – 800
> 800
(b)
32
25
-8
-1
-2
Russia and CIS regions
EU
U.S.
98
Mexico
18
19
24
27
-1
Middle East
China
44
Africa
India
151
Southeast Asia
-5
South America
Oceania
28
< -10
-10 – -2
-2 – 0
0 – 60
60 – 200
> 200
(c)
CAN
U.S.
EU
Russia and CIS regions
Middle East
China
India
Africa
Southeast Asia
South America
Oceania
< 1.8
1.8 – 4.6
4.6 – 4.9
4.9 – 6.5
6.5 – 11.8
> 11.8
(d)
CAN
U.S.
EU
Russia and CIS regions
Middle East
China
India
Africa
Southeast Asia
South America
Oceania
< 0.4
0.4 – 0.5
0.5 – 1.5
1.5 – 4.5
4.5 – 7.0
> 7.0

313

Figure 2. Global immiCO_2 and immiCO_2 flows. Panel (a) illustrates the global immiCO_2 and the critical sub-regional flows in 2015 (Mt). Panel (b) shows the changes in immiCO_2 and the critical sub-regional flows during 1995–2015 (Mt). The colour of nations in the world maps shows their immiCO_2 (a) and immiCO_2 changes (b). The arrows start from the origins of immigrants and end at their destinations (at the sub-regional scale). The numbers and width of the arrows indicate the immiCO_2 (a) and the changes in immiCO_2 (b). The red arrows indicate an increased immiCO_2 caused by the migration flows, while the blue ones represent a decrease. Panel (c) illustrates the per capita immiCO_2 in each sub-region in 2015 (ton per capita), where the colour of the sub-regions in the world maps shows their per capita immiCO_2. Panel (d) shows the portion of immiCO_2 in total CO_2 footprint for each sub-region in 2015, where the colour of the sub-regions in the world maps shows their proportions of immiCO_2 in total CO_2 footprint.

Impacts of International Migration on Global CO_2 Emissions. We evaluate the relative contribution of the international migration to global CO_2 emissions, by decomposing global CO_2 emissions into six socioeconomic determinants (i.e., CO_2 emission intensity, production structure, final demand structure, per capita final demand, original population, and migration structure). Figure 3 reveals that global CO_2 emissions have increased steadily during 1995–2015, with the increasing per capita final demand being the largest contributor. The reduction of CO_2 emission intensity has the most significant contribution to global CO_2 mitigation. The changes in the original population and international migrants structure have kept increasing global CO_2 emissions during 1995–2015. Natural population growth, which is the second largest contributor to global CO_2 emissions, contributes to an increase in global CO_2 emissions by over 4% every five years while changes in the international migration structure act as the third largest contributor. The pushing effects of migration structure changes vary across different time periods, with the highest being 0.7% during 2005–2010 and the lowest being 0.1% during 2010–2015. The impacts of international migration structure changes on global CO_2 emissions are expected to be lower in recent years, because the migration structures of major migration destinations have been plateaued. The changes in the final demand structure have relatively small impacts on global CO_2 emissions during 1995–2015. In general, changes in the quantity, structure, and affluence of international immigrants have contributed to global CO_2 emissions increase during 1995–2015, while final demand structure changes of international immigrants have little effects on global CO_2 emissions during this time period.

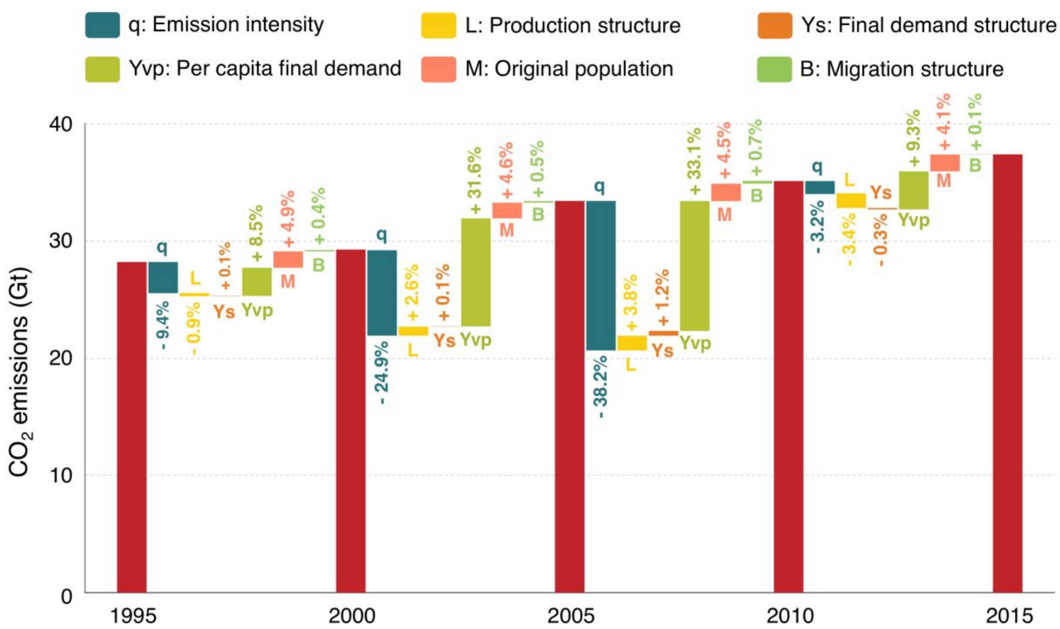


Figure 3. Impacts of socioeconomic transition and migration trend on changes in global CO_2 emissions during 1995–2015. The positive values indicate that socioeconomic factor changes contribute to the increase of CO_2 emissions, while the negative values mean that the socioeconomic factor changes lead to the mitigation of CO_2 emissions, if other factors remain constant.

DISCUSSION

This study for the first time examined the CO_2 footprint of international immigrants. The CO_2 footprint of international immigrants has increased by 65% during 1995–2015, while that of the global population (i.e., global total CO_2 emissions) has increased by 33% during the same period. Meanwhile, the portion of the CO_2

footprint of international immigrants in global total CO_2 emissions has also increased. International migrants accounted for 3.4% of the total population in 2015, but its CO_2 footprint was as high as 7.9%. However, in 1995 the portion of international immigrants and their CO_2 footprint was only 2.8% and 6.3%, respectively. Since migration is generally from relatively poorer regions to richer regions, immigrants would typically live in more advanced economies with significant lifestyle change. Their consumption of living necessities (e.g., foods and clothes), housing, infrastructures, health care, and education would be more CO_2 intensified, and cause more massive CO_2 emissions. This finding facilitates policy makers to reconsider the role and status of global population mobility in CO_2 emissions. Population mobility will accompany the development and transformation of human society for a long time. The understanding of the CO_2 footprint of human migration in this study will contribute to current efforts and routes to tackle climate changes. At the same time, this study reveals that migration structure tends to be stable in recent years, and the changes in the number of immigrants are the main factor influencing migration-related CO_2 emissions.

Policy implication I: CO_2 reduction targets of the Paris Agreement and subsequent agreements must consider the effects of global migration. Many nations have set their Nationally Determined Contributions (NDCs) since the Paris Agreement in 2016[42]. However, CO_2 emission changes caused by global population movements have not been fully considered in current targets. The allocation of responsibilities for global CO_2 emission reduction can be different when considering the impact of international migration. For net immiCO_2 importers, immigrants contribute to CO_2 emissions in these nations, which increases the challenges of CO_2 emission reduction. Based on our results, the U.S. is still a primary destination of global migrants. It is likely to maintain this trend for a long time to come. Thus, the pressure for CO_2 emission reduction in the U.S. will be more severe in the future. The U.S., as the second largest CO_2 emitter in the world, has withdrawn from the Paris Agreement. This situation will pose great challenges to global climate changes. Among other major signatories, developed nations such as those in the EU are also major migration destinations. They need to consider future changes in the number and structure of population movements when setting their NDCs.

Policy implication II: Both production-side and demand-side measures are required to curb CO_2 emissions caused by international migration.

On one hand, production-side measures are important to offset the impacts of international migration on global CO_2 emissions. For producers, decreasing their CO_2 emission intensity is beneficial to lowering CO_2 footprint of the whole supply chain. Although international migration affects the consumption, the decreased CO_2 emission intensity can offset the impact of consumption pattern changes on CO_2 emissions to some extent. Since migration restriction is not a desirable option for economic development, immigrant inflow nations should accelerate both the reduction of CO_2 emission intensity of their own economic systems and the transition to the post-fossil energy era. In this way, even if the migration pushes up the overall population, it will not cause a significant increase in CO_2 emissions.

Compared with the U.S., the overall CO_2 footprint of immigrants in Europe (especially in Nordic countries such as Denmark and Sweden) is much lower. Nordic countries have made significant efforts to reduce CO_2 emissions. Their own CO_2 footprint is relatively low, despite immigrant inflows. Subsequently, there is no significant promotion of their own CO_2 emissions. This fully illustrates that reducing the intensity of CO_2 emissions in their economies can significantly reduce the boosting effects of CO_2 emissions brought by immigrants.

The individual CO_2 footprint will have a downward trend, if immigrants move from high CO_2 emitting nations to low CO_2 emitters. In some Middle East energy-dependent nations, immigrants from India and other major nations can significantly boost their CO_2 emissions. How to accelerate the transition to a post-fossil energy era in relevant nations will be a major challenge.

On the other hand, demand-side measures need to focus on major immigrant inflow nations, and sustainable consumption strategies of major immigrant inflow nations need to consider the trade-off effects of future migration. Major immigrant inflow nations should fully consider CO_2 boosting effects of future migration, especially in nations with high CO_2 emissions (e.g., the U.S. identified in this study). Since international migration is inevitable in the context of globalization, it is crucial for immigrant inflow nations to optimize consumption behaviors (e.g., guiding the consumption through carbon tax on finished goods and services) and accelerate technology improvements. In particular, consumption behaviors of immigrants should be guided through tax or financial incentives to decrease immiCO_2. Moreover, industries should be encouraged to choose upstream inputs with lower CO_2 emission intensities. In this way, the immigrant inflow nations may not suffer huge rises in CO_2 emissions under the impact of international migration.

Limitations. This study focuses on the macro-scale analyses. We assume that the consumption structure of immigrants is the same as that of native people in immigrant destination. The ratio of immigrants to total population is used to analyze the impact of international migration on global CO_2 emissions. Other underlying factors influencing CO_2 emissions through international migration are not considered due to data unavailability. These factors (e.g., lifestyles in different immigrant destinations, destination selection of immigrants, and consumption custom of different ethnic groups) can be further considered in future studies based on micro-level databases and social surveys.

In this study, we only calculated the CO_2 emission effects of global migration, without considering other effects caused by the migration (e.g., economic and social impacts). The primary cause of immigrants' CO_2 emissions is also related to the high-carbon economic systems of destination nations. The relevant policies should focus on how to reduce the CO_2 footprint of their own economic systems. Meanwhile, there is also a trend of international migration to low-income or low-carbon nations. In the future, global migration will become more diversified, and thus the CO_2 footprint of immigrants will be more diversified.

Uncertainty. The MRIO tables and global CO_2 emissions in this study are from the Eora database[37, 38]. Data of other global MRIO databases (e.g., GTAP[43], WIOD[44], EXIOBASE[45-47]) are not identical with that of Eora, which may lead to differences in results. Moreover, the international migration data are based on the number of documented immigrants. The undocumented immigrants, which also draw international attention, are not considered in this study due to data unavailability. These issues can be further addressed when the databases and statistical accuracy are improved.

ASSOCIATED CONTENT

Supporting Information

The supporting information provides supplemental Figures and Data supporting the main text. In the SI, Figure S1 for the international migration population and migration change; and Figure S2 for the national immi CO_2 and immiCO_2 flows. In the Supporting Data, Data S1 for the immigrant polulation and total polulation of nations; Data S2 for the immiCO_2 of nations; Data S3 for the proportions of immiCO_2 in total CO_2 footprint of nations; and Data S4 for the list of nations and associated sub-regions.

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Notes

The authors declare no competing financial interests.

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