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Will technology advances alleviate climate change? Dual effects of technology change on aggregate carbon dioxide emissions

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ABSTRACT

The relationship between technology change and carbon dioxide emissions is complex. Existing research has emphasized technology progress in reducing carbon emission intensity but has ignored the impact of technology progress on economic growth, which leads to changes in carbon dioxide emissions. We argue that technology has relatively independent economic and environmental attributes. To provide evidence for this, we developed a method to distinguish the scale effect of technology change and its influence on economic scale from the intensity effect of technology change and its influence on carbon emission intensity. We applied this method to study the impact of technology change on carbon dioxide emissions in 95 countries between 1996 and 2007. We found that technology change indeed reduced aggregate carbon dioxide emissions, but the scale and intensity effects of technology change separately expressed positive and negative values. As a consequence, previous studies that only consider the intensity effect overestimate the impact of technology change on carbon dioxide emissions. Our findings yield important considerations for carbon dioxide emissions control in policy making.

Introduction

Climate change has become a global concern. Reducing aggregate CO_2 emissions to alleviate global warming is a core priority in addressing climate change. There are two ways to achieve reductions in CO_2 emissions from economic activities: lowering the amount of CO_2 generation in production activities and end-of-pipe control of CO_2 emissions. End-of-pipe control of CO_2 emissions mainly depends on Carbon Capture and Storage (CCS), but CCS technology is facing a lot of problems such as engineering practice and public acceptance (Webley, 2014; Chen et al., 2015), it is still in its experimental stages and comes at a high cost (Nykvist, 2013; Scott, 2013). Consequently, the reduction of CO_2 emissions through end-of-pipe control is limited (Li et al., 2013). Hindering CO_2 generation in production activities is the main approach to reduce aggregate CO_2 emissions.

Technology change can influence the amount of CO_2 generation in production activities. At present, it is widely recognized the role of technology progress in CO_2 emissions reduction. Not only do all countries of the world emphasize lowering CO_2 emissions depending on technology progress, but also international societies like the United Nations (UN) appeal for the transfer of advanced technology from developed countries to developing countries in order to assist in the mitigation of climate change (De Coninck and Sagar, 2015; UNFCCC, 2015; Zhang and Yan, 2015) and the international cooperation of technology development in order to control climate change together (El-Sayed and Rubio, 2014; Ockwell et al., 2015; Rubio, 2016). Therefore, a scaled-up R&D funding is invested in technology development to mitigate climate change (Wiesenthal et al., 2012). A great deal of research evaluated the impacts of some specific technologies on CO_2 emissions from micro perspective, especially energy conservation and low carbon technologies such as renewable energy technologies, and found dramatic CO_2 emissions reduction effects (Kalt and Kranzl, 2011; Albino et al., 2014; Zhang et al., 2014; Pavić et al., 2016; Tokimatsu et al., 2016). It seems that technology progress is sure to lower aggregate CO_2 emissions. Nonetheless, an obvious fact is that aggregate CO_2 emissions has dramatically increased since industrial revolution (Boden et al., 2015), along with the similarly dramatic progress in technology (Fig. 1). Every tremendous progress in technology in modern society, not only brought about the improvements in energy and environmental efficiency, but also greatly stimulated the development of economy and the corresponding energy consumption, which is known as the "rebound effect" (Hertwich, 2005; Herring and Roy, 2007; Sorrell, 2007; Sorrell and Dimitropoulos, 2008; Sorrell et al., 2009; Grant et al., 2016; Lin and Zhao, 2016; Vivanco et al., 2016; Wei and Liu, 2017). Some interesting questions arise: although the development of some low carbon

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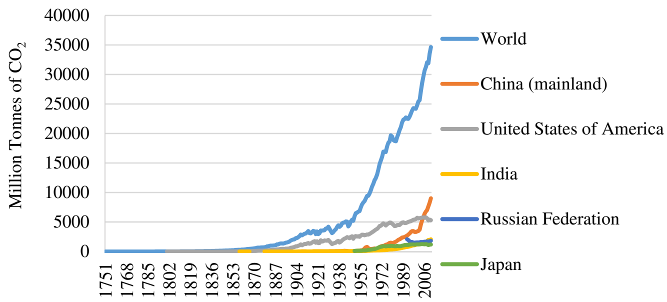


Fig. 1. Global and major national CO_2 emissions.

technologies can lower CO_2 emissions, how will technology development influence aggregate CO_2 emissions from macro perspective? Will technology development indeed lower aggregate CO_2 emissions?

Generally speaking, technology improvement driven by R&D activities can promote amelioration of an economic development pattern, adjustment of an energy structure, and the upgrading of an industrial structure, thus effectively reducing CO_2 emissions per unit of gross domestic product (GDP) (Grubb, 2004; Barrett, 2006; Edmonds et al., 2007; Fischer and Newell, 2008; Bosetti et al., 2009). On the other hand, technology improvement plays an important role in promoting economic growth (Romer, 1990; Grossman and Helpman, 1991; Hu et al., 2005; Wang, 2007; Clarke et al., 2008; Allen, 2012; Bhattacharya et al., 2015), countries and firms generally pay attention to their R&D activities and increase their R&D expenditures for technology innovation so that promote economic growth (C.H. Wang et al., 2013; D.H.M. Wang et al., 2013; Sánchez and Maldonado, 2015). However, technology improvement increases aggregate CO_2 emissions by increasing the economic scale. Current research in the fields of economy and environment have separately investigated the effect of technology change on economic growth and on the reduction in carbon emission intensity; however, studies have not combined the two aspects to comprehensively analyze the overall impact of technology change on aggregate CO_2 emissions. A detailed analysis of the positive role of technology change in decreasing aggregate CO_2 emissions by lowering carbon emission intensity and its negative role, which leads to increasing aggregate CO_2 emissions due to increases in the scale of economic output, would help us better understand the overall impact of technology change on aggregate CO_2 emissions. How we integrate the two aspects into an analytical framework to comprehensively evaluate the dual effects of technology change on aggregate CO_2 emissions is an important subject to be settled. To address these knowledge gaps, we developed a decomposition model that combines the positive and negative roles of technology change in order to not only evaluate the overall impact but also investigate the impact pathways of technology change on aggregate CO_2 emissions.

Existing studies on the influence of technology change on pollutant (CO_2) emissions from macro perspective can be divided into three categories: research to identify the factors affecting pollution emissions based on decomposition analysis, which decomposes pollutant emission change into various coordinate effects (scale effect, technology effect and so on), of which the technology effect was evaluated by using the change in carbon emission intensity as technology change (Grossman and Krueger, 1995; Antweiler et al., 2001; Luukkanen and Kaivo-oja, 2002; Stern, 2002; Wang et al., 2005; Wu et al., 2005; Liu, 2007; Zhang et al., 2009); research using a total factor productivity index as technology change to construct an econometric model or decomposition model to analyze the influence of technology change on aggregate CO_2 emissions (Pasurka, 2006; Zhou and Ang, 2008; Li, 2010); and research using scenarios about the impact of technology change on aggregate CO_2 emissions and using indexes, such as the change in carbon emission intensity, as technology change (Kemfert and Truong, 2007; Steckel et al., 2011; Astrom et al., 2013; Serrenho et al., 2014). Such research has focused on the impact of technology change on carbon emission intensity but has ignored that technology change can promote economic scale, which leads to increased CO_2 emissions. Although the second category of research has combined the economic and environmental elements into a comprehensive analytical framework, these studies calculated the productivity change based on technologies with some pre-assumptions. Pasurka (2006) calculated productivity change based on output distance function which treated good and bad outputs symmetrically (Färe et al., 1986); Chung et al. (1997) and Färe et al. (2001) calculated productivity change based on directional distance function which treated good and bad outputs asymmetrically. As a result, the previous research treated technology with an economic attribute (which affects economic scale) and an environmental attribute (which affects carbon emission intensity) intertwined and the same. However, they are relatively independent and different in reality. For example, environmentally friendly technology progress can result in greater reduction of carbon emission intensity when compared with an increase in the economic scale. Therefore, these studies had analytical bias. Furthermore, these studies could not identify the dual effects of technology change on aggregate CO_2 emissions.

The remainder of this paper is organized as follows: Methodology section presents the models for studying the impact of technology change on aggregate CO_2 emissions. Empirical analysis section provides an application of the models to 95 countries between 1996 and 2007 and discusses the empirical results, and Conclusion section concludes.

Methodology

Dual effects model

Technology change can affect CO_2 emissions in two ways: it can cause an increase in the scale of economic output, resulting in an increase in aggregate CO_2 emissions, or it can reduce carbon emission intensity, resulting in lower aggregate CO_2 emissions. Here, the change in aggregate CO_2 emissions influenced by the change to the scale of economic output resulting from technology change is called the scale effect of technology change, while the change in aggregate CO_2 emissions caused by the change in carbon emission intensity is called the intensity effect of technology change. Any technology advancement will have implications for both. In this research we analyze the dual effects of the intensity of technology change and the scale of technology change on aggregate CO_2 emissions (Fig. 2). Different from existing research, which viewed the economic attribute and environmental attribute of technology are the same, this paper deems that technology with an economic attribute and technology with an environmental attribute are relatively independent; this causes asynchronization between the scale effect and the intensity effect. For this reason, it is necessary to separately study the impacts of technology change on increasing the economic output scale and reducing carbon emission intensity and then to investigate the combined effects of technology change on aggregate CO_2 emissions.

Based on a decomposition model, we constructed a quantity model to analyze the impact of technology change on aggregate CO_2 emissions.

Aggregate CO_2 emissions were expressed as follows:

$$E = I \times Y, \tag{1}$$

where E represents aggregate CO_2 emissions; $I = E/Y$ is the carbon emission intensity, which denotes technology with an environmental attribute; and Y represents economic output.

The change in aggregate CO_2 emissions from year t to $t+1$ can then be expressed by.

$$\Delta E = \Delta I \times Y + I \times \Delta Y + \Delta I \times \Delta Y, \tag{2}$$

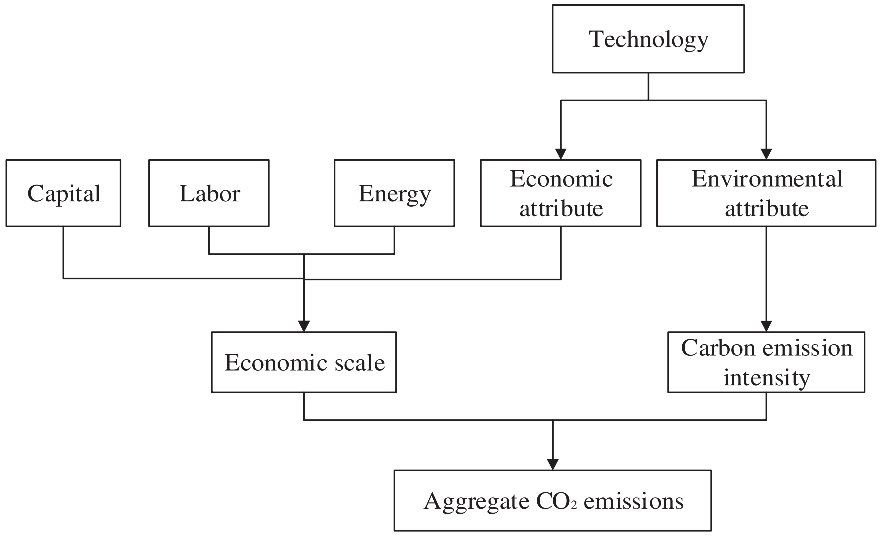


Fig. 2. Flow chart of how technology change influences CO_2 emissions.

where ΔE, ΔI, and ΔY are changes to CO_2 emissions, carbon emission intensity, and economic output, respectively.

The change in economic output can be further decomposed as the contribution of technology change and factor inputs (such as capital, labor, and energy input) as follows:

$$\Delta Y = \Delta Y_T + \Delta Y_R, \tag{3}$$

where ΔY_T and ΔY_R are economic output change from technology change and factor inputs, respectively.

By inserting Eq. (3) into Eq. (2), we obtain

$$\begin{aligned}\Delta E &= \Delta I \times Y + I \times (\Delta Y_T + \Delta Y_R) + \Delta I \times (\Delta Y_T + \Delta Y_R) \\ &= (\Delta I \times Y + I \times \Delta Y_T + \Delta I \times \Delta Y_T) + \Delta Y_R \times (I + \Delta I).\end{aligned} \tag{4}$$

The right side of the equation shows the influence of technology change and factor inputs, which are represented by ΔE_T and ΔE_R, on aggregate CO_2 emissions.

ΔE_T was then decomposed into the scale effect and intensity effect of technology change as follows:

$$\begin{aligned}\Delta E_T &= \Delta I \times Y + I \times \Delta Y_T + \Delta I \times \Delta Y_T \\ &= (I \times \Delta Y_T + 0.5 \times \Delta I \times \Delta Y_T) + (\Delta I \times Y + 0.5 \times \Delta I \times \Delta Y_T).\end{aligned} \tag{5}$$

The right side of the equation shows the scale effect and intensity effect of technology change. There are a number of methods for the allocation of the residual term; here we distribute the residual term to each variable on the basis of the "equally distributed" principle (Ang and Zhang, 2000).

Parameters

ΔY_T

We used the productivity change parameter (Luenberger indicator) to characterize technology change with an economic attribute and then calculated the change in economic output due to technology change. According to Chambers (1996) and Chambers et al. (1996), the Luenberger indicator can be expressed by.

$$L_t^{t+1}{}_P = \frac{1}{2} \times \left\{ \left[S^t(X_{t+1}, Y_{t+1}) - S^t(X_t, Y_t) \right] + \left[S^{t+1}(X_{t+1}, Y_{t+1}) - S^{t+1}(X_t, Y_t) \right] \right\}, \tag{6}$$

where X_t, X_{t+1} are the factor inputs of year t and $t+1$, respectively; Y_t, Y_{t+1} are the economic output of year t and $t+1$, respectively; S^t, S^{t+1} are the production efficiencies of actual production activity relative to the production frontier of year t and $t+1$, respectively. For example, $S^t(X_t, Y_t)$ is the production efficiency of actual production activity in year t relative to the production frontier in year t. We used the slacks-based measure (SBM) model to calculate the production efficiency of each country (Tone, 2001).

To compute the production efficiency $S^t(X_t, Y_t)$, we assumed that each country uses J kinds of factor inputs $x = (x_1, \ldots, x_J) \in X$ to produce the economic output, and the input–output vector of country n in time t is $(X_t{}^n, Y_t{}^n)$. The variable returns to scale (VRS) technologically feasible output set in a t period can be described by $P^t = \{(Y_t{}^n, X_t{}^n) : \sum_{n=1}^{N} \lambda_n{}^t Y_t{}^n \geq Y_t{}^n; \sum_{n=1}^{N} \lambda_n{}^t x_{tj}{}^n \leq x_{tj}{}^n, \forall j; \sum_{n=1}^{N} \lambda_n{}^t = 1, \lambda_n{}^t \geq 0, \forall n\}$, where $\lambda_n{}^t$ denotes an $n \times 1$ weighting vector that serves to construct the production frontier and $\sum_{n=1}^{N} \lambda_n{}^t = 1$ serves to construct the VRS production frontier. Essentially, the VRS production frontier typifies best practice technology (Lovell, 2003). The production efficiency of country n_0 can be computed by the following SBM model:

$$S^t(X_t{}^{n_0}, Y_t{}^{n_0}) = min \frac{1 - \frac{1}{J} \times \sum_{j=1}^{J} \frac{s_{tj}{}^{n_0-}}{x_{tj}{}^{n_0}}}{1 + \frac{s_t{}^{n_0+}}{Y_t{}^{n_0}}} \tag{7}$$

$$\text{s.t.} \begin{cases} x_{tj}{}^{n_0} - s_{tj}{}^{n_0-} = \sum_{n=1}^{N} \lambda_n{}^t x_{tj}{}^n, j = 1, \ldots, J \\ Y_t{}^{n_0} + s_t{}^{n_0+} = \sum_{n=1}^{N} \lambda_n{}^t Y_t{}^n \\ \sum_{n=1}^{N} \lambda_n{}^t = 1 \\ s_{tj}{}^{n_0-}, s_t{}^{n_0+}, \lambda_n{}^t \geq 0, n = 1, \ldots, N \end{cases}$$

where $(x_{tj}{}^{n_0}, Y_t{}^{n_0})$ represents the input–output vector of country n_0, and $(s_{tj}{}^{n_0-}, s_t{}^{n_0+})$ represents the input–output slack vectors.

Based on the Luenberger indicator, the changes to economic output contributed by technology change from t to $t+1$ was defined as follows:

$$\Delta Y_T = L_t^{t+1}{}_P \times Y_t, \tag{8}$$

Table 1
Description of the main abbreviations.

Abbreviation	Description
E	Aggregate CO_2 emissions
I	Carbon emission intensity
Y	Economic output
ΔE	Changes to CO_2 emissions
ΔE_T	Influence of technology change on aggregate CO_2 emissions
ΔE_R	Influence of factor inputs on aggregate CO_2 emissions
ΔI	Changes to carbon emission intensity
ΔY	Changes to economic output
ΔY_T	Economic output change from technology change
ΔY_R	Economic output change from factor inputs
${L_t^{t+1}}_P$	Luenberger indicator
S^t	Production efficiency of economic activity

ΔI

In accordance with Grossman and Krueger (1995), we argue that carbon emission intensity is influenced by technology. The carbon emission intensity change influenced by technology change from t to $t+1$ can be expressed as follows:

$$\Delta I = I_{t+1} - I_t = \frac{E_{t+1}}{Y_{t+1}} - \frac{E_t}{Y_t}. \tag{9}$$

Table 1 summarizes the main abbreviation and symbols used in this manuscript for quick reference.

Empirical analysis

Data

Case studies were used to demonstrate the impact of technology change on aggregate CO_2 emissions. We used the data of 95 countries over the period 1996–2007, which included 35 high-income countries, 31 upper middle-income countries, 20 lower middle-income countries, and 9 low-income countries.[1] The main inputs of economic activity included capital, labor, and energy input; the main outputs included economic output and environmental output. Specific information for the related variables is shown in Table 2. These data were mainly collected from the World Development Indicators of the World Bank (The World Bank, 2015).

We used the perpetual inventory method to convert gross fixed capital formation into the indicator of capital input. This formula is $K_{nt} = (1-\delta)\times K_{n(t-1)} + I_{nt}$, where n is the $n-th$ country, t is the year, δ is the depreciation rate (taken to be 6%), and I_{nt} represents the gross fixed capital formation measured in million US dollars (year 2000). We took 1990 as the base year to calculate the capital stock by using the formula $K_{n1990} = I_{n1990}/\eta$, in which η is 10%. The aggregate labor force (people in thousands), energy use (kilotonnes of oil equivalent), GDP (million US dollars, year 2000), and aggregate CO_2 emissions (kilotonnes) were used as the indicators of labor input, energy input, economic output, and environmental output, respectively. The descriptive statistics of all the variables are shown in Table 3.

[1] We used 35 high-income countries (Australia, Austria, Belgium, Brunei Darussalam, Canada, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hong Kong, Hungary, Iceland, Ireland, Italy, Japan, Korea Republic, Luxembourg, Malta, Netherlands, New Zealand, Norway, Poland, Portugal, Republic of Trinidad and Tobago, Singapore, Slovenia, Spain, Sweden, Switzerland, United Kingdom, United States); 31 upper middle-income countries (Algeria, Argentina, Azerbaijan, Belarus, Botswana, Brazil, Bulgaria, Chile, China, Costa Rica, Cuba, Dominican Republic, Gabon, Iran, Jordan, Kazakhstan, Latvia, Macedonia, Malaysia, Mexico, Namibia, Panama, Peru, Romania, Russian Federation, South Africa, Thailand, Tunisia, Turkey, Uruguay, Venezuela); 20 lower middle-income countries (Armenia, Bolivia, Cameroon, Cote d'Ivoire, Egypt, El Salvador, Guatemala, Honduras, India, Indonesia, Morocco, Nicaragua, Pakistan, Paraguay, Philippines, Senegal, Sudan, Syrian Arab Republic, Ukraine, Zambia); and nine low-income countries (Bangladesh, Benin, Ethiopia, Kenya, Kyrgyz Republic, Mozambique, Tajikistan, Tanzania, Togo).

Table 2
Description of selected indicators and data.

	Variable	Indicator	Unit
Input	Stock of fixed capital	Gross fixed capital formation	Million US$ in 2000
	Labor	Labor force	1000 people
	Energy	Energy use	Kiloton of oil equivalent
Desirable output	Economic output	GDP	Million US$ in 2000
Undesirable output	Environmental output	CO_2 emissions	Kiloton

GDP, gross domestic product.

Dual effects

We used MaxDEA Pro 6 software (developed by Cheng Gang and Qian Zhenhua, Beijing, China) to calculate production efficiency $S^t(X_t, Y_t)$ according to Eq. (7). The productivity change (${L_t^{t+1}}_P$) of each country was calculated according to Eq. (6), and the economic output change of each country as a result of technology change (ΔY_T) was calculated according to Eq. (8). The carbon emission intensity change (ΔI) of each country resulting from the technology change contribution was calculated according to Eq. (9). Based on the above results, we estimated the annual impact of technology change on aggregate CO_2 emissions over the period 1996–2007 and analyzed the scale and intensity effects of technology change according to Eq. (5), and present the empirical results in Table 4. We compared the magnitude of the impact of technology change component with the impact of factor input component on aggregate CO_2 emissions according to Eq. (4), and present the results in Fig. 3. We also compared the impact of technology change based on the method developed in this research with traditional method, and present the results in Fig. 4.

Scale effect of technology change

Results showed that the scale effect of technology change on aggregate CO_2 emissions led to increasing the scale of economic output and then increasing the amount of aggregate CO_2 emissions for the 95 sampled countries. From 1996 to 2007, the scale effect of technology change resulted in an average annual increase of 1828 kt aggregate CO_2 emissions per country, accounting for 0.73% of aggregate CO_2 emissions in

Table 3
Descriptive statistics of all the variables (1996–2007).

Groups	Variable	Mean	Standard deviation	Minimum	Maximum
H	x_1	1,729,649	4,025,502	6768	23,368,179
	x_2	14,002	27,083	133	157,254
	x_3	144,655	377,201	676	2,336,546
	y	741,646	1,833,213	3199	11,670,846
	b	349,809	947,687	2063	5,836,474
UM	x_1	364,044	736,373	1077	5,873,054
	x_2	37,339	129,554	473	773,053
	x_3	102,322	260,798	980	1,962,439
	y	151,411	303,301	3136	2,456,684
	b	288,443	811,084	1213	6,533,018
LM	x_1	133,045	255,163	3985	1,638,976
	x_2	34,597	87,192	1434	443,664
	x_3	51,900	109,384	1769	595,105
	y	59,754	119,739	1576	773,393
	b	118,660	279,219	1806	1,611,042
L	x_1	20,804	30,013	1649	145,027
	x_2	15,761	18,312	1690	68,087
	x_3	9691	7700	1731	30,703
	y	10,901	15,579	716	69,671
	b	7460	9518	986	43,715

H, high income; UM, upper middle income; LM, lower middle income; L, low income. x_1, gross fixed capital formation; x_2, labor force; x_3, energy use; y, gross domestic product; b, CO_2 emissions.

Table 4
Dual effects of technology change on aggregate CO_2 emissions[a]. Unit: kiloton, %.

National type	Scale effect		Intensity effect		Combined effect	
	Amount	Proportion	Amount	Proportion	Amount	Proportion
H	3347	0.95	−8252	−2.35	−4904	−1.40
UM	1614	0.55	−8104	−2.78	−6490	−2.22
LM	357	0.30	−2460	−2.05	−2103	−1.75
L	−77	−1.01	−62	−0.82	−139	−1.83
ALL	1828	0.73	−6208	−2.48	−4380	−1.75

[a] Results show the average values of the sample countries in each income group. To obtain the results of any specific country, please contact the author. H, high income; UM, upper middle income; LM, lower middle income; L, low income; ALL, all countries. Amount refers to the average annual change in CO_2 emissions affected by technology change between1997 and 2007; proportion is the ratio of the average annual change in CO_2 emissions caused by technology change to aggregate CO_2 emissions in 1996 for each national type.

the base year (1996). Overall, the results indicated that countries tended to promote economic growth through technology improvement, which in turn increased aggregate CO_2 emissions.

From the perspective of income, we found the scale effect of technology change to differ among the different income types. Technology change had the most notable positive value of scale effect on aggregate CO_2 emissions for high-income countries, with an average of 0.95 t CO_2 emissions added per 100 t. With decreasing income, the scale effect of technology change gradually declined until becoming negative for the low-income countries. For the 31 upper middle-income countries and 20 lower middle-income countries, the scale effects of technology change increased by 0.55 t and 0.30 t CO_2 emissions per 100 t, respectively. Take Japan (H), China (UM) and India (LM) as examples, the scale effects of technology change led to increases of 0.85, 0.31 and 0.22 t CO_2 emissions per 100 t, respectively. In contrast, for the low-income countries this effect led to an average decrease of 1.01 t CO_2 emissions per 100 t.

Currently, countries generally emphasize promoting economic growth by relying on technology improvement; this is particularly true for developed countries, such as the United States, which stresses that "technology growth is the backbone of the American economy" (Council of Economic Advisers, 2015). From an economic perspective, technology change plays an important role in economic growth for many countries; however, it is important to note its adverse impact on global warming due to CO_2 emissions.

For low-income countries, the data reported here suggest that they are less advanced compared to other countries and they are reliant on extensive economic growth rather than technology progress. This result agrees well with the finding of Li and Wang (2014). Therefore, we can realize that although technology regression for low-income countries decreases the scale of economic output, it is good for carbon reduction. Otherwise, technology progress driven economic development would augment CO_2 emissions from low-income countries.

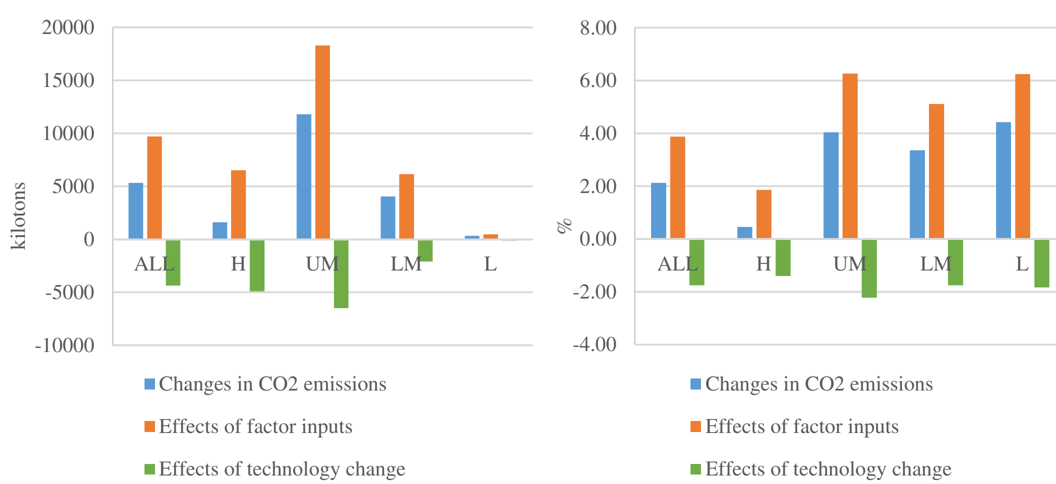
Intensity effect of technology change

The intensity effect of technology change on aggregate CO_2 emissions reduced CO_2 emissions in the 95 countries by decreasing the carbon intensity. This led to an average annual reduction of 6208 kt CO_2 emissions per country, giving an average of 2.48 t CO_2 emissions reduction per 100 t.

On an income level, the intensity effect of technology change led to reductions in CO_2 emissions for all income types. Among them, upper middle-income countries had the most prominent response, with an average reduction of 2.78 t CO_2 emissions per 100 t. This was followed by high-income and lower middle-income countries, which showed reductions of 2.35 t and 2.05 t per 100 t CO_2 emissions, respectively. Take United States (H), China (UM) and India (LM) as examples, the intensity effects of technology change led to decreases of 2.24, 3.55 and 2.19 t CO_2 emissions per 100 t, respectively. The intensity effect for the low-income countries was least, resulting in an average reduction of only 0.82 t per 100 t of CO_2 emissions.

There are a number of reasons that explain our findings. For upper middle-income countries, they have developed many high carbon industries, and fossil fuels are their main energy source. This can be seen from their industrial and energy structures. Therefore, these countries can be easier to lower their carbon emission intensity compared with high-income and lower middle-income countries. However, for low-income countries, their industrial structures have not been modernized and high carbon industries are undeveloped. Therefore, these countries are much harder to lower their carbon emission intensity compared with other countries. In the future, along with the adjustment of an energy structure and the upgrading of an industrial structure in upper middle-income countries, their intensity effect may be much more notable. However, for low-income countries, their energy structures are powered mainly by nonfossil-fuel energy currently; along with the transfer of energy from biomass to fossil-fuel energy, their intensity effect may be even weaker.

To summarize, our findings have some consistency with Grossman and Krueger (1995) and indicate that technology change is able to



(a) Amount of average annual change (b) Percent of average annual change

Fig. 3. Comparison of the effects between technology change and factor inputs. H, high income; UM, upper middle income; LM, lower middle income; L, low income; ALL, all countries. The vertical axis of these two figures are the amount and ratio of the average annual change in CO_2 emissions for each national type, respectively.

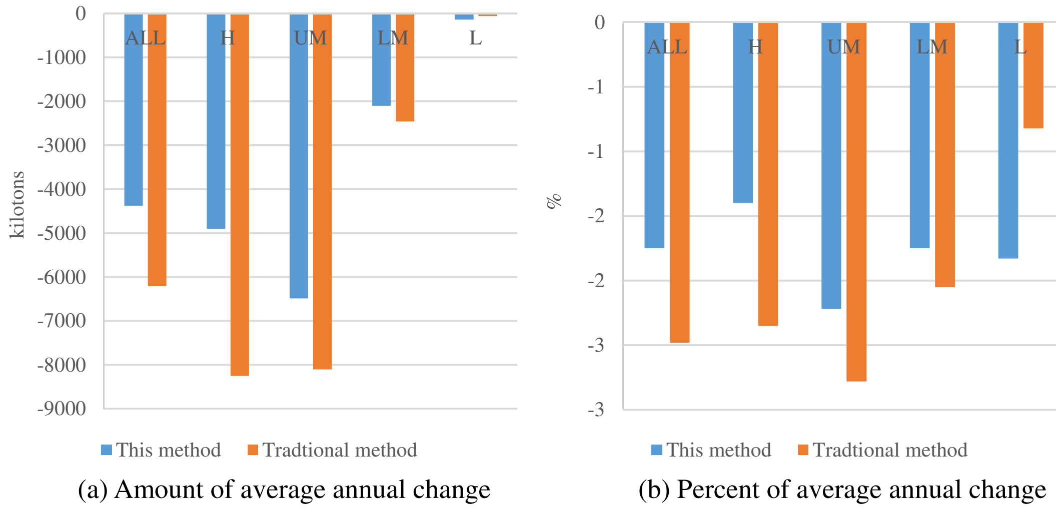


Fig. 4. Comparison of the results produced by the developed method in this paper and traditional method. H, high income; UM, upper middle income; LM, lower middle income; L, low income; ALL, all countries. The vertical axis of these two figures are the amount and ratio of the average annual change in CO_2 emissions for each national type, respectively.

reduce carbon emission intensity, thereby reducing CO_2 emissions from economic activity.

Combined effects of technology change

The combined effects of technology change on aggregate CO_2 emissions reduced the CO_2 emissions of each of the 95 countries on average by 4380 kt, accounting for 1.75% of average CO_2 emissions for the 95 countries examined.

Negative values of intensity effect were greater than positive values of scale effect of technology change in high-income, upper middle-income, and lower middle-income countries, while scale and intensity effects were both negative in low-income countries. The combined effects of technology change led to decreases of 2.22 t, 1.83 t, 1.75 t, and 1.40 t CO_2 emissions per 100 t in upper middle-income, low-income, lower middle-income, and high-income countries, respectively. For the upper middle-income countries, the high negative effect of technology change was mainly due to its relatively large negative intensity effect. Take China as an example, the effect of technology change led to a decrease of 3.24 t CO_2 emissions per 100 t. In contrast, technology change in the high-income countries had the smallest negative value of combined effect on CO_2 emissions because the positive scale effect in these countries weakened the negative combined effects. Take United States and Japan as examples, the effects of technology change only led to reductions of 0.96 and 0.43 t CO_2 emissions per 100 t, respectively.

Comparison of the effects between technology change and factor inputs

We computed the impact of factor inputs on aggregate CO_2 emissions and compared with the influence of technology change (Fig. 3). Results showed that the effect of factor inputs on aggregate CO_2 emissions led to increasing the amount of aggregate CO_2 emissions for the 95 sampled countries, which is different from the effect of technology change. From 1996 to 2007, the effect of factor inputs resulted in an average annual increase of 9705 kt CO_2 emissions per country. As a result, if the technology of 2007 would have remained that of 1996, the average annual growth rate of CO_2 emissions would have been 3.88%, 1.75% more than the increase of CO_2 emissions in reality. The positive effect of factor inputs surpassed by far the negative effect of technology change on aggregate CO_2 emissions, making an average annual increase of 5325 kt CO_2 emissions per country.

From the perspective of income, we found the effects of factor inputs and technology change to differ among the different income types. Although upper middle-income countries had the most notable negative effect of technology change (average annual of 6490 kt), they also had the most notable positive effect of factor inputs (average annual of 18,286 kt), which contributed to their largest increase in CO_2 emissions. Low-income countries had the largest percentage change in CO_2 emissions (4.42%) due to their notable positive effect of factor inputs (6.25%), despite their amount change in CO_2 emissions was not conspicuous.

Comparison of the results produced by the developed method in this paper and traditional method

We also compared the impact of technology change on aggregate CO_2 emissions based on the method constructed in this paper with traditional method which only considered the intensity effect of technology change (Fig. 4). We found that the method developed in this paper suggests lower negative effect than traditional method for the 95 sampled countries. Traditional method overestimated 29.45% of the effect of technology change in CO_2 emissions reduction compared with the method developed in this paper (average annual of 6208 vs 4380 kt).

On an income level, traditional method overestimated the effect of technology change at various degrees for the high-income, upper middle-income, and lower middle-income countries; while underestimated for the low-income countries. The extent of overestimation was the largest for the high-income countries, with an average annual of 3348 kt CO_2 emissions or 40.57% of exaggeration; while there was an average annual of 77 kt CO_2 emissions per country or 55.40% of underestimation for the low-income countries.

Relationship between the effects of technology change and the level of economic development

We found scale effects and intensity effects to differ among the different income levels. To investigate how economic development affects the impacts of technology change on aggregate CO_2 emissions, we studied the relationship between effects of technology change and the level of economic development (Fig. 5).

The scale effect of technology change gradually increased with economic development. Low-income countries had a negative scale effect of technology change. As economic development increased, so did the scale effect, which became positive. The scale effects were caused by technology change with an economic attribute; thus, the notable difference in scale effects among the different income groups was because countries were impacted differently by their economic development attributable to technology change.

In contrast to the scale effect of technology change, the negative intensity effect of technology change was strengthened and then receded with economic development. The negative intensity effect was most

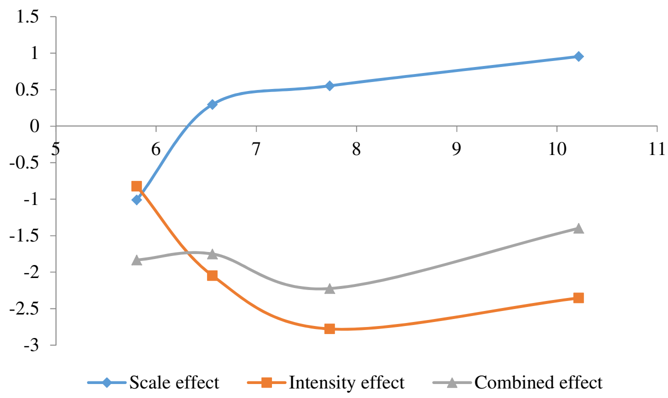


Fig. 5. Relationship between the effects of technology change and economic development. Note: The horizontal axis is the natural logarithm of per capita GDP. The vertical axis is the ratio of the average annual change in CO_2 emissions caused by technology change to aggregate CO_2 emissions in 1996 for each national type.

notable in the upper middle-income level. Due to their differences in technology change with an environmental attribute, countries with different levels of economic development reflected different intensity effects. The intensity effect for the upper middle-income countries was highest because they had the most notable technology improvement, which decreased carbon emission intensity. This was followed by the high-income and lower middle-income countries. The intensity effect for the low-income countries was lowest, which suggests that these countries pay little attention to developing environmentally friendly technologies.

Conclusion

Research on the relationship between technology change and CO_2 emissions may yield important considerations for CO_2 emissions control policies. Technology progress is often deemed to be one of the main approaches for reducing aggregate CO_2 emissions. Existing research has focused on the positive role of technology progress in decreasing aggregate CO_2 emissions by lowering carbon emission intensity. However, technology growth also plays an important role in promoting economic growth. Current research has ignored the role of technology change in increasing aggregate CO_2 emissions by increasing the scale of economic output, leading to biased results. We argue that technology change has dual effects on aggregate CO_2 emissions. On one hand, technology improvement with an economic attribute increases aggregate CO_2 emissions by promoting economic growth (scale effect). On the other hand, technology improvement with an environmental attribute decreases aggregate CO_2 emissions by reducing carbon emission intensity (intensity effect). We constructed a decomposition model to analyze the intensity effect and scale effect of technology change on aggregate CO_2 emissions to identify the impact pathways of technology change on aggregate CO_2 emissions.

A case study of CO_2 emissions from 95 countries based on data gathered over the period 1996–2007 indicated that technology change helps reduce CO_2 emissions in general and that we can reduce CO_2 emissions through technology improvement. However, the scale effect of technology change increases CO_2 emissions, and previous studies that only considered the intensity effect overestimate the impact of technology change on CO_2 emissions. As a consequence, the scale effect of technology improvement needs to be factored in, otherwise the assumed contribution of technology improvement on CO_2 emissions reduction will be overstated, especially for high-income countries. Although an emphasis is placed on improving the quality of economic development and promoting economic growth through advancements in technology, the role of technology change in lowering carbon emission intensity also needs to be a focus in order to reduce overall CO_2 emissions. Especially for high-income countries, it is more important to focus on the development and application of low carbon production technologies to offset the notable positive value of scale effect of technology change on aggregate CO_2 emissions.

This research inspires us to treat technology improvement with deliberation. We should be aware that technology progress is a sword with two blades in lowering aggregate CO_2 emissions. The scale effect of technology progress leads to increase of CO_2 emissions, albeit the intensity effect has negative impact on CO_2 emissions. Therefore, technology progress does not necessarily alleviate global warming. Countries should not blindly emphasize lowering CO_2 emissions depending on technology progress, and should focus on promoting the progress in low carbon production technologies. In addition, for international technology transfer, it is important for developing countries to avoid introducing advanced technology from developed countries in the name of climate change mitigation while purposely promoting economic growth that ultimately results in an increase in CO_2 emissions.

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