Renewable and Sustainable Energy Reviews 132 (2020) 110090

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

Does emission trading lead to carbon leakage in China? Direction and channel identifications

Bo Zhou [a], Cheng Zhang [b], Qunwei Wang [a,*], Dequn Zhou [a]

[a] College of Economics and Management, Nanjing University of Aeronautics and Astronautics, Nanjing, 211106, China
[b] School of Economics, Nanjing University of Finance and Economics, Nanjing, 210023, China

ARTICLE INFO

Keywords:
Emission trading
Carbon leakage direction
Carbon leakage channel
Shift-share method
Difference-in-difference-in-differences model

ABSTRACT

Unilateral emission trading may lead to carbon leakage. The leakage direction and channel are critical to multilateral emission mitigation. Despite the increasing number of investigations into the carbon leakage induced by emission trading, there is a lack of empirical research on the specific leakage channels related to the emission trading market. This paper develops a difference-in-difference-in-differences model to identify carbon leakage directions in emission trading pilots in China. The issue of whether market participation and industrial transfer are the specific leakage channels related to emission trading is also examined. Emission trading pilots lead to reverse carbon leakage, which moves from the non-pilot region to the pilot region. Market participation and industrial transfer are confirmed to be the specific leakage channels in emission trading. Of the two channels, market participation is the one that determines the reverse direction.

1. Introduction

The issue of carbon emissions being generated by human beings has become a problem that needs to be addressed and resolved at a global level. However, current mitigation policies are mostly unilaterally implemented. The risk with any unilateral mitigation policy is that an extra carbon transfer between a carbon-constrained region and a non- or less-constrained one will appear. In such cases, global carbon emissions may not actually be reduced by the policy, so the desired effect is not obtained. The carbon transfer caused by the differences between one region's constraint efforts compared to other regions' is defined as carbon leakage [1,2]. Carbon transfers can also originate in the differences between different regions' production factor prices and industrial chain divisions, as well as other factors [3]. Therefore, carbon leakage is regarded as a component of carbon transfers, which only has a causal link with unilateral mitigation policies.

Up till now, the direction of carbon leakage has been confirmed in some mitigation policies in many countries, as going from a carbon-constrained region to a non- or less-constrained one [4]. This study defines the carbon leakage that moves in this direction as forward carbon leakage. This direction is consistent with the pollution haven hypothesis (PHH). The PHH holds that a region with stricter emission constraints will cause carbon-intensive industries to shift to regions with less stringent constraints. This can be done by imposing ever-increasing emission reduction costs, which effectively causes the latter region to become a pollution haven [5–9].

Theoretically, carbon leakage is also likely to shift emissions from a non- or less-constrained region to a carbon-constrained one. This is defined as reverse carbon leakage. This direction is counter-intuitive; however, it is also in accordance with the factor endowment hypothesis (FEH). The comparative advantage of industrial transfers partly lies in local factor endowment and production technology. Generally speaking, a region that takes the lead in stricter emission constraints is also more likely to be capital-dominated. This type of region tends to attract carbon-intensive industries [10]. If the effectiveness of emission constraints in these regions is relatively insufficient or inadequate, then reverse carbon leakage will occur.

With regard to market-based emission mitigation policies, emission trading programs and policies have been applied in the European Union, the United States, China and other countries or regions [11–15]. In China, starting in 2014, the National Development and Reform Commission (NDRC) began creating emission trading pilots in seven provinces and cities, including Beijing, Chongqing, Guangdong, Hubei, Shanghai and Tianjin,[1] respectively, with industrial enterprises as the main traders [16]. Although the existence of carbon leakage caused by

* Corresponding author.
E-mail address: wqw0305@126.com (Q. Wang).

[1] Shenzhen was merged into Guangdong in this study.

https://doi.org/10.1016/j.rser.2020.110090
Received 7 January 2020; Received in revised form 22 June 2020; Accepted 12 July 2020
Available online 28 July 2020

Abbreviations

PHH	pollution haven hypothesis
FEH	factor endowment hypothesis
NDRC	National Development and Reform Commission
RGGI	Regional Greenhouse Gas Initiative
CGE	computable general equilibrium
EU ETS	European Union Emissions Trading System
IO	input-output
LCA	life cycle assessment
GM	gravity model
SSM	shift-share method
DID	difference-in-differences
DDD	difference-in-difference-in-differences
PSM	propensity score matching
SCM	synthetic control method
SUTVA	stable unit treatment value assumption

emission trading pilots seems likely, the leakage direction between the pilot region and the non-pilot region is still uncertain, according to the above brief theoretical analysis. In addition, emission trading pilots are implemented separately from each other; pilot provinces also have gaps in market participation levels, which in turn are at least a partial indication of the strictness of emission constraints. Forward or reverse carbon leakage may also occur between pilot provinces [17]. Whether or not emission trading pilots can effectively promote China's overall carbon emission mitigation efforts is directly dependent on carbon leakage issues. Consequently, a detailed study of the carbon leakage that is caused by emission trading pilots is clearly warranted.

The study's objective is to empirically determine whether emission trading pilots lead to forward or reverse carbon leakage and, if so, in which channels such leakages are generated. In particular, specific channels related to the emission trading market are under investigation. To be specific, this study first calculates net carbon transfers between provinces in China. Then, the carbon leakage induced by emission trading pilots is separated from the net carbon transfers, to conclude the leakage direction. Finally, this study examines whether two specific channels, including market participation and industrial transfer, are the carbon leakage channels in emission trading pilots.

The remainder of this paper is organized as follows: Section 2 presents a literature review and comments on existing literature. Section 3 introduces this study's research methods and data sources. Section 4 provides and analyzes the empirical results. Section 5 includes the main conclusions and relevant policy implications.

2. Literature review

2.1. The carbon leakage direction caused by emission trading

An increasing number of studies are focusing on the carbon leakage caused by emission trading. Taking the Regional Greenhouse Gas Initiative (RGGI) as the research object, it is found that forward carbon leakage exists in the United States [18,19]. With Hubei (one of the pilot provinces in China) as the research subject, Tan et al. (2018) use a method that combines a computable general equilibrium (CGE) model with decomposition analysis [20]. The study concludes that the forward carbon leakage of Hubei's emission trading pilot is mainly caused by the inter-provincial transfer of energy-intensive industries. Wang et al. (2018) and Zhang et al. (2019) present a simulated result with regard to emission trading in China; the study's results indicate inevitable forward carbon leakage [21,22].

Multiple scholars have also examined the carbon leakage direction of the European Union Emissions Trading System (EU ETS). However, the conclusions of these studies have significant inconsistencies. In a number of studies, scholars agree that the EU ETS will lead to forward carbon leakage [23–28]. This is the conclusion reached by some scholars, in spite of the fact that the subsequent quota allocation rule is aimed at avoiding carbon leakage to the greatest possible extent. These rules allow some sectors facing the risk of carbon leakage to be exempt from auction, and as such, forward carbon leakage cannot be effectively prevented [29]. Other scholars express different opinions. For example, Reinaud (2008) examines the heavy industry sectors and finds that the EU ETS does not cause any carbon leakage in these sectors [30]. Naegele and Zaklan (2019) confirm that the enhanced environmental regulations stemming from the EU ETS do not have a significant impact on the embodied carbon emissions of manufacturing enterprises, thus denying the possibility of the EU ETS leading to any carbon leakage [31].

2.2. Potential carbon leakage channels

To moderate the carbon leakage caused by emission trading, one effective method is to optimize carbon leakage channels. By reviewing the existing literature, potential carbon leakage channels that come from emission trading can be summarized into two categories, namely internal channels and external channels.

The term "internal channels" refers to characteristics of the emission trading market. One such characteristic is market participation. Whether referring to the EU ETS [32,33] or emission trading pilots [34–36], some scholars find that market participation levels are unsatisfactory, and this undermines the incentive effect of emission trading on investment in emission reduction technologies. Thus, inadequate participation levels may have a complicated impact on carbon leakage.

The category of external channels mainly includes industrial transfer channels and energy channels. These are also common carbon leakage channels found with other emission mitigation policies. Some scholars maintain that, the larger a region's economic scale is, the greater the levels of industrial transfer and carbon transfer received from others will be [37]. The existence of an energy channel means that the price of fossil fuel energy will fall, due to a reduction in demand. This will result in increased fossil fuel energy consumption in a non- or less-constrained region, which in turn will ultimately lead to increased carbon emissions.

2.3. Estimate carbon leakage and carbon transfer

Carbon leakage may exist in various unilateral emission mitigation policies and not just in unilateral emission trading. Existing literature mainly uses CGE models to estimate the carbon leakage rates of current and future policies. However, the volume of carbon leakage rates varies dramatically, depending on the models, assumptions, data and contexts [38–42].

Carbon transfer between countries, regions and industries has recently been a developing and hot research topic. Carbon transfer levels are calculated by various methods, which can be summarized as follows: Firstly, input-output (IO) analysis is frequently used. As the most popular method used to calculate carbon transfer levels, IO analysis begins with the framework established by Leontief (1970) [43]. This framework measures embodied carbon emissions based on IO tables [44–46]. The second most popular method used to measure carbon transfer levels is life cycle assessment (LCA). This method traces changes in the stocks and flows of a certain product during its life, in order to analyze the carbon transfer levels [47]. The third most popular method uses the gravity model (GM). By deriving a theoretical gravity equation for a trade's carbon emissions content, which accounts for intermediate inputs (both domestic and imported), carbon transfer levels can be estimated [48]. Lastly, there is the index constructed method. Zhang et al. (2014) construct an index to determine the carbon transfer directions between provinces in China[2] [49].

Based chiefly on IO analysis, the inter-regional and interprovincial carbon transfers in China are being extensively studied. Scholars agree that carbon transfers in China mainly occur between the developing provinces in the central and western regions, and the developed provinces along the east coast. Moreover, carbon-intensive industries are found to be the main transfer sector [50–53]. Pan et al. (2018) capture more detailed results [54]. This study finds that the emissions caused by construction in the east and west, and technology-intensive manufacturing in the center (largely investment-related) are the major components of the increasing emission transfers. The results were obtained by constructing a Chinese provincial multiyear and multisector IO model.

2.4. Comment on existing literature

Despite the various methods used to estimate existing carbon leakage and carbon transfers in China, two aspects are still worth expanding. Firstly, in terms of estimation methods, existing literature mainly estimates carbon leakage by means of the CGE model. However, the results of this simulating method may be affected by parameter settings and model assumptions. As for calculating carbon transfer levels, most existing studies are based on IO analysis. China's IO tables are compiled by the National Bureau of Statistics every five years, thereby limiting the possibility of being combined with other methods, such as econometric modelling.

Secondly, as regards research objectives, existing studies mainly focus on verifying the carbon leakage channels that are caused by general emission mitigation policies, specifically the external channels mentioned above. However, internal channels may also have ambiguous moderation effects on carbon leakage. Therefore, it is necessary to take internal channels into consideration to more comprehensively clarify the carbon leakage channels caused by emission trading.

The marginal contributions of this paper are summarized as follows: At a theoretical level, based on the distinction between carbon transfer and carbon leakage, this study separates the carbon leakage caused by emission trading pilots from net carbon transfers. This study also identifies the directions and channels of carbon leakage. Meanwhile, this study improves our understanding of how carbon leakage occurs, and how the carbon leakage direction is determined, especially in emission trading. Empirically, this study takes emission trading pilots as a case study, discovering the dynamic relationship between carbon leakage direction and market participation. This study also discovers how the industrial transfer channel affects the amount of carbon leakage. The findings provide new suggestions for policy designers in China – and across the world – on how to mitigate carbon leakage. Fig. 1 shows the identification strategy.

3. Methodology and data

3.1. Shift-share method used to calculate net carbon transfers

3.1.1. Why is the shift-share method chosen to calculate net carbon transfers?

Some scholars adopt IO analysis to calculate the net carbon transfers of a certain economy as the difference between embodied carbon emissions in imports and exports [50,55,56]. As this study explains in Section 2.4, China's IO tables are compiled every five years; provincial IO tables are currently only updated to 2012. Therefore, this study cannot calculate net carbon transfers after 2014, which is the year emission trading pilots were set up, by adopting IO analysis.

Unlike IO analysis, the shift-share method (SSM) is able to calculate every year's net carbon transfers, based on the differences between different provinces' rates of carbon emissions. Consequently, this paper applies SSM, rather than IO analysis, to calculate the net carbon transfers of each industry in the provinces covered by this study.

3.1.2. Shift-share method

Before adopting the SSM to calculate net carbon transfers, this study divides all the research samples into two parts, including the pilot region and the non-pilot region. The pilot region includes the samples which implement an emission trading market. The non-pilot region includes the samples that have not implemented an emission trading market.

The SSM decomposes the carbon emission growth of one sample into two parts, including normal growth and net carbon transfer. Normal growth is calculated by the mean growth rate of all samples; net carbon transfer represents the emission variation, which is calculated according to the difference between the rate of the specified sample and the mean rate of all samples [57–61].

Furthermore, this study develops the SSM to decompose the net carbon transfer of one sample into inter-regional and intra-regional transfers, according to which region the sample belongs to. The term "inter-regional transfer" refers to the carbon transfer from the samples in the other region, and is calculated as the emission variation from the difference between the growth rates of the region this sample is in and the mean growth rate of all samples. The term "intra-regional transfer" refers to the carbon transfer from the samples in the same region, and is calculated as the emission variation from the difference between the growth rates of the sample and the region this sample is in.

This study takes sectors in provinces as samples. The carbon emission growth of one sector in province j in region i in year t is obtained as follows:

$$
\begin{aligned}
C_{ijt} - C_{ij0} &= C_{ij0}\frac{C_{ijt}-C_{ij0}}{C_{ij0}} = C_{ij0}\left(\frac{C_{ijt}-C_{ij0}}{C_{ij0}} + \frac{C_t - C_0}{C_0} - \frac{C_t - C_0}{C_0} + \frac{C_{it}-C_{i0}}{C_{i0}} - \frac{C_{it}-C_{i0}}{C_{i0}}\right) \\
&= \underbrace{C_{ij0}\frac{C_t - C_0}{C_0}}_{NORM} + \underbrace{C_{ij0}\left(\frac{C_{it}-C_{i0}}{C_{i0}} - \frac{C_t-C_0}{C_0}\right)}_{INTER} + \underbrace{C_{ij0}\left(\frac{C_{ijt}-C_{ij0}}{C_{ij0}} - \frac{C_{it}-C_{i0}}{C_{i0}}\right)}_{INTRA}
\end{aligned}
\tag{1}
$$

The variable meanings and units in Formula (1) are summarized in Table 1. A positive net carbon transfer means that the transfer direction is inward, while conversely, a negative net transfer would indicate the direction is outward.

[2] The index is constructed as the ratio of the mean carbon emission growth rate of a certain province to that of the whole country during a specific period. An index of more than and less than 1 represents the inward and outward net carbon transfer of the province, respectively; an index equal to 1 represents relative balance between the provinces.

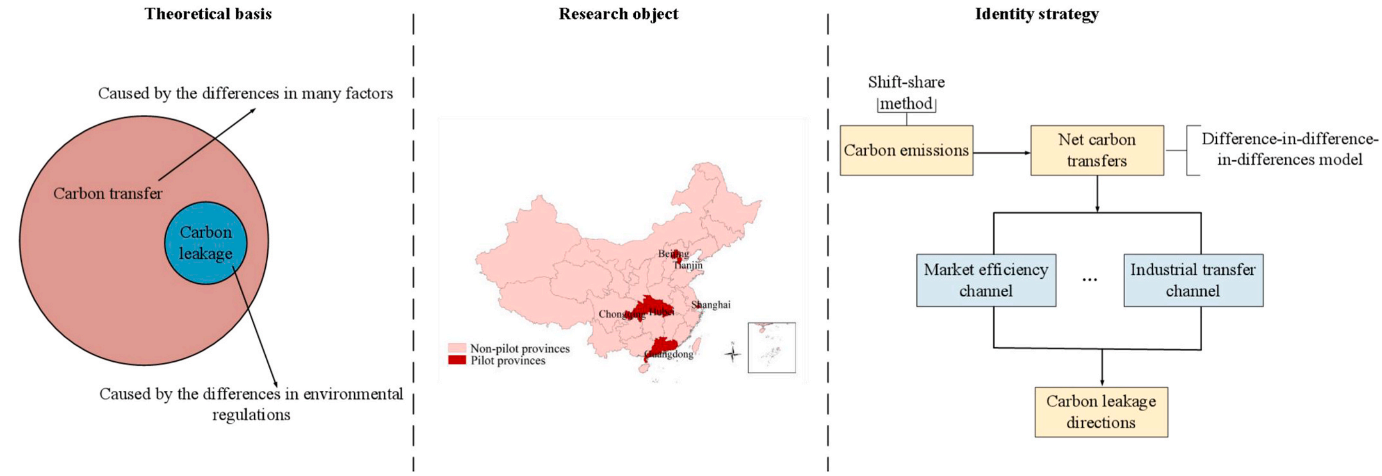

Fig. 1. Identification strategy.

Table 1
Variables in Formula (1).

Variables	Variable meanings	Units
C_t	The carbon emissions of the sector in the whole country in year t	10^4 tons
C_{it}	The carbon emissions of the sector in region i in year t	
C_{ij0}	The carbon emissions of the sector in province j in region i in the base year	
C_{ijt}	The carbon emissions of the sector in province j in region i in year t	
NORM	Normal carbon emission growth	
INTER	Inter-regional industry net carbon transfer	
INTRA	Intra-regional industry net carbon transfer	
TOTAL	Total industry net carbon transfer	

Sources: The authors drew this table.

3.2. Difference-in-difference-in-differences model used to identify carbon leakage directions

Emission trading pilots were officially established in 2014, and were launched in six provinces and cities, thus providing a quasi-experimental study setting. This paper separates the net carbon transfer, which has causality, with emission trading pilots and is referred to as carbon leakage [4].

When assessing the causal effects of a certain policy, a difference-in-differences (DID) model is widely used [62–65]. A DID model makes it possible to identify the direction of carbon leakage by the sign of the double-differences between a treatment group and a control group, during both a treatment period and control period. The treatment group includes the emitters in the emission trading market, while the control group includes the emitters which are not in the emission trading market. The treatment period means the period after the establishment of the emission trading market; the control period means the period before the establishment of the emission trading market.

In this study, the industrial sectors in the pilot provinces are the treatment group, and industrial sectors in the non-pilot provinces are the control group. The years before emission trading pilots are the control period, and the years after emission trading pilots are the treatment period. Taking inter-regional carbon leakage as an example, and referring to existing literature which adopts a DID model to study emission trading pilots [16], this study sets the DID model as:

$$INTER_{jt} = a_0 + a_1 Y{\cdot}R_{jt} + \gamma_j + \gamma_t + \delta_j Z_{jt} + e_{jt} \tag{2}$$

In Formula (2), a and δ denote coefficients; $Y*R$ equals 1 if and only if province j is in the treatment group and if $t>t^*$ (t^* is the year emission trading pilots were officially established). Otherwise, $Y*R$ equals 0. Also, γ_i and γ_t represent province fixed and year fixed effects, respectively; Z_{jt} is the set of controlled variables, and e is the random error. The sign of coefficient a_1 represents the direction of inter-regional carbon leakage.

One concern is that the unbiased evaluation results from the DID model partially depend on common trends in the dependent variables in the control and treatment groups. Net carbon transfer, however, is calculated by the difference between the carbon emission rates of provinces, regions and the whole country. Therefore, the trends of net carbon transfer in the control and treatment groups may be totally opposite. As such, for the purposes of this study, there is a concern that the DID model may not be effective or reliable.

This concern can be addressed by employing a difference-in-difference-in-differences (DDD) model.[3] Using this model, this study adds new samples (namely other sectors besides industry) into the control group. Differential trends also exist in these sectors in different provinces. In addition, these sectors are not affected by emission trading pilots, considering that industrial enterprises are major traders in the market. The intention when using a DDD model to address this concern is to capture the differential trends in these sectors by DID regression. Then, this study subtracts the differential trends from the result in Formula (2). Accordingly, differential trends between the control and treatment groups are allowed [70,71].

In this study, the DDD model is established as follows:

$$INTER_{jkt} = b_0 + b_1 Y{\cdot}R{\cdot}I_{jkt} + \gamma_{jk} + \gamma_{jt} + \gamma_{kt} + \gamma_j + \gamma_k + \gamma_t + \delta_{jk} Z_{jkt} + e_{jkt} \tag{3}$$

In Formula (3), k denotes sectors; γ_j, γ_k and γ_t represent province fixed, sector fixed and year fixed effects, respectively; γ_{jk}, γ_{jt} and γ_{kt} represent province-sector fixed, province-year fixed and sector-year fixed effects, respectively. Also, $Y*R*I$ is equal to 1 if and only if sector k is industry and province j is in the control group, and if $t>t^*$ (t^* is the year emission trading pilots were officially established). Otherwise, $Y*R*I$ equals 0. Significantly, a negative b_1 represents inter-regional forward carbon leakage caused by emission trading pilots; otherwise, a positive b_1 represents inter-regional reverse carbon leakage.

The other concern is whether Formula (3) violates the Stable Unit Treatment Value Assumption (SUTVA). There are necessarily spillovers between control and treatment groups, since a change in net carbon transfer in one group leads to the converse change in the other group. In this case, the result is an over-estimated carbon leakage. However, this

[3] The other current methods used to address this concern include the propensity score matching (PSM) method [65,66] and synthetic control method (SCM) [67–69]. The PSM method is more effective for large sample research, while SCM is difficult to use to further study the complex effects of characteristic differences in treatment samples.

issue does not influence the identification accuracy of the carbon leakage direction, and the conclusion of Formula (3) will hold, even if the SUTVA is violated.

3.3. Difference-in-difference-in-differences model used to identify carbon leakage channels

This paper identifies two potential carbon leakage channels, namely market participation and industrial transfer. Of the two, the existence of a market participation channel means that the carbon leakage direction caused by emission trading pilots is determined by the level of market participation [34,35]. Market participation measures the participation level of emitters in emission trading pilot markets. With regard to the industrial transfer channel, this study examines whether provinces with a relatively larger industry scale will receive more industry transfers [9,37].

Continuing with the adoption of the DDD model, in order to identify the market participation channel, $Y*R*I$ in Formula (3) is replaced with the market participation variable MP; then, this study develops the DDD model as:

$$INTER_{jkt} = c_0 + c_1 MP_{jkt} + \gamma_{jk} + \gamma_{jt} + \gamma_{kt} + \gamma_j + \gamma_k + \gamma_t + \delta_{jk} Z_{jkt} + e_{jkt} \tag{4}$$

where c_1 represents the effect of the market participation channel on the direction of inter-regional carbon leakage.

In addition, the DDD model used to identify the industrial transfer channel is developed as follows:

$$INTER\_IT_{jkt} = d_0 + d_1 Y{\cdot}R{\cdot}I{\cdot}ES_{jkt} + d_2 Y{\cdot}R{\cdot}I + \gamma_{jk} + \gamma_{jt} + \gamma_{kt} + \gamma_j + \gamma_k + \gamma_t + \delta_{jk} Z_{jkt} + e_{jkt} \tag{5}$$

$$INTER_{jkt} = e_0 + e_1 Y{\cdot}R{\cdot}I{\cdot}ES_{jkt} + e_2 Y{\cdot}R{\cdot}I_{jkt} + e_3 INTER\_IT_{jkt} + \gamma_{jk} + \gamma_{jt} + \gamma_{kt} + \gamma_j + \gamma_k + \gamma_t + \delta_{jk} Z_{jkt} + e_{jkt} \tag{6}$$

In Formulas (5) and (6), ES and $INTER\_IT$ represent economic scale and inter-regional industrial transfer, respectively; d_1 measures the moderating effect of economic scale on the inter-regional industrial transfer channel, and e_1 measures the moderating effect of economic scale on the direction of inter-regional carbon leakage. Finally, e_3 measures the effect of the inter-regional industrial transfer channel on the direction of inter-regional carbon leakage. The moderating effects of the industrial transfer channel and economic scale can be tenable, if and only if all of d_1, e_1 and e_3 are significant.

3.4. Variables and data

Carbon emissions in this study are calculated based on the consumption of 19 forms of energy [72]. Table 2 summarizes the controlled variables and other variables used in this study. Among these, some of the factors that influence carbon transfer are set as controlled variables, and these include carbon intensity (*CI*) and economic growth (*EGR*). Existing literature confirms the significant effect of carbon intensity on carbon transfer [73] and has also established that regions and sectors with faster economic growth will receive more carbon transfer [74]. Carbon intensity is defined as the ratio of carbon emissions and output value, while economic growth is measured as the rate of output value.

Table 2
Controlled variables and other variables in this study.

Variables	Variable meanings	Calculation methods	Units
CI	Carbon intensity	Ratio of carbon emissions and output value	10^{-4} tons/yuan
EGR	Economic growth	Rate of output value	%
MP	Market participation	Ratio of trading amount to quota amount in the emission trading market	%
INTER_IT	Inter-regional industrial transfer	Sector' s inter-regional output value transfer between provinces	10^8 yuan
INTRA_IT	Intra-regional industrial transfer	Sector' s intra-regional output value transfer between provinces	10^8 yuan
TOTAL_IT	Total industrial transfer	Sector' s total output value transfer between provinces	10^8 yuan
ES	Economic scale	Natural logarithm of output value	–

Sources: The authors drew this table.

Other variables used in this study include market participation (*MP*), industrial transfer (*IT*), and economic scale (*ES*). To evaluate market participation, Yi et al. (2020) adopt three indicators, namely the concentration of transaction volume, the concentration of trading volume, and the proportion of effective trading days [75]. This study chooses the ratio of trading amount to quota amount as an indicator. This indicator is chosen because the oversupplied quota amount is the main reason for the low trading amount and market participation. Industrial transfer is defined as a sector's output value transfer between provinces, and is calculated by SSM. Similar to carbon transfer, the total industrial transfer (*TOTAL_IT*) is decomposed into the inter-regional industrial transfer (*INTER_IT*) and inter-regional industrial transfer (*INTRA_IT*). Economic scale is represented by the natural logarithm of output value [76].

Study data from 1997 to 2016 were collected from six major sectors, including (a) farming, forestry, animal husbandry, fishery, and water conservancy; (b) industry; (c) construction; (d) transport, storage, postal, and telecommunications services; (e) wholesale, retail trade, and catering services, and (f) other sectors in China's 30 provinces (except Tibet, Hong Kong, Macao, and Taiwan). All data were collected from the China Statistical Yearbook, China Industry Economy Statistical Yearbook, China Energy Statistical Yearbook, China Statistical Yearbook on the Environment, and provincial statistical yearbooks. The data pertaining to the market participation of emission trading pilots were all collected from the Environomist China Carbon Market Research Report 2016 & 2017. All price-specific data were adjusted to year-2000 levels, to eliminate the influence of price fluctuations.

4. Empirical results and discussion

4.1. Inter-regional, intra-regional and total industrial net carbon transfers

For Formula (1), Figs. 2 and 3 present inter-regional, intra-regional and total industrial net carbon transfers before and after the existence of emission trading pilots, respectively. The periods are from 1998 to 2013, and 2014–2016, respectively. More detailed information is provided in Appendix Tables A, B and C. Formula (1) shows that the SSM is an elementary algebra method, which indicates that this study can conclude the precise results of net carbon transfers, without standard deviations.

During the periods from 1998 to 2013 and 2014–2016, inter-regional industrial net carbon transfers are almost all negative in all pilot provinces, while in non-pilot provinces, the net carbon transfers are almost all positive. A significant amount of industrial net carbon transfers were received in non-pilot provinces from pilot ones. However, the amount of carbon transfers was exceptionally weak from 2014 to 2016. The pilot region incorporates China's political and cultural center (Beijing), economic center (Shanghai) and the province with the highest output value of service sectors (Guangdong). The consumption of coal, electric power, and other carbon-intensive production, which supported the rapid economic growth of these developed provinces, are factored in. Most of the energy sources were largely provided by the non-pilot region.

Intra-regional industrial net carbon transfers are closely related to a province's own industrial structure and resource endowment. The pilot regions of Chongqing, Guangdong, Hubei and Tianjin, all of which retain an advantage in their proportions of industry, received carbon transfers from Beijing and Shanghai during the study period. The non-pilot regions of Fujian, Jiangsu and Shandong (which enjoy relatively larger

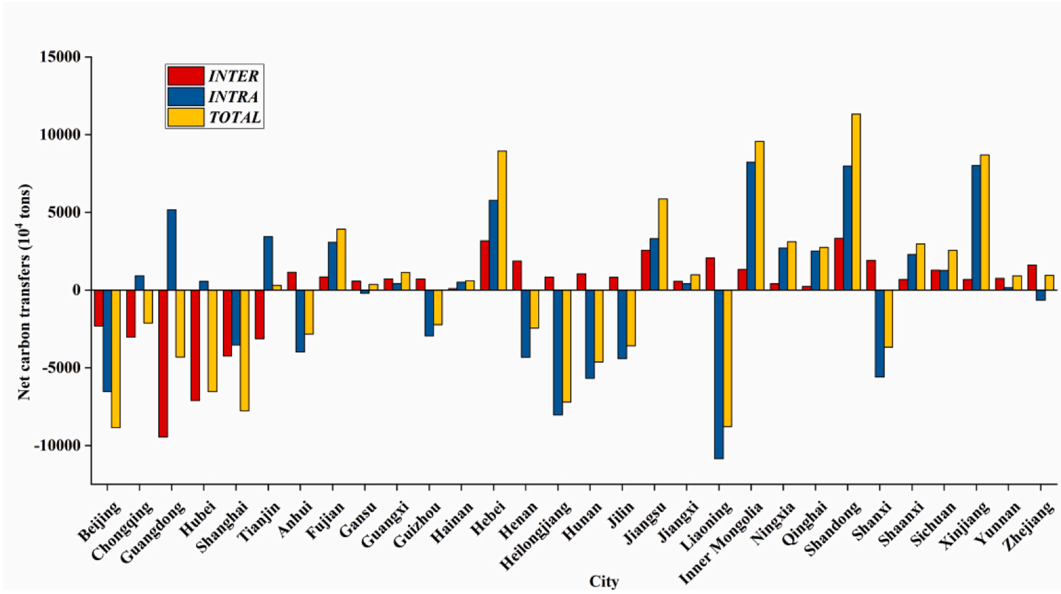

Fig. 2. Inter-regional, intra-regional and total industrial net carbon transfers from 1998 to 2013.

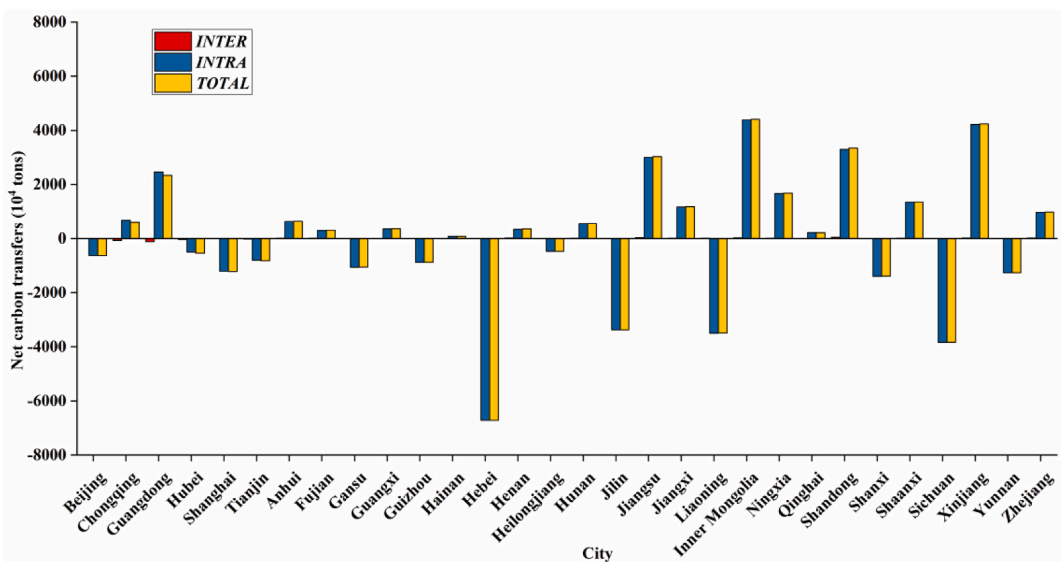

Fig. 3. Inter-regional, intra-regional and total industrial net carbon transfers from 2014 to 2016.

industrial scales), together with Inner Mongolia, Ningxia, Shaanxi and Xinjiang (all of which are coal-rich) received a large number of carbon transfers from the other non-pilot provinces.

Total industrial net carbon transfer directions mostly correspond with intra-regional industrial net carbon transfer directions in non-pilot provinces. Meanwhile, in pilot provinces, inconsistencies were noted in Chongqing, Guangdong and Hubei during the years from 1998 to 2013. When looking at all provinces as a whole, the total industrial net carbon transfer directions in some provinces switched during the sample period. For example, the transfer directions in Tianjin, Gansu, Hebei, Sichuan and Yunnan switched from inward to outward, while in Chongqing, Guangdong, Anhui, Henan and Hunan, the opposite occurred. Taken together, the industrial net carbon transfers calculated by SSM are in line with the situation in reality, as well as with the findings of Zhang et al. (2014) [49], which adopted a similar calculating method (using SSM).

4.2. *Carbon leakage directions*

4.2.1. *Inter-regional, intra-regional and total carbon leakage directions*

Table 3 provides the results of inter-regional, intra-regional and total carbon leakage directions using Formula (3). This study examines whether the coefficients of the $Y*R*I$ variable are significantly positive or negative. A significantly positive coefficient indicates reverse carbon leakage; a significantly negative coefficient indicates forward carbon leakage.

Whether controlled variables are added or not, the coefficients of the $Y*R*I$ variable are significantly positive in Columns (1) (2) (7) and (8). This finding indicates that emission trading pilots have led to inter-regional reverse carbon leakage from non-pilot regions to pilot regions and total reverse carbon leakage. To the best of our knowledge, this is the first finding related to reverse carbon leakage. One plausible explanation for the reverse direction is that market participation in pilot markets is at a low level. This implies that emitters receive so many free emission quotas that they can expand their production scales accordingly. As such, the result is more emissions and reverse carbon leakage in pilot provinces. This study will empirically study how the leakage direction is determined in Section 4.3.

For the country as a whole, the current reverse carbon leakage may actually promote carbon emission mitigation in China. Pilot provinces have relatively advanced production technologies and emission reduction technologies available to them [77]. Therefore, the carbon emission growth rate of the whole country may be reduced as a result. Emission trading, essentially a market-based emission mitigation policy, can also reduce mitigation costs [78]. Therefore, reverse carbon leakage can more effectively, and to a greater extent, reduce mitigation costs for the whole country.

The violation of SUTVA in Formula (3) may nullify the results related to intra-regional carbon leakage in Columns (3) and (4). The coefficients of the *Y*R*I* variable in Columns (3) and (4) (specifically −14.14 and −13.76, respectively) were not significant and statistically negated intra-regional carbon leakage. However, the spillovers of intra-regional carbon leakage (supposing the spillovers did exist), made them different, in that the effects on industrial net carbon transfers in each of the pilot provinces, as well as intra-regional carbon leakage, may not be captured by the DDD model.

To reconfirm the existence or otherwise of intra-regional carbon leakage, this study replaces *INTRA* with the absolute values of itself, namely $|INTRA|$. Then, intra-regional carbon leakage is re-identified, using Formula (3). Columns (5) and (6) in Table 3 show the results, whereby the coefficients of the *Y*R*I* variable are significantly negative and robust. This finding indicates that intra-regional carbon leakage indeed exists and that it weakens intra-regional industrial net carbon transfers. Consequently $|INTRA|$ is consistently adopted as the dependent variable in later sections, when intra-regional carbon leakage is studied.

4.2.2. The heterogeneity of carbon leakage directions in pilot provinces

Pilot provinces may contribute heterogeneously to carbon leakage directions, since no unified emission trading market has been established thus far [17].

The province dummy variable *R* in *Y*R*I* was separated into six dummy variables representing six pilot provinces, so that *Y*R*I* was separated to *Y*BJ*I*, *Y*CQ*I*, *Y*GD*I*, *Y*HB*I*, *Y*SH*I* and *Y*TJ*I*. These variables represent the effects of emission trading pilots in Beijing, Chongqing, Guangdong, Hubei, Shanghai and Tianjin, respectively, on carbon leakage directions. Table 4 provides the regression results.

In Columns (1) and (2), only the *Y*GD*I* and *Y*HB*I* coefficients are significant and robust. This finding indicates that emission trading pilots in Guangdong and Hubei aggravated inter-regional reverse carbon leakage, while the others did not. In Columns (3) and (4), the *Y*BJ*I* and *Y*HB*I* coefficients are negative and pass the significance tests. This result shows that Beijing and Hubei weaken intra-regional industrial net carbon transfers. Columns (5) and (6) provide evidence that Guangdong was the sole contributor to total reverse carbon leakage from the positive and robust coefficients of *Y*GD*I*. This study will further examine the reasons for this heterogeneity in Section 4.3.

4.2.3. Robustness tests

The robustness of the above results needs to be further tested; therefore, this paper conducts two vital robustness tests.

Pre-existing trend test: This paper tests whether or not the control and treatment group selection, as well as the DDD model, effectively addresses pre-existing different trends. Following the example set by Greenstone and Hanna (2014) [79], the year trend dummy variable *Trend* is added into Formula (3). The new model, as per Formula (7), can show the existence of pre-existing trends. If the signs of the coefficients of *Y*R*I* are inconsistent with the signs in Table 1, the trend was different before the pilot, across both pilot and non-pilot regions. This was not addressed in Formula (3) and led to biased identifications of carbon leakage directions.

$$INTER_{jkt} = f_0 + f_1 Y\cdot R\cdot I_{jkt} + f_2 Trend_{jkt} + \gamma_{jk} + \gamma_{jt} + \gamma_{kt} + \gamma_j + \gamma_k + \gamma_t + \delta_{jk} Z_{jkt} + e_{jkt} \tag{7}$$

Here, *Trend* in Formula (7) ranges from −16 (for 16 years before the pilot commenced in a province) through 2 (for 2 years after the pilot was implemented in a province), and is set as 0 for the year 2014. Also, *Trend* is set as 0 for non-pilot provinces.

Table 5 provides the results of the pre-existing trend test. The *Trend* coefficients are highly significant, showing a pre-existing different trend. Also, the signs of the *Y*R*I* coefficients are consistent with those in Table 3. The test results ensure the robustness of the carbon leakage directions in Section 4.2.1, the control and treatment group selection, as well as the DDD model, thereby effectively addressing the pre-existing different trend issue.

Falsification test. The NDRC issued the *Notice on carbon emission trading pilot systems* in October 2011. Consequently, industrial enterprises in pilot provinces could apply active and additional measures to mitigate emissions (prior to 2014). These measures could be taken, either to avoid being included in the trader list, or to prepare for emission trading pilots. A falsification test can help to observe whether or not this possibility exists. Retaining only the samples from 1997 to 2013, and setting 2012 as the first year of emission trading pilots, this study re-regresses Formula (3).

The result in Table 6 illustrates that the *Y*R*I* coefficients are as highly significant as the ones in Table 3. However, all of the signs became the opposite, indicating that there is forward inter-regional and total carbon leakage. Also there is intra-regional carbon leakage, which strengthens intra-regional industrial net carbon transfers. Some industrial enterprises in pilot provinces may take measures after the *Notice on carbon emission trading pilot systems*, thereby leading to extra carbon transfers to other provinces.

Inter-regional, intra-regional, and total carbon leakage before 2014 did, indeed, exist. That said, the carbon leakage before 2014 was not the outcome of emission trading pilots. Therefore, setting 2014 as the first

Table 3
Inter-regional, intra-regional and total carbon leakage directions.

Variables	*INTER*		*INTRA*		$\|INTRA\|$		*TOTAL*	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
*Y*R*I*	370.87***	370.20***	−14.14	−13.76	−208.01**	−207.40**	370.87**	356.06**
	(9.01)	(8.99)	(-0.11)	(-0.12)	(-2.10)	(-2.09)	(2.59)	(2.51)
_cons	−0.25***	−2.48***	−82.34	−82.37	−53.91	−54.76	−18.61	−84.83
	(-5.02)	(-5.15)	(-0.35)	(-1.52)	(-1.37)	(-1.37)	(-0.33)	(-1.49)
Fix effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controlled variables	No	Yes	No	Yes	No	Yes	No	Yes
A-R^2	0.16	0.16	0.02	0.02	0.37	0.37	0.31	0.33

Notes: t values are shown in brackets; ***, **, * indicate statistical significance at 1%, 5% and 10% levels, respectively.
Sources: The authors developed this table based on empirical results.

Table 4
The heterogeneity of carbon leakage directions.

Variables	*INTER*		*|INTRA|*		*TOTAL*	
	(1)	(2)	(3)	(4)	(5)	(6)
*Y*BJ*I*	29.35	30.06	−77.34*	−77.47*	44.82	60.40
	(0.85)	(0.87)	(-1.84)	(-1.84)	(0.38)	(0.51)
*Y*CQ*I*	28.55	28.67	40.22	37.87	58.33	56.59
	(0.82)	(0.83)	(0.49)	(0.46)	(0.49)	(0.48)
*Y*GD*I*	85.80**	85.18**	−29.47	−29.34	235.02**	221.57*
	(2.47)	(2.45)	(-0.36)	(0.36)	(1.97)	(1.87)
*Y*HB*I*	92.24***	92.39***	−139.39*	−140.22*	−9.32	−7.55
	(2.66)	(2.66)	(-1.69)	(-1.70)	(-0.08)	(-0.06)
*Y*SH*I*	55.17	55.07	−55.80	−54.96	18.22	17.40
	(1.59)	(1.59)	(-0.68)	(-0.67)	(0.15)	(0.15)
*Y*TJ*I*	35.80	36.16	−61.92	−62.46	−20.15	−13.43
	(1.03)	(1.04)	(-0.75)	(-0.76)	(-0.17)	(-0.11)
_cons	2.21*	−0.76	−55.01	−55.50	−16.66	−82.99
	(1.88)	(-0.05)	(-1.40)	(-1.39)	(-0.29)	(-1.45)
Fix effects	Yes	Yes	Yes	Yes	Yes	Yes
Controlled variables	No	Yes	No	Yes	No	Yes
A-R^2	0.14	0.14	0.37	0.37	0.31	0.33

Notes: t values are shown in brackets; ***, **, * indicate statistical significance at 1%, 5% and 10% levels, respectively.
Sources: The authors developed this table based on empirical results.

Table 5
Pre-existing trend test.

Variables	*INTER*	*|INTRA|*	*TOTAL*
*Y*R*I*	814.62***	−520.40***	524.20***
	(15.40)	(-4.34)	(3.08)
Trend	−47.00***	32.89***	−27.61**
	(-15.32)	(4.61)	(-2.73)
_cons	−9.86	−46.58	−71.53
	(-0.63)	(-1.19)	(-1.29)
Fix effects	Yes	Yes	Yes
Controlled variables	Yes	Yes	Yes
A-R^2	0.22	0.38	0.33

Notes: t values are shown in brackets; ***, **, * indicate statistical significance at 1%, 5% and 10% levels, respectively.
Sources: The authors developed this table based on empirical results.

Table 6
Falsification test.

Variables	*INTER*	*|INTRA|*	*TOTAL*
*Y*R*I*	−741.88***	236.25***	−644.74***
	(-14.07)	(1.99)	(-3.78)
_cons	−2.776	−35.47	−69.80
	(-0.16)	(-0.85)	(-1.17)
Fix effects	Yes	Yes	Yes
Controlled variables	Yes	Yes	Yes
A-R^2	0.26	0.38	0.35

Notes: t values are shown in brackets; ***, **, * indicate statistical significance at 1%, 5% and 10% levels, respectively.
Sources: The authors developed this table based on empirical results.

year of emission trading pilots provides a high level of accuracy for identifying carbon leakage direction.

4.3. Carbon leakage channels

What drives reverse carbon leakage in China's emission trading pilots? Why are the carbon leakage directions different in different pilot provinces? In terms of reverse direction being counter-intuitive, the answers to the above questions are valuable, and can help better understand reverse carbon leakage. Following the existing literature dealing with carbon leakage channels (which this paper reviews in Section 2.2), this study assumes that carbon leakage channels may be the driving factor, and then identifies market participation and industrial transfer channels using Formulas (4) (5) and (6).

4.3.1. Market participation channel

This study examines whether the coefficients of the *MP* variable are significantly positive or negative. A significantly positive coefficient indicates that market participation leads to reverse carbon leakage, while a significantly negative coefficient indicates that market participation leads to forward carbon leakage. Table 7 provides the identifying results in the market participation channel. For intra-regional carbon leakage, only the market participation channel is identified. To be specific, the *MP* coefficient in Column (2) is significantly negative, indicating that intra-regional carbon leakage will emerge, due to improved market participation. This will also weaken intra-regional carbon leakage. This can help explain why only the pilots in Beijing and Hubei, with all the participation levels of their markets being higher than the average of the six pilots (as shown in Fig. 4), have led to intra-regional carbon leakage.

On the contrary, an improvement of market participation at this stage will not lead to inter-regional and total carbon leakage. In terms of Columns (1) and (3), neither of the *MP* coefficients is significant. However, the results do not deny the existence of market participation channel, because only the linear relationship between market participation and carbon leakage direction is denied in Columns (1) and (3).

This paper further explores whether a non-linear relationship exists between carbon leakage direction and market participation, drawing on the environmental Kuznets curve and Potter hypothesis.[4] Specifically, the variable MP^2 has been added into Formula (4) as an independent variable. The coefficients of *MP* and MP^2 in Columns (4) and (6) are significantly positive and negative, respectively. Inter-regional and total carbon leakage will switch from a reverse direction to a forward direction as market participation increases, and the switch points are 5.52% and 4.26%,[5] respectively (as shown in Figs. 5 and 6). When the ratio of the trading amount to the quota amount is lower than these two switch

[4] The environmental Kuznets curve means that, with an increase of income per capita, environmental pollution will show an inverted U-type curve, which first increases and then decreases [80]. The Potter hypothesis holds the view that strict environmental regulations can induce efficiency and encourage innovations in regulated enterprises [81].

[5] According to the results in Columns (4) and (6), the market participation levels on the inflection points of inverted U-type curves are 2.76% and 2.13%, respectively. The market participation levels on the switch points are twice as high as those on the inflection points, at 5.52% and 4.26%, respectively.

Table 7
Channel tests of market participation.

Variables	*INTER*	*|INTRA|*	*TOTAL*	*INTER*	*|INTRA|*	*TOTAL*
	(1)	(2)	(3)	(4)	(5)	(6)
MP	82.28	−83.04**	37.78	260.39***	−52.81	333.12**
	(1.25)	(-2.22)	(0.70)	(5.44)	(-0.46)	(2.03)
MP^2				−47.21***	−8.01	−78.27*
				(-3.94)	(-0.28)	(-1.90)
_cons	81.58	−54.92	−83.57	−1.86	−54.96	−84.03
	(1.09)	(-1.38)	(-1.46)	(-0.11)	(-1.38)	(-1.47)
Inflection point				2.76		2.13
Fix effects	Yes	Yes	Yes	Yes	Yes	Yes
Controlled variables	Yes	Yes	Yes	Yes	Yes	Yes
A-R^2	0.16	0.37	0.34	0.15	0.37	0.33

Notes: t values are shown in brackets; ***, **, * indicate statistical significance at 1%, 5% and 10% levels, respectively. The units of inflections are written as %.
Sources: The authors developed this table based on empirical results.

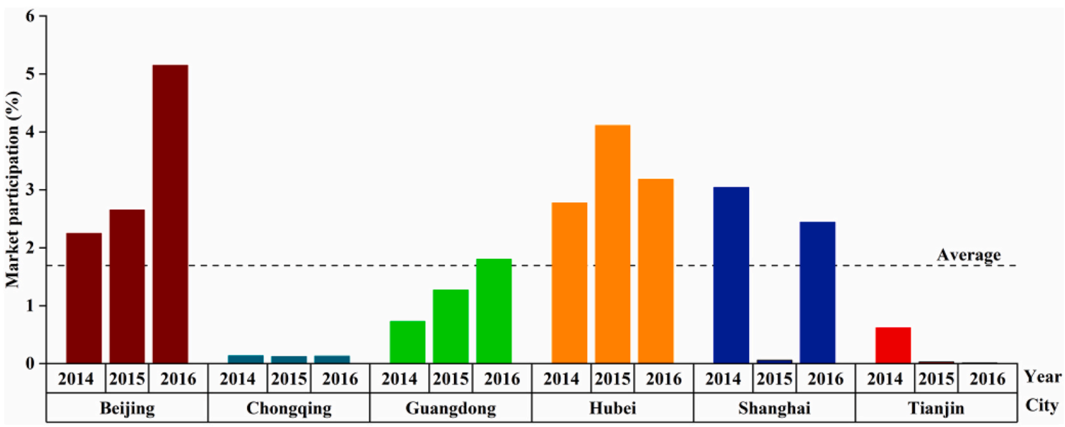

Fig. 4. The participation of pilot markets.

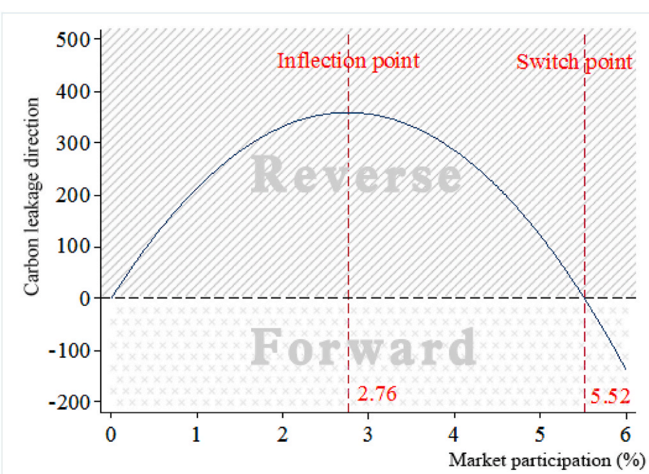

Fig. 5. Inter-regional carbon leakage direction switch caused by market participation.

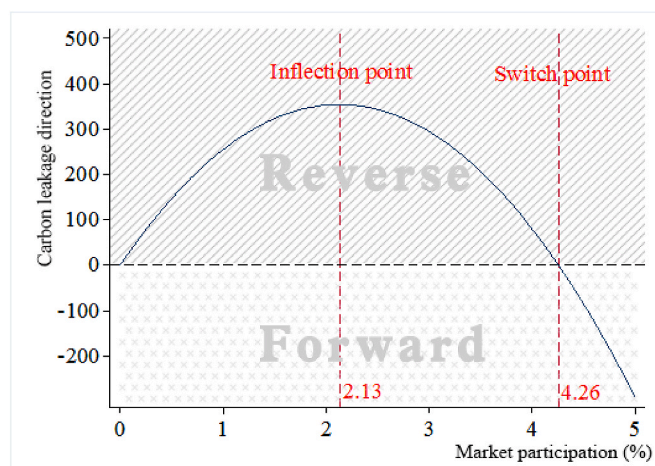

Fig. 6. Total carbon leakage direction switch caused by market participation.

points, then both inter-regional and total reverse carbon leakage will occur. When the ratio exceeds these two switch points, inter-regional and total forward carbon leakage may emerge. At the same time, no such inverted U-type relationship exists between intra-regional carbon leakage and market participation, as Column (5) demonstrates.

The market participation of each pilot was basically lower than the switch point. Thus, current emission trading pilots lead to inter-regional and total reverse carbon leakage. In addition, the market participation levels of some pilots were close to 0 or to the switch points. Therefore, carbon leakage directions in these pilots are not significant.

What requires explanation is why inter-regional and total carbon leakage have an inverted U-type relationship with market participation. In the initial stage of emission trading pilots, market managers may issue a large number of free emission quotas and financial subsidies, in order to attract emitters to engage in market transactions. However, emitters may then expand their production scales accordingly and decrease investment in emission mitigation. These actions result in reverse carbon leakage. With rising market participation, some emitters, who are still able to afford the carbon price at this time, may use budgetary funds

Table 8
Channel tests of industrial transfers.

Variables	*INTER_IT*	*|INTRA_IT|*	*TOTAL_IT*	*INTER*	*|INTRA|*	*TOTAL*
	(1)	(2)	(3)	(4)	(5)	(6)
*Y*R*I*ES*	47.63***	−22.78	69.54***	791.46**	151.51	172.23*
	(9.03)	(-1.35)	(3.22)	(1.99)	(1.46)	(1.94)
*Y*R*I*	−349.25***	179.62	−548.87***	−54.58	−1541.35	−1289.42
	(-7.32)	(1.18)	(-2.81)	(-1.23)	(-1.64)	(-0.96)
INTER_IT				0.88***		
				(6.16)		
|INTRA_IT|					1.14***	
					(10.65)	
TOTAL_IT						1.26***
						(10.58)
_cons	−0.56	5.07	−14.56*	−2.00	−60.41	−66.27
	(-0.28)	(0.80)	(-1.79)	(-0.12)	(-1.54)	(-1.18)
Fix effects	Yes	Yes	Yes	Yes	Yes	Yes
Controlled variables	Yes	Yes	Yes	Yes	Yes	Yes
A-R^2	0.14	0.35	0.18	0.17	0.39	0.16

Notes: t values are shown in brackets; ***, **, * indicate statistical significance at 1%, 5% and 10% levels, respectively.
Sources: The authors developed this table based on empirical results.

originally intended for technological innovation to purchase quotas. In this case, the level of reverse carbon leakage will further deteriorate. After the level of market participation exceeds the switch point, emitters will more actively participate in market transactions, thus bringing about higher carbon prices. Eventually, the higher prices will exceed the costs of emission mitigation technology. Investment in technology innovation and reduction in production scale are the two choices for emitters. However, both these courses of action will ultimately lead to inter-regional and total forward carbon leakage.

4.3.2. *Industrial transfer channel*

This study examines whether the coefficients of the *Y*R*I*ES* variable are significantly positive or negative. A significantly positive coefficient indicates that industrial transfers lead to reverse carbon leakage, while a significantly negative coefficient indicates that market participation leads to forward carbon leakage. Table 8 presents the identifying results in the industrial transfer channel. The presence of an intra-regional industrial transfer channel was not verified for the not significant *Y*R*I*ES* coefficients in Columns (2) and (5). Emission trading pilots may weaken intra-regional industrial net carbon transfers through other channels, such as technological innovation.

Pilot provinces with larger industrial scales will receive more reverse carbon leakage through industrial transfers. To be specific, the *Y*R*I*ES* coefficients in Columns (1) and (3) are significantly positive, thereby indicating that provinces with larger industrial scales receive more industrial transfers from non-pilot regions. The *INTER_IT* and *TOTAL_IT* coefficients in Columns (4) and (6) are significantly positive, thereby revealing that industrial transfers lead to inter-regional and total reverse carbon leakage.

Fig. 7 shows the industrial scale of each pilot province. Guangdong and Hubei are leading in terms of industrial scale and exceed the average of the six pilots. These are also the only two pilot provinces that received reverse carbon leakage.

The promotion of reverse carbon leakage in industrial transfers may be rooted in the current loosely-regulated issuance of emission quotas. In order to stimulate emitters' enthusiasm for participating in emission trading pilots and to maintain the current trend of economic growth, market managers in pilots issue emission quotas with considerable redundancies. For example, the annual quotas in Guangdong and Hubei are equal to approximately 400 million tons and 324 million tons, respectively. The annual industrial carbon emissions since 2014 in the same two provinces are approximately 350 million tons and 220 million tons, respectively. These redundancies objectively reduce the pressure of emission mitigation in pilots and promote industrial transfers from non-pilot provinces to pilot provinces [28,82–84]. In addition, according to FEH, large-scale provinces have advantages in terms of factor endowment and industrial base, which will naturally become the preferred destination for industrial transfers.

5. Conclusions and policy implications

Based on the calculations of inter-regional, intra-regional, and total industrial net carbon transfers in China by SSM, this paper adopts a DDD model to separate the carbon leakage caused by emission trading pilots

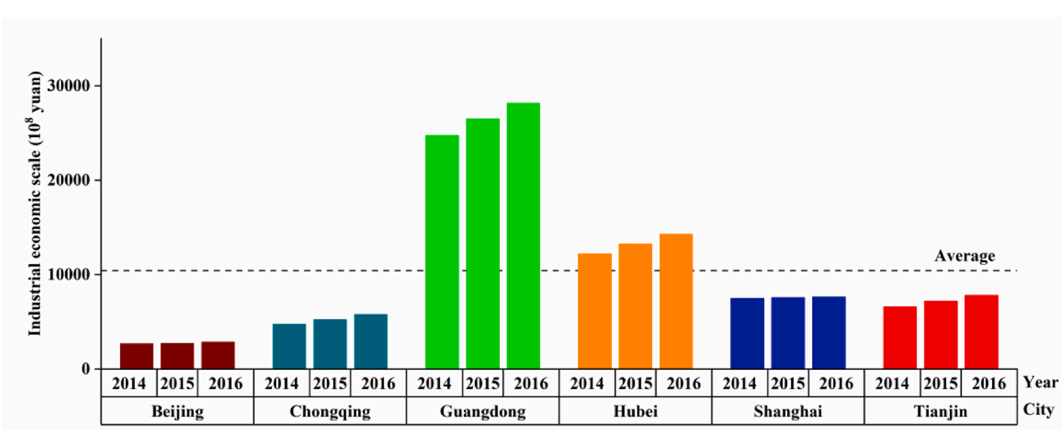

Fig. 7. Industrial economic scale of pilot provinces from 2014 to 2016.

from net carbon transfers. Carbon leakage directions are identified, as well as market participation and industrial transfer channels. The main conclusions are summarized as follows:

Firstly, emission trading pilots lead to reverse carbon leakage, which moves from the non-pilot region to the pilot region. Emission trading pilots also lead to intra-regional carbon leakage, thereby weakening the net carbon transfers between pilot provinces. Total reverse carbon leakage emerges as a direct result of emission trading pilots.

Secondly, the direction of inter-regional and total carbon leakage is enormously dependent on the market participation in emission trading. As market participation levels improve, the direction of inter-regional and total carbon leakage will gradually switch from reverse to forward; the switch points are at market participation levels of 5.52% and 4.26%, respectively. Furthermore, promoting market participation will cause intra-regional carbon leakage, which will monotonically decrease intra-regional net carbon transfers.

Finally, inter-regional and total reverse carbon leakage scales rely on industrial transfer channels. Provinces with larger industrial scales will receive more industrial transfers from non-pilot provinces, which in turn will lead to more inter-regional and total reverse carbon leakage. Conversely, industrial transfer channels did not exist in intra-regional carbon leakage during the period covered by this study.

Based on the above conclusions, this paper also scrupulously proposes several recommendations on how to avoid carbon leakage in emission trading. First of all, it is recommended to introduce real-time supporting policies related to carbon leakage in emission trading markets. When market participation rises to the switch point, some policies (such as border tax adjustment) should immediately be put into effect to mitigate and prevent forward carbon leakage. Secondly, it is recommended that countries and regions involved in emission trading – and which have relatively large economic scales and low market participation levels – should further strengthen their governmental support for the research and development of emission mitigation technologies. Such countries and regions may already be in trouble with their emission mitigation efforts, due to reverse carbon leakage. Local governments could also support the research and development of new technologies by means of carbon price protection, which would at least partially relieve reverse carbon leakage. Last but not the least, it is recommended that emission quotas should be limited at the initial stage of emission trading. Our research shows that quota redundancy may be the main cause low levels of market participation, and for industrial transfers. Reasonable quota allocations will help achieve an emission mitigation effect [85], while at the same time avoiding both forward and reverse carbon leakage.

Credit author statement

Bo Zhou: Methodology, Software, Data, Writing, Cheng Zhang: Conceptualization, Writing, Editing. Qunwei Wang: Investigation, Reviewing and Editing, Supervision. Dequn Zhou: Conceptualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study is grateful for financial support provided by the National Natural Science Foundation of China (grant numbers: 71922013, 71834003, 71804189 & 71703065).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2020.110090.

Appendix

Table A
Inter-regional industrial carbon transfers

Regions	Provinces	1998–2013		2014–2016		Regions	Provinces	1998–2013		2014–2016	
		Transfer	Percentage	Transfer	Percentage			Transfer	Percentage	Transfer	Percentage
Pilots	Beijing	−2309.34	−41.33%	2.03	0.05%	Non-pilots	Hunan	1041.28	14.03%	8.55	0.05%
	Chongqing	−3031.34	−55.69%	−70.87	−0.62%		Jilin	825.01	14.53%	−4.18	−0.03%
	Guangdong	−9464.57	−86.17%	−118.65	−0.35%		Jiangsu	2555.24	18.32%	28.94	0.05%
	Hubei	−7107.09	−68.52%	−39.35	−0.17%		Jiangxi	564.01	15.82%	9.94	0.08%
	Shanghai	−4233.40	−55.62%	−6.84	−0.06%		Liaoning	2063.67	13.58%	9.21	0.03%
	Tianjin	−3127.98	−81.31%	−20.07	−0.16%		Inner Mongolia	1330.30	26.12%	22.30	0.07%
Non-pilots	Anhui	1143.84	13.40%	11.13	0.05%		Ningxia	410.70	31.27%	10.09	0.10%
	Fujian	845.58	23.23%	10.12	0.05%		Qinghai	242.98	23.66%	3.84	0.06%
	Gansu	579.97	14.72%	4.81	0.04%		Shandong	3337.09	19.98%	47.72	0.07%
	Guangxi	710.30	16.62%	5.40	0.04%		Shanxi	1922.36	18.26%	6.25	0.02%
	Guizhou	709.70	18.08%	2.00	0.02%		Shaanxi	683.41	15.30%	11.05	0.07%
	Hainan	93.76	17.25%	1.09	0.05%		Sichuan	1287.20	14.49%	7.73	0.03%
	Hebei	3177.24	20.98%	3.54	0.01%		Xinjiang	679.23	21.01%	19.11	0.09%
	Henan	1870.06	18.70%	15.49	0.05%		Yunnan	754.91	16.71%	1.37	0.01%
	Heilongjiang	834.54	10.12%	2.25	0.02%		Zhejiang	1611.33	20.18%	16.01	0.05%

Table B
Intra-regional industrial carbon transfers

Regions	Provinces	1998–2013 Transfer	1998–2013 Percentage	2014–2016 Transfer	2014–2016 Percentage	Regions	Provinces	1998–2013 Transfer	1998–2013 Percentage	2014–2016 Transfer	2014–2016 Percentage
Pilots	Beijing	−6540.73	−117.06%	−627.04	−16.15%	Non-pilots	Hunan	−5674.54	−76.48%	546.05	3.19%
	Chongqing	906.60	16.66%	677.33	5.91%		Jilin	−4418.03	−77.82%	−3372.22	−25.02%
	Guangdong	5157.06	46.95%	2456.73	7.20%		Jiangsu	3314.15	23.77%	3001.19	5.62%
	Hubei	570.93	5.50%	−499.60	−2.22%		Jiangxi	413.98	11.61%	1163.20	9.12%
	Shanghai	−3538.31	−46.49%	−1208.07	−9.81%		Liaoning	−10843.39	−71.33%	−3500.67	−10.18%
	Tianjin	3444.44	89.54%	−799.35	−6.46%		Inner Mongolia	8228.80	161.57%	4386.73	13.62%
Non-pilots	Anhui	−3972.91	−46.55%	627.82	3.10%		Ningxia	2704.48	205.92%	1667.19	17.07%
	Fujian	3074.99	84.47%	299.72	1.56%		Qinghai	2509.35	244.33%	219.51	3.21%
	Gansu	−207.58	−5.27%	−1061.36	−8.80%		Shandong	7983.93	47.79%	3299.96	4.58%
	Guangxi	425.51	9.96%	361.57	2.44%		Shanxi	−5594.15	−53.13%	−1401.19	−4.36%
	Guizhou	−2941.39	−74.94%	−883.52	−8.42%		Shaanxi	2288.57	51.25%	1340.43	7.99%
	Hainan	504.01	92.73%	79.69	3.82%		Sichuan	1267.03	14.26%	−3841.34	−13.99%
	Hebei	5775.41	38.14%	−6717.67	−10.86%		Xinjiang	8016.25	247.98%	4217.74	19.46%
	Henan	−4317.25	−43.16%	343.38	1.01%		Yunnan	160.51	3.55%	−1266.34	−8.19%
	Heilongjiang	−8036.90	−97.49%	−473.29	−3.79%		Zhejiang	−660.87	−8.28%	963.42	3.18%

Table C
Total industrial carbon transfers.

Regions	Provinces	1998–2013 Transfer	1998–2013 Percentage	2014–2016 Transfer	2014–2016 Percentage	Regions	Provinces	1998–2013 Transfer	1998–2013 Percentage	2014–2016 Transfer	2014–2016 Percentage
Pilots	Beijing	−8850.07	−158.39%	−625.01	−16.10%	Non-pilots	Hunan	−4633.26	−62.45%	554.60	3.24%
	Chongqing	−2124.74	−39.03%	606.46	5.29%		Jilin	−3593.02	−63.29%	−3376.40	−25.05%
	Guangdong	−4307.51	−39.22%	2338.08	6.85%		Jiangsu	5869.39	42.09%	3030.13	5.67%
	Hubei	−6536.16	−63.02%	−538.95	−2.39%		Jiangxi	977.99	27.43%	1173.14	9.20%
	Shanghai	−7771.71	−102.11%	−1214.91	−9.87%		Liaoning	−8779.72	−57.75%	−3491.46	−10.15%
	Tianjin	316.46	8.23%	−819.42	−6.62%		Inner Mongolia	9559.10	187.69%	4409.03	13.69%
Non-pilots	Anhui	−2829.07	−33.15%	638.95	3.15%		Ningxia	3115.18	237.19%	1677.28	17.17%
	Fujian	3920.57	107.70%	309.84	1.61%		Qinghai	2752.33	267.99%	223.35	3.27%
	Gansu	372.39	9.45%	−1056.55	−8.76%		Shandong	11321.02	67.77%	3347.68	4.65%
	Guangxi	1135.81	26.58%	366.97	2.48%		Shanxi	−3671.79	−34.87%	−1394.94	−4.34%
	Guizhou	−2231.69	−56.86%	−881.52	−8.40%		Shaanxi	2971.98	66.55%	1351.48	8.06%
	Hainan	597.77	109.98%	80.78	3.87%		Sichuan	2554.23	28.75%	−3833.61	−13.96%
	Hebei	8952.65	59.12%	−6714.13	−10.85%		Xinjiang	8695.48	268.99%	4236.85	19.55%
	Henan	−2447.19	−24.46%	358.87	1.06%		Yunnan	915.42	20.26%	−1264.97	−8.18%
	Heilongjiang	−7202.36	−87.37%	−471.04	−3.77%		Zhejiang	950.46	11.90%	979.43	3.23%

Notes: In Tables A, B and C, the units of carbon transfer are 10^4 tons, and the percentages are based on carbon emissions in 1998 and 2014, respectively.

References

[1] IPCC. Climate change 1995: economic and social dimensions of climate change. Cambridge: Cambridge University Press; 1996.
[2] Gerlagh R, Kuik O. Spill or leak? Carbon leakage with international technology spillovers: a CGE analysis. Energy Econ 2014;45:381–8.
[3] Kim M, Kim T. Estimating impact of regional greenhouse gas initiative on coal to gas switching using synthetic control methods. Energy Econ 2016;59:328–35.
[4] Zhang Z. Trade and climate change: focus on carbon leakage, border carbon adjustments and WTO consistency. Found Trends® Microecon 2018;12(1):1–108.
[5] Pethig R. Pollution, welfare, and environmental policy in the theory of comparative advantage. J Environ Econ Manag 1976;2(3):160–9.
[6] Copeland B, Taylor M. North-South trade and the environment. Q J Econ 1994;109 (3):755–87.
[7] Kuik O, Gerlagh R. Trade liberalization and carbon leakage. Energy J 2003;24(3): 97–120.
[8] Balistreri E, Rutherford T. Subglobal carbon policy and the competitive selection of heterogeneous firms. Energy Econ 2012;34(2):S190–7.
[9] Candau F, Dienesch E. Pollution haven and corruption paradise. J Environ Econ Manag 2017;85:171–92.
[10] Antweiler W, Copeland B, Taylor M. Is free trade good for the environment? Am Econ Rev 2001;91(4):877–908.
[11] del Río P. Why does the combination of the European Union Emissions Trading Scheme and a renewable energy target makes economic sense? Renew Sustain Energy Rev 2017;74:824–34.
[12] Keohane N. Cap and trade, rehabilitated: using tradable permits to control US greenhouse gases. Rev Environ Econ Pol 2009;3(1):42–62.
[13] Liu L, Chen C, Zhao Y, et al. China's carbon-emissions trading: overview, challenges and future. Renew Sustain Energy Rev 2015;49:254–66.
[14] Wang K, Zhang X, Yu X, et al. Emissions trading and abatement cost savings: an estimation of China's thermal power industry. Renew Sustain Energy Rev 2016;65: 1005–17.
[15] Yu D, Xu C. Mapping research on carbon emissions trading: a co-citation analysis. Renew Sustain Energy Rev 2017;74:1314–22.
[16] Zhou B, Zhang C, Song H, et al. How does emission trading reduce China's carbon intensity? An exploration using a decomposition and difference-in-differences approach. Sci Total Environ 2019;676:514–23.
[17] Zhang D, Karplus V, Cassisa C, et al. Emissions trading in China: progress and prospects. Energy Pol 2014;75:9–16.
[18] Chen Y. Does a regional greenhouse gas policy make sense? A case study of carbon leakage and emissions spillover. Energy Econ 2009;31(5):667–75.
[19] Huang L, Zhou Y. Carbon prices and fuel switching: a quasi-experiment in electricity market. Environ Resour Econ 2019;72:1–46.
[20] Tan X, Liu Y, Cui J, et al. Assessment of carbon leakage by channels: an approach combining CGE model and decomposition analysis. Energy Econ 2018;74:535–45.
[21] Wang X, Teng F, Wang G, et al. Carbon leakage scrutiny in ETS and non-ETS industrial sectors in China. Resour Conserv Recycl 2018;129:424–31.
[22] Zhang P, Yin G, Duan M. Distortion effects of emissions trading system on intra-sector competition and carbon leakage: a case study of China. Energy Pol 2019; 111126.
[23] Demailly D, Quirion P. CO2 abatement, competitiveness and leakage in the European cement industry under the EU ETS: grandfathering versus output-based allocation. Clim Pol 2006;6(1):93–113.
[24] Kuik O, Hofkes M. Border adjustment for European emissions trading: competitiveness and carbon leakage. Energy Pol 2010;38(4):1741–8.
[25] Monjon S, Quirion P. Addressing leakage in the EU ETS: border adjustment or output-based allocation? Ecol Econ 2011;70(11):1957–71.
[26] Martin R, Muûls M, De Preux L, et al. On the empirical content of carbon leakage criteria in the EU Emissions Trading Scheme. Ecol Econ 2014;105:78–88.
[27] Paroussos L, Fragkos P, Capros P, et al. Assessment of carbon leakage through the industry channel: the EU perspective. Technol Forecast Soc Change 2015;90: 204–19.
[28] Koch N, Mama H. Does the EU Emissions Trading System induce investment leakage? Evidence from German multinational firms. Energy Econ 2019;81: 479–92.

[29] Clò S. Grandfathering, auctioning and carbon leakage: assessing the inconsistencies of the new ETS directive. Energy Pol 2010;38(5):2420–30.
[30] Reinaud J. Issues behind competitiveness and carbon leakages: focus on heavy industry. IEA Information Paper, OECD/IEA; 2008. p. 92–106.
[31] Naegele H, Zaklan A. Does the EU ETS cause carbon leakage in European manufacturing? J Environ Econ Manag 2019;93:125–47.
[32] Montagnoli A, De Vries F. Carbon trading thickness and market efficiency. Energy Econ 2010;32(6):1331–6.
[33] Daskalakis G. On the efficiency of the European carbon market: new evidence from Phase II. Energy Pol 2013;54:369–75.
[34] Zhao X, Jiang G, Nie D, et al. How to improve the market efficiency of carbon trading: a perspective of China. Renew Sustain Energy Rev 2016;59:1229–45.
[35] Zhao X, Wu L, Li A. Research on the efficiency of carbon trading market in China. Renew Sustain Energy Rev 2017;79:1–8.
[36] Fan X, Lv X, Yin J, et al. Quantifying market efficiency of China's regional carbon market by multifractal detrended analysis. Energy Procedia 2018;152:787–92.
[37] Schaeffer R, Leal De Sa A. The embodiment of carbon associated with Brazilian imports and exports. Fuel Energy Abstr 1996;37(3):955–60.
[38] Babiker MH. Climate change policy, market structure and carbon leakage. J Int Econ 2005;65:421–45.
[39] Sinn HW. Public policies against global warming: a supply side approach. Int Tax Publ Finance 2008;15:360–94.
[40] Alexeeva-Talebi V, Böhringer C, Löschel A, Voigt S. The value-added of sectoral disaggregation: implication on competitive consequences of climate change policies. Energy Econ 2012;34:127–42.
[41] Branger F, Quirion P. Climate policy and the 'carbon haven' effect. Wiley Interdiscipl. Rev.: Climate Change 2014;5(1):53–71.
[42] Carbone JC, Rivers N. The impacts of unilateral climate policy on competitiveness: evidence from computable general equilibrium models. Rev Environ Econ Pol 2017;11(1):24–42.
[43] Leontief W. Environmental repercussions and the economic structure: an input–output approach. Rev Econ Stat 1970;52(3):262–71.
[44] Wiedmann T, Lenzen M, Turner K, Barrett J. Examining the global environ-mental impact of regional consumption activities-part 2: review of input-output models for the assessment of environmental impacts embodied in trade. Ecol Econ 2007;61(1): 15–26.
[45] Su B, Ang B. Multi-region input-output analysis of CO2 emissions embodied in trade: the feedback effects. Ecol Econ 2011;71:42–53.
[46] Ning Y, Miao L, Ding T, et al. Carbon emission spillover and feedback effects in China based on a multiregional input-output model. Resour Conserv Recycl 2019; 141:211–8.
[47] Andrew R, Forgie V. A three-perspective view of greenhouse gas emission responsibilities in New Zealand. Ecol Econ 2008;68(1–2):194–204.
[48] Aichele R, Felebermayr G. Kyoto and carbon leakage: an empirical analysis of the carbon content of bilateral trade. Rev Econ Stat 2015;97(1):104–15.
[49] Zhang W, Li F, Hu Y. The study of province transfers and reduction responsibilities of China's CO2 emissions. China Industrial Economics 2014;3:57–69 [In Chinese)].
[50] Sun L, Wang Q, Zhang J. Inter-industrial carbon emission transfers in China: economic effect and optimization strategy. Ecol Econ 2017;132:55–62.
[51] Xie R, Hu G, Zhang Y, et al. Provincial transfers of enabled carbon emissions in China: a supply-side perspective. Energy Pol 2017;107:688–97.
[52] Zhou D, Zhou X, Xu Q, et al. Regional embodied carbon emissions and their transfer characteristics in China. Struct Change Econ Dynam 2018;46:180–93.
[53] Meng J, Zhang Z, Mi Z, et al. The role of intermediate trade in the change of carbon flows within China. Energy Econ 2018;76:303–12.
[54] Pan C, Peters G, Andrew R, et al. Structural changes in provincial emission transfers within China. Environ Sci Technol 2018;52(22):12958–67.
[55] Guan D, Reiner DM. Emissions affected by trade among developing countries. Nature 2009;462:159.
[56] Peters G, Minx J, Weber C, et al. Growth in emission transfers via international trade from 1990 to 2008. Proc Natl Acad Sci Unit States Am 2011;108(21):8903–8.
[57] Fuchs V. The determinants of the redistribution of manufacturing in the United States since 1929. Rev Econ Stat 1962;44(2):167–77.
[58] Norton R, Rees J. The product cycle and the spatial decentralization of American manufacturing. Reg Stud 2007;41(S1):S61–71.
[59] Grossi L, Mussini M. A spatial shift-share decomposition of electricity consumption changes across Italian regions. Energy Pol 2018;113:278–93.
[60] Yang D, Gao X, Xu L, et al. Constraint-adaptation challenges and resilience transitions of the industry–environmental system in a resource-dependent city. Resour Conserv Recycl 2018;134:196–205.
[61] Zhou X, Zhou D, Wang Q. How does information and communication technology affect China's energy intensity? A three-tier structural decomposition analysis. Energy 2018;151:748–59.
[62] Ashenfelter O, Card D. Using the longitudinal structure of earnings to estimate the effect of training programs. Rev Econ Stat 1984;67(4):648–60.
[63] Meyer B. Natural and quasi-experiments in economics. J Bus Econ Stat 1995;13(2): 151–61.
[64] Sunak Y, Madlener R. The impact of wind farm visibility on property values: a spatial difference-in-differences analysis. Energy Econ 2016;55:79–91.
[65] Zhang C, Zhou B, Wang Q. Effect of China's western development strategy on carbon intensity. J Clean Prod 2019;215:1170–9.
[66] Dehejia R, Wahba S. Propensity score-matching methods for nonexperimental causal studies. Rev Econ Stat 2002;84(1):151–61.
[67] Abadie A, Gardeazabal J. The economic costs of conflict: a case study of the Basque Country. Am Econ Rev 2003;93(1):113–32.
[68] Kim D, Suen Y, Lin S. Carbon dioxide emissions and trade: evidence from disaggregate trade data. Energy Econ 2019;78:13–28.
[69] Kahane L, Sannicandro P. The impact of 1998 Massachusetts gun laws on suicide: a synthetic control approach. Econ Lett 2019;174:104–8.
[70] Buscha F, Maurel A, Page L, et al. The effect of employment while in high school on educational attainment: a conditional difference-in-differences approach. Oxf Bull Econ Stat 2012;74(3):380–96.
[71] Moser P, Voena A. Compulsory licensing: evidence from the trading with the enemy act. Am Econ Rev 2012;102(1):396–427.
[72] Zhang C, Wang Q, Shi D. Scenario-based potential effects of carbon trading in China: an integrated approach. Appl Energy 2016;182:177–90.
[73] Su B, Ang B, Low M. Input-output analysis of CO2 emissions embodied in trade and the driving forces: processing and normal exports. Ecol Econ 2013;88:119–25.
[74] Pan W, Pan W, Shi Y, et al. China's inter-regional carbon emissions: an input-output analysis under considering national economic strategy. J Clean Prod 2018; 197:794–803.
[75] Yi L, Liu Y, Li Z, et al. Study on serviceability and efficiency of seven pilot carbon trading exchanges in China. Sci Total Environ 2020;703:135465.
[76] Wooldridge J. Introductory econometrics: a modern approach. Nelson Education; 2015.
[77] Wang Q, Zhao Z, Zhou P, et al. Energy efficiency and production technology heterogeneity in China: a meta-frontier DEA approach. Econ Modell 2013;35: 283–9.
[78] Xian Y, Wang K, Wei Y. Would China's power industry benefit from nationwide carbon emission permit trading? An optimization model-based ex post analysis on abatement cost savings. Appl Energy 2019;235:978–86.
[79] Greenstone M, Hanna R. Environmental regulations, air and water pollution, and infant mortality in India. Am Econ Rev 2014;104(10):3038–72.
[80] Grossman G, Krueger A. Economic growth and the environment. Q J Econ 1995; 110(2):353–77.
[81] Porter M, Van der Linde C. Toward a new conception of the environment-competitiveness relationship. J Econ Perspect 1995;9(4):97–118.
[82] Fujimori S, Masui T, Matsuoka Y. Gains from emission trading under multiple stabilization targets and technological constraints. Energy Econ 2015;48:306–15.
[83] Schmidt R, Heitzig J. Carbon leakage: grandfathering as an incentive device to avert firm relocation. J Environ Econ Manag 2014;67(2):209–23.
[84] Acemoglu D, Aghion P, Bursztyn L, et al. The environment and directed technical change. Am Econ Rev 2012;102(1):131–66.
[85] Bel G, Joseph S. Policy stringency under the European Union Emission trading system and its impact on technological change in the energy sector. Energy Pol 2018;117:434–44.