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Potential gains from carbon emissions trading in China: A DEA based estimation on abatement cost savings

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Abstract: China has recently launched its pilot carbon emissions trading markets. Theoretically, heterogeneity in abatement cost determines the efficiency advantage of market based programs over command and control policies on carbon emissions. This study tries to answer the question that what will be the abatement cost savings or GDP loss recoveries from carbon emissions trading in China from the perspective of estimating the potential gains from carbon emissions trading. A DEA based optimization model is employed in this study to estimate the potential gains from implementing two carbon emissions trading schemes compared to carbon emissions command and control scheme in China. These two schemes are spatial tradable carbon emissions permit scheme and spatial-temporal tradable carbon emissions permit scheme. The associated three types of potential gains, which are defined as the potential increases on GDP outputs through eliminating technical inefficiency, eliminating suboptimal spatial allocation of carbon emissions permit, and eliminating both suboptimal spatial and temporal allocation of carbon emissions permit, are estimated by an ex post analysis for China and its 30 provinces over 2006-2010. Substantial abatement cost savings and considerable carbon emissions reduction potentials are identified in this study which provide one argument for implementing a market based policy instrument instead of a command and control policy instrument on carbon emissions control in China.

Keywords: Carbon emissions; DEA; Emissions trading; Potential gains; Tradable permit

1 Introduction

China is a key player in international climate negotiations since it is the world's largest carbon emitter. As long as climate change continues to be one of the priorities on the international political agenda, China will continue facing enormous domestic pressures to control its carbon emissions and international pressures to commit to a mandatory carbon emissions target (Wei et al, 2014). In the 2009 Copenhagen climate change summit, Chinese government announced a goal to decrease its carbon emissions per unit of GDP (carbon emissions intensity) by 40-45% by 2020 compared with the 2005 level. To achieve this goal, Chinese

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government had implemented several regulations on energy conservation and carbon emissions control since 2006. The 11^{th} Five Year Plan (FYP) (2006-2010), which was adopted as the general guidance for China's economic and social development each five years, had put forward a national target to reduce the energy consumption per unit of GDP (energy consumption intensity) by 20% by the end of 2010 compared with 2005. This energy consumption intensity reduction target was additionally disaggregated and assigned to each province of China, which ranges from 16% to 22% reduction across different provinces. In the 12^{th} FYP (2011-2015), Chinese government further set a target of reducing carbon emissions intensity by 17%, associated with a 16% energy consumption reduction target, by the end of 2015 compared with 2010. These national targets had also been disaggregated and assigned at the regional level for China's provinces as their mandatory energy conservation and carbon emissions reduction constraints over provincial economic development.

To realize the joint goal of economic growth and carbon emissions control, Chinese government is attempting to adopt various policy instruments including command and control policies and market based policies. The national carbon emissions intensity reduction goal and its assignment to China's each province were considered as the command and control policy instrument for carbon emissions reduction which was mainly implemented both in the 11^{th} and 12^{th} FYP periods. Another approach for pollutant emission control is known as market based regulatory strategy that sets the stage for the use of tradable permit system to achieve a reduction in pollutant emission at minimal cost, for example, the U.S. tradable permits program for SO_2 started with the enactment of the Clean Air Act (Sueyoshi and Goto, 2013), and the EU Emissions Trading System (EU ETS) established as a tool for reducing greenhouse gas emissions cost-effectively (Zhu and Wei, 2013). Nevertheless, China has just recently (June of 2013) launched its pilot markets for carbon emissions trading in selected seven provinces/ municipalities (Shenzhen, Beijing, Shanghai, Tianjin, Guangdong, Chongqing and Hubei), and the carbon emissions trading scheme is still at the pilot experiment stage. Although a nationwide carbon emissions trading system has not yet established, with the experiences from the pilot markets, China is prompting to establish a unified national carbon emissions trading system during 2016-2020 (NDRC, 2014).

As pointed out by Färe et al. (2013, 2014), with the implement of tradable permit programs, concerns arise over what are the potential gains from pollutant emissions trading. The potential gains also can be seen as carbon emissions abatement cost savings, or reductions on economic output loss caused by carbon emissions control, when implementing market based instrument such as carbon emissions trading scheme instead of command and control policy. Theoretically, heterogeneity in abatement cost determines the efficiency advantage of market based instruments such as carbon emissions permits trading over command and control policies on carbon emissions. The carbon emissions permits market offers companies or facilities that facing high marginal emissions abatement costs the opportunity to purchase the right to emit CO_2 from companies or facilities with lower abatement costs, and thus this instrument is expected to yield abatement cost savings compared to the command and control instrument to carbon control regulation (Carlson et al., 2000). In other words, carbon emissions permits trading takes advantage of the fact that emissions abatement costs vary across firms and utilities and encourages firms and utilities with lower carbon emissions control costs to undertake more CO_2 reductions. In addition, since each individual entity has the flexibility to choose the course of action for achieving abatement compliance at its least cost, investment in technology or procedure for abatement would flow to where has the lowest abatement cost, the marginal abatement cost becomes equalized across all entities (Chan et al., 2012; Goulder and Schein, 2013), and therefore, the CO_2 abatement target is achieved at the lowest cost. This is the reason that emissions permits trading is generally considered a cost effective form of abatement policy instrument.

Since different Chinese provinces usually have various economic growth modes, natural resource endowments and energy consumption patterns, industrial structures and technological levels, the carbon emissions abatement cost of different Chinese provinces are also likely to be different (Zhou et al., 2013; Cui et al., 2014; Wang and Wei, 2014). Therefore, carbon emissions trading may be effective to help China to realize the potential gains or to reduce the economic output loss from carbon emissions control. This also explains the attempt of Chinese government to establish the pilot carbon emissions trading market in the 12th FYP period. Since China has only recently launched its seven pilot trading markets, and the identified potential gains from trade will be the primary argument for introducing tradable permits and establishing a national emissions trading system in China in the coming five years, it is very interesting to find out what will be the theoretical potential gains, or the abatement cost savings, from trading carbon emissions in China among different provinces.

In this study, we try to answer this question through an ex post analysis based on China's regional data over the period of 2006-2010 and through utilizing a data envelopment analysis (DEA) based optimization model associated with three trading schemes, i.e., no tradable permits (or command and control) scheme, spatial tradable permits scheme, and spatial-temporal tradable permits scheme. During the 11th FYP period, there was no carbon emissions trading pilot market in China, and the regulations on energy consumption intensity reduction were implemented as command and control policies at the national and provincial levels for carbon emissions control. Thus, the observed carbon emissions and economic output (GDP at national level or GRP at provincial level) of the 11th FYP period are taken as the baseline for estimating the potential gains from spatial tradable permits scheme and spatial-temporal tradable permits scheme. These estimated potential gains also imply the abatement cost savings, or the reductions on GDP loss caused by carbon emissions control, from carbon emissions trading at the national and provincial levels.

In specific, the command and control scheme seeks the maximum provincial GRP output subject to the regulated carbon emissions of each province not be exceeded, which represents a no tradable emissions permits scheme. The spatial tradable scheme maximize the regional GRP outputs given that the carbon emissions permits can be reallocated among different provinces, but the national total emissions permit could not be exceeded in each year. The spatial-temporal tradable scheme search the maximum GRP outputs for all provinces given that carbon emissions permits can be reallocated among different provinces and in different years, but keeping the national total emissions permit over the entire study period non-increasing. If a higher level of production of GRP than the observed GRP, i.e. GRP under the command and control policy, can be achieved while maintaining the observed or regulated level of carbon emissions through implementing the carbon emissions trading scheme, then the increase of GRP demonstrates the potential gains from carbon emissions trading. In specific, potential gains estimated by spatial tradable scheme reveal the unrealized abatement cost savings or the potential reductions on GRP loss associated with eliminating spatial regulatory rigidity on carbon emissions trading, and potential gains estimated by spatial-temporal tradable scheme denote the unrealized abatement cost savings or the potential reductions on GRP loss associated with eliminating both spatial and temporal regulatory rigidity on carbon emissions trading. The potential gains from trading estimated in this study provide an upper limit on the potential cost of transaction of carbon emissions trading, and the associated carbon emissions reduction potentials from trading identified in this study provide one argument for implementing a market based policy instrument of carbon emissions trading scheme in China for carbon emissions control.

2 Literature review

There have been several previous researches attempt to analyze the influence of introducing emissions trading mechanism in China. Some researches provided overviews on the status of China's current emissions trading pilot markets, and other researchers investigated the economic impact and the emissions reduction effect of emissions trading scheme in China. These researches also can be divided into studies that focus on estimating the impacts of emissions trading in China at the national level, the regional level (especially for the pilot markets), and the industrial sector level (electricity, building, transportation, etc.).

The first group of studies focuses on introducing China's pilot emissions trading market. Jotzo and Löschel (2014) and Zhang et al. (2014) provided comprehensive overviews of the current status of China's seven emission trading pilot cities and provinces. They pointed out that there exist large differences on the design features in these pilots which reflecting the diverse settings and proprieties of the emissions trading schemes. The challenges of establishing China's future national emissions trading scheme, e.g., risk on emissions permits over allocation, and uncertainty on intensity based emissions reduction target setting were discussed in their studies. As the first urban level emissions trading scheme operated in China, the Shenzhen emissions trading scheme and the development of its regulatory framework were overviewed in Jiang et al. (2014). In addition, Wu et al. (2014) provided an overview of the latest progress of Shanghai's emissions trading scheme.

The second group of studies tries to analyze the impact of emissions trading in China. For the estimation of the impact at the national level, Hübler et al. (2014) assessed the influence of implementing China's 45% carbon intensity reduction target via emissions trading, and found a 1% GDP loss in 2020 due to the reduction target. Cui et al. (2014) investigated the cost-saving effects of carbon emissions trading in China also for the 2020 target. Through allowing for an interprovincial emissions trading scheme, they detected a total abatement cost reduction of 4.5% to 23.7% for different trading policy scenarios. They also pointed out that carbon emissions trading lead different impacts among provinces and the cost-saving effects in China's east and west regions are more significant than those in central regions. Similarly, Zhou et al. (2013) modeled the economic impact of interprovincial emissions reduction quota trading scheme in China and their estimation results showed that China's total emission abatement cost could be reduced by 40 percent by implementing such a trading scheme. Liu and Wei (2014) further assessed the impact of a joint Europe-China emissions trading system and found that such a joint system increases total carbon emissions from fossil fuels, but helps China to achieve its renewable energy target. Hübler et al. (2014) also measured the benefit of China for linking China's emissions trading system to the EU ETS. Particularly focusing on China's electricity pricing regulation regime, Li et al. (2014) assessed the environmental impacts of emissions trading system in China which indicated a 6.8-11.2% total carbon emissions reduction ranges in short-term with a carbon price at 100 Yuan/tonne. Cong and Wei (2010) studied the potential impact of carbon emissions trading on China's electricity sector and indicated that carbon emissions trading could internalize environmental cost and stimulate the development of environmentally friendly technologies. Also focusing on China's electricity sector, Teng et al. (2014) examined the challenges and opportunities of introducing the emissions trading system. Similar studies could be found in transportation sector (Chen et al., 2013) and construction industry (Ni and Chan, 2014).

For the estimation of the impact at the regional pilot market level, Huang et al. (2015) investigated the carbon abatement technologies investment in coal-fired power industry of Shenzhen under Shenzhen's emissions trading system. Their results indicate that the emissions trading system is a driving force for the short term technology investment of coal-fired power industry in Shenzhen. Zhu et al. (2013) proposed a programming method and applied it to plan carbon emissions with trading scheme for Beijing's electricity industry. Their optimization results provided a solution for energy supply, electricity generation, carbon emissions permits allocation, and capacity expansion of the electricity sector in Beijing. Wang et al. (2015) analyzed the economic impact of emissions trading scheme among four energy intensive sectors, i.e., power, refinery, cement, and iron & steel industries in Guangdong. The estimation results reveal that the emissions trading scheme can reduce the mitigation cost. In specific, with the emissions trading scheme, the economic outputs of all sectors are higher and the GDP loss is lower than the command and control scheme without emissions trading, and thus this emissions trading scheme leads Guangdong's GDP to recover by 2.6 billion USD compared to the command and control scenario. Liu et al. (2013) examined the carbon abatement effects of separated provincial emission trading markets and linked inter-provincial market. Two pilot markets of Hubei and Guangdong were analyzed for comparison and the simulation results imply that the linked market provides higher social welfare and leads to lower carbon intensity both for China and for Hubei-Guangdong bloc than those in the separated markets.

As discussed above, Zhou et al. (2013) and Cui et al. (2014) had provided good estimations on the abatement cost saving effects of carbon emissions trading in China if an interprovincial emissions trading system is constructed. Our current research estimates the carbon emissions abatement cost savings or the GDP loss recoveries in China from another perspective through estimating the potential gains from carbon emissions trading. There are three advantages of our estimation. Firstly, the calculation of marginal abatement cost on carbon emissions over the study period for China at the provincial level is not necessary. Since such calculation is highly relying on the input and output data as capital, labor, intermediate resources and energy consumption, as well as depending on the parametric or non-parametric approaches utilized (Carlson et al., 2000; Zhou et al., 2014; Wang and Wei, 2014), the avoiding of this calculation helps to reduce the estimation uncertainty. Secondly, the specific calculation of actual carbon emissions reduction from the command and control scheme that Chinese government implemented during the study period is not necessary. Since there is no accurate officially reported data on provincial carbon emissions reduction, the emission data utilized by exist studies are major calculated based on the government released carbon intensity reduction data and economy data (Wang et al., 2012; Wei et al., 2012), the avoiding of this calculation helps to simplify the data collection and estimation procedures. Thirdly, the setting of initial allocation of carbon emissions reduction target among China's provinces with given scenario is not necessary. Since our estimation is an ex post analysis based on actual data, any assumption on initial emissions permits allocation that did not real implemented during the study period will be lack of reliability.

To our knowledge, the current study provides the first attempt to identify the potential gains from carbon emissions trading in China under various regulatory schemes for carbon emissions reductions.

The remainder of this study is organized as follows. Section 3 introduces the models utilized to estimate the potential gains from carbon emissions trading. Section 4 presents the data. In Section 5, we discuss the empirical results, and in Section 6, we summarize the findings.

3 DEA based models for identifying potential gains from trade

To estimate the potential gains from carbon emissions trading, we apply a data envelopment analysis (DEA) (Cooper et al., 2011) based model. It should be noticed that DEA has been widely utilized in the study of tradable emissions permits allocation which is considered as a first step for starting the emissions permits trading process (Wang et al., 2013c). For instance, Lozano et al. (2009) proposed an approach for emissions permits reallocation using a centralized point of view. Three objectives of maximizing total production, minimizing total emissions and minimizing consumption of inputs were proposed with different priorities in their study for reallocating emissions permits through several DEA based models. This centralized resources allocation concept was further developed in Wu et al. (2013), Sun et al. (2014) and Feng et al. (2015). In specific, Wu et al. (2013) applied their approach in the agricultural greenhouse gas emissions permits allocation for 15 EU members, and Feng et al. (2015) provide an empirical application of their model to carbon emissions abatement allocation for 21 OECD countries. The centralized DEA approaches were also applied in China's CO_2 emissions reduction allocation. For example, by utilizing a slack based measure DEA model, Wei et al. (2012) identified the CO_2 emissions reduction burden of each Chinese province for realizing China's 2020 national carbon intensity reduction pledge. Furthermore, Zhou et al. (2014) proposed a more specific optimal allocation of CO_2 emissions in China based on different spatial and temporal allocation strategies associated with several centralized DEA models, and the optimal path for CO_2 emissions control in each Chinese province was determined in their study.

In current study, we follow the calculation process proposed in Färe et al. (2013, 2014) but make an application extension from the coal fired power plant carbon emissions trading to China's interprovincial carbon emissions trading. By using the observed data of China's 30 provinces for the 2006-2010 period, the maximal production of desirable outputs are estimated under three sequential schemes, i.e., the no tradable permits (NT) scheme, the spatial tradable permits (ST) scheme, and the spatial-temporal tradable permits (STT) scheme.

NT scheme seeks the maximum desirable output subject to observed level of undesirable output of each province unchanged, i.e., there is no tradable emissions permit. Although China did not have a clear command and control regulations on carbon emissions during the 2006-2010 period, it did have a regulation on energy conservation that the national energy consumption intensity should be reduced by 20% by the end of 2010 compared with 2005, and this energy intensity reduction target was disaggregated and assigned to each province of China. Since the energy consumption intensity reduction regulation and energy conservation effort are closely interrelated with carbon emissions control, we assume in this study that the observed GDP and carbon emissions are results of compliance to a command and control regulations on carbon emissions in China, which is also taken as the baseline policy scenario for comparative analysis. These observed values on provincial GDP and carbon emissions are further utilized as baselines for estimating the potential gains and emissions reduction potentials from carbon emissions trading.

ST scheme maximize the desirable output given that the emission permit of undesirable output can be reallocated among regions, but the total amount of emissions for all provinces could not increase in each year. This scheme represents the spatial tradable regulations on carbon emissions.

STT scheme calculates the maximal desirable outputs that all provinces may achieve when the emissions can be reallocated among different provinces and in different years, but keeping the total amount of emissions for all provinces over the entire study period non-increasing. This scheme allows for intertemporal trading, i.e., trading with depositing and borrowing, of carbon emissions permits.

If the region under calculation is possible to obtain higher level of desirable output than its observed production of desirable output while maintaining its observed level of carbon emissions through eliminating technical inefficiency, or if it is possible to maintain the total observed level of carbon emissions of all regions under calculation through implementing the carbon emissions trading schemes, then the difference between the higher level of desirable output and the observed desirable output demonstrates the potential gains from trade.

In this study, there are one desirable output (y) of GRP, one undesirable output (b) of carbon emissions, and three inputs (x_1, x_2 and x_3) of energy, labor and capital stock, for each of the j=1,…,30 provinces of China over t=1,…,5 years. For the appropriate choice of inputs and outputs, see Cook et al. (2014). When the modeling of undesirable outputs is included, DEA models can be classified into two groups, namely the models based on applying traditional DEA associated with undesirable outputs transformation, and the models using original undesirable outputs but relying on their weakly disposable assumption. In the first classification, undesirable outputs will (i) firstly be transformed to their reciprocals (Lovell et al., 1995) and then dealt as strongly disposable desirable outputs; (ii) indirectly be treated as strongly disposable desirable outputs after a linear monotone transformation (Seiford and Zhu, 2002; Seiford and Zhu, 2005; Zhu 2014); or (iii) directly be treated as inputs which are freely or strongly disposable (Hailu and Veeman, 2001). In the second classification, the environmental production technology (Färe et al., 1989), which is a joint production principle between desirable and undesirable outputs, and the weak disposability assumption are applied to model undesirable outputs (Cook and Zhu, 2014). In this study, the environmental production technology and the weak disposability assumption are utilized for modeling[2]. We

[2] In the case of energy and emissions performance evaluation, undesirable outputs, such as CO_2, SO_2 and NO_x emissions, are usually resulting from the combustion of fossil fuel. Usually, reducing CO_2 emissions may directly related to reducing fossil fuel consumption, whereas SO_2 and NO_x emissions may be reduced through applying technical instrument such as installing scrubbers, and there may be an indirect link between SO_2 or NO_x emissions and fossil fuel consumption. Therefore, it will be more appropriate to model CO_2 emissions as weakly disposable undesirable outputs while model SO_2 and NO_x emissions as freely disposable undesirable outputs. In the current study, only CO_2 emissions are taken into account, thus we just utilize

first apply the following model to estimate the maximal GRP output production for the *l*th province at the *t*th period.

$$
\begin{aligned}
& R_l^{NTt} = \max \tilde{y}_l^{NTt} \\
& s.t. \ \sum_{j=1}^{30} \lambda_j^t y_j^t \geq \tilde{y}_l^{NTt} \\
& \quad \sum_{j=1}^{30} \lambda_j^t b_j^t = b_l^t \\
& \quad \sum_{j=1}^{30} \lambda_j^t x_{ij}^t \leq x_{il}^t \quad i = 1,\dots,3 \\
& \quad \lambda_j^t \geq 0 \qquad j = 1,\dots,30
\end{aligned} \tag{1}
$$

The constant returns to scale (CRS) and weak disposability on emissions are imposed in Model (1) and in which, λ_j^t is the intensity variable, y_j^t, b_j^t, x_{ij}^t are observed level of desirable output, undesirable output, inputs, respectively, and $\tilde{y}_l^{NTt}$ is maximization of desirable output. R_l^{NTt} denotes the optimal GDP production for province *l* at year *t* under command and control regulations, i.e., there is no tradable permit on carbon emissions.

The following equations (2) and (3) calculate the total maximized GRP production for all provinces at year *t* and the total maximized GRP production for all provinces over the entire study period under command and control regulations.

$$TR^{NTt} = \sum_{l=1}^{30} R_l^{NTt} \quad t = 1,\dots,5 \tag{2}$$

$$TTR^{NT} = \sum_{t=1}^{5} TR^{NTt} \tag{3}$$

Then, in order to estimate the maximal GRP output at each *t* year given the carbon emissions permits are tradable in that year, we apply the following model to obtain the maximization of the sum of each province's GRP production in each t year.

$$
\begin{aligned}
& TR^{STt} = \max \sum_{l=1}^{30} \tilde{y}_l^{STt} \\
& s.t. \ \sum_{j=1}^{30} \lambda_{jl}^t y_j^t \geq \tilde{y}_l^{STt} \quad l = 1,\dots,30 \\
& \quad \sum_{j=1}^{30} \lambda_{jl}^t b_j^t = \tilde{b}_l^t \quad l = 1,\dots,30 \\
& \quad \sum_{j=1}^{30} \lambda_{jl}^t x_{ij}^t \leq x_{il}^t \quad i = 1,\dots,3 \quad l = 1,\dots,30 \\
& \quad \lambda_{jl}^t \geq 0 \quad j = 1,\dots,n \quad l = 1,\dots,30 \\
& \quad \sum_{l=1}^{30} \tilde{b}_l^t \leq \sum_{l=1}^{30} b_l^t
\end{aligned} \tag{4}
$$

Model (4) also imposes the CRS and weak disposability on emissions. λ_{lj}^t is the intensity

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weak disposability assumption for potential gains estimation modeling.

variable, y_j^t, b_j^t, x_{ij}^t are observed level of desirable output, undesirable output, inputs, respectively. $\tilde{y}_l^{STt}$ is maximization of desirable output, $\tilde{b}_l^t$ is tradable undesirable output, and both of them are variables. TR^{STt} denotes the sum of the optimal GRP production for all 30 province at year *t* when spatial tradable permits are implemented. It should be noticed that the last constraint in Model (4) indicates that the sum of the tradable undesirable output, $\sum_{l=1}^{30}\tilde{b}_l^t$, should not exceed the aggregate allowed undesirable output emissions, $\sum_{l=1}^{30} b_l^t$, which is the observed total amount of emissions subject to tradable permits in year *t*. This observed total amount of carbon emissions also equals to the national total carbon emissions under command and control scheme, since we take the command and control scheme as the baseline for estimating the potential gains from trading.

The following Equations (5) and (6) calculate the maximized GRP production for each province at year *t* and the total maximized GRP production for all provinces over the entire study period with the spatial tradable permits in each year.

$$R_l^{STt} = \tilde{y}_l^{STt} \quad l = 1,\ldots,30 \quad t = 1,\ldots,5 \qquad (5)$$

$$TTR^{ST} = \sum_{t=1}^{5} TR^{STt} \qquad (6)$$

To estimate the maximal GRP output when the carbon emissions permit is tradable not just among provinces but also over years during the entire period, the following model is applied.

$$\begin{aligned}
& TTR^{STT} = \max \sum_{t=1}^{5}\sum_{l=1}^{30} \tilde{y}_l^{STTt} \\
& s.t. \ \sum_{j=1}^{30} \lambda_{jl}^t y_j^t \geq \tilde{y}_l^{STTt} \\
& \quad \sum_{j=1}^{30} \lambda_{jl}^t b_j^t = \tilde{b}_l^t \quad l = 1,\ldots,30 \quad t = 1,\ldots,5 \\
& \quad \sum_{j=1}^{30} \lambda_{jl}^t x_{ij}^t \leq x_{il}^t \quad i = 1,\ldots,3 \quad l = 1,\ldots,30 \quad t = 1,\ldots,5 \\
& \quad \lambda_{jl}^t \geq 0 \quad j = 1,\ldots,30 \quad l = 1,\ldots,30 \quad t = 1,\ldots,5 \\
& \quad \sum_{t=1}^{5}\sum_{l=1}^{30} \tilde{b}_l^t \leq \sum_{t=1}^{5}\sum_{l=1}^{30} b_l^t
\end{aligned} \qquad (7)$$

The CRS and weak disposability on emissions settings, the variable of λ_{lj}^t, and the parameters of y_j^t, b_j^t, x_{ij}^t in Model (7) are similar to those in the above two Models (1) and (4). In addition, variables of $\tilde{y}_l^{STTt}$ and $\tilde{b}_l^t$ are maximization of desirable output and tradable undesirable output, respectively. TTR^{STT} denotes the sum of the optimal GRP production for all 30 province over all year during the entire study period when spatial-temporal tradable permits are implemented, i.e., to deposit and to borrow carbon emissions permits are allowed.

Similarly, the last constraint in Model (7) indicates that the sum of the tradable undesirable output, $\sum_{t=1}^{5}\sum_{l=1}^{30}\tilde{b}_l^t$, should less than or at least equal to the aggregate allowed undesirable output emissions, $\sum_{t=1}^{5}\sum_{l=1}^{30}b_l^t$, which is the observed total amount of emissions subject to tradable permits during the entire study period that cover all 5 years. This observed total amount carbon emissions also equals to the 5 years national total carbon emissions under command and control scheme.

The last two Equations (8) and (9) calculate the maximized GRP production for each province at year t and the total maximized GDP production for all provinces at year t with the spatial-temporal tradable permits over the entire study period.

$$R_l^{STTt} = \tilde{y}_l^{STTt} \quad l = 1,...,30 \quad t = 1,...,5 \qquad (8)$$

$$TR^{STTt} = \sum_{l=1}^{30} TR_l^{STTt} \quad t = 1,...,5 \qquad (9)$$

It should be noticed that, same as Färe et al. (2013, 2014), Models (1) and (4) are considered contemporaneous approach in which each province is benchmarked against those provinces that belong to the same year, and thus each year has its own production possibility set. Moreover, Model (7) covers all provinces over the entire study period and thus it has a combined production possibility set that each province in each year is benchmarked against a unified efficiency frontier.

Models (1), (4) and (7) presented above are based on linear programming that the CRS assumption is applied. In order to give greater flexibility to these models, the assumption of variable returns to scale (VRS) is also applied and the corresponding models can be found in the Appendix. We emphasis that since the VRS assumption is not directly linked with weak disposability assumption (Färe and Grosskopf 2003; Kuosmanen, 2005; Zhou et al., 2008; Murty et al., 2012) which is utilized for modeling CO_2 emissions in this study, the DEA based potential gains estimation models that satisfy these two assumptions need to be specifically formulated by utilizing an addition abatement factor which keeps proportional reductions on both desirable and undesirable outputs (Picazo-Tadeo and Prior, 2009). This specific formulation leads a nonlinear programming (although could be linearized efficiently) and complicates the estimation process. In addition, as pointed by several recent studies (e.g. Aparicio et al., 2013; Hampf and Krüger, 2014), the utilization of weak disposability assumption may lead to part of the frontier of the desirable and undesirable output set exhibits a negative slope. This may lead to a situation that inefficient observations located on this part are identified as efficient ones. To avoid this problem, we follow the concept of Aparicio et al. (2013) in which a nested output set is utilized. However, the limitation of this approach is the VRS model has not been derived. Therefore, in this study, the ex post estimation and analysis is mainly based on CRS models. Note that, in recent study of carbon emissions abatement allocation (Feng et al., 2015), the desirable GDP output is concave with respect to the undesirable carbon emissions output, however, in the current study, this property is not in our estimation of Model (1) since the nested output set is applied as mention above.

To summarize, R^{NTt} (no tradable permit estimation or command and control estimation) calculates the maximum GDP production when technical inefficiency is eliminated, and thus we define $R^{NTt}-y$ as the Type I potential gains which identifies the potential desirable output increase associated with eliminating inefficiency. R^{STt} (spatial tradable permit estimation) calculates the maximum GDP production when technical inefficiency is eliminated, suboptimal spatial allocation of carbon emissions permit is eliminated, and gains from spatial trading are allowed. Thus, $R^{STt}-R^{NTt}$ can be defined as the Type II potential gains which identifies the potential desirable output increase associated with eliminating regulatory rigidity through allowing the trade of carbon emissions permits among different regions within each single year. R^{STTt} (spatial-temporal tradable permit estimation) calculates the maximum GRP production when technical inefficiency is eliminated, both suboptimal spatial and suboptimal temporal allocation of carbon emissions permits are eliminated, and gains from spatial-temporal trading are allowed. Therefore, $R^{STTt}-R^{STt}$ is defined as the Type III potential gains identifying the potential desirable output increase associated with eliminating regulatory rigidity through additionally allowing the trade of carbon emissions permits over different period, i.e., the intertemporal depositing and borrowing of carbon emissions permits are allowed. In this study, Type II and III potential gains represent the estimated carbon abatement cost savings or carbon control leaded GRP loss recoveries from implementing interprovincial and intertemporal carbon emissions trading policy instruments instead of command and control policies on carbon emissions control.

4 Data

For calculating the potential gains from carbon emissions trading in China, we collect the regional data from 2006-2010 which covers the 11th Five-Year-Plan (FYP) period. During this period, the Chinese government proposed and implemented series of regulations and policies for energy conservation and related carbon emissions control (Wang et al., 2012), and these efforts have played a role in eliminating the inefficiency of energy utilization and carbon emissions. In specific, during this period, a national energy intensity reduction target was proposed and disaggregated, and each province of China has to reduce it energy intensity by 16%-22% within five years so as to realize the national target. These energy intensity reduction targets are tightly interrelated with carbon emissions control regulations and thus could also be seen as command and control regulations on carbon emissions. However, during this period, market based regulatory strategy of tradable permits program for carbon emissions was not implemented as a scheme for controlling carbon emissions in China. Therefore, the calculation based on the data of this period will help to answer the question that what are the potential gains or abatement cost savings from trade if the national carbon emissions trading system is established in China during the 11th FYP period. In our estimation, China's 30 provinces over 5 years are the observations and, it should be noticed that, due to interprovincial commuting and trade, not all of the provinces are absolute economically independent, i.e., there may be neighborhood effects that the provinces are influenced with each other. In order to reduce efficiency evaluation bias caused by neighborhood effects, DEA based efficiency measure can at best be considered as short run evaluation instead of long run evaluation from practical point of view, and thus we consider that 5 year length study period in our estimation is appropriate.

As mentioned above, in this study, we use one desirable output y (GRP production), one undesirable output b (carbon emissions), and three input x_1 to x_3 (energy consumption, number of labor and capital stock) for calculation. The data on labor and the GRP are obtained from China Statistical Yearbooks (2007-2011). The capital stock data are obtained from Shan (2008) and our estimation (Wang et al., 2013b) through the perpetual inventory method. The data on energy consumption[3] are collected from China Energy Statistical Yearbook. Since there are no official statistics on CO_2 emissions at the regional level in China, we estimate the CO_2 emissions from fossil fuel consumptions. Firstly, the fossil fuel consumptions[4] (including the final consumptions and the consumptions in conversion) are converted into calorific value according to the conversion factors (NBS, 2013). Then, they are further translated into CO_2 emissions according to the carbon emissions factors (IPCC, 2006) and oxidation rate. The monetary GRP data and capital stock data have been converted into 2010 constant price and the energy consumption data has been converted into tonnes of coal equivalent (tce), i.e., standard coal equivalent, according to the conversion factors provided in China Energy Statistical Yearbook. The data set consists of 30 provinces over 5 years. Summary statistics for each year during the study period are reported in Table 1.

[Insert Table 1 here]

5 Results and analysis

Model (1) and Equations (2) and (3) are first employed to estimate the maximal GRP output for each province at each year under the command and control regulation that each province seeks to maximize its GRP production with the observed levels of carbon emissions. If a higher GRP output is identified than the observed GRP output, it means that there exists technical inefficiency for the province under estimation. The difference between the maximal GRP output and the observed GRP output ($R^{NTt} - y$) represents the Type I potential gains from eliminating technical inefficiency. Then, Model (4) and associated Equations (5) and (6) are employed to estimate the Type II potential gains ($R^{STt} - R^{NTt}$) from eliminating spatial regulatory rigidity, i.e., allowing carbon emissions permits to be traded spatially across different province in a given year. The Type II potential gains represent the unrealized gains from not allowing the reallocation of carbon emissions permits among provinces. Finally, Model (7) and related Equations (8) and (9) are employed to calculate the Type III potential gains ($R^{STTt} - R^{STt}$) from additionally eliminating temporal regulatory rigidity, that is, to allow

[3] In this study, energy consumption indicates the total energy consumption but excludes the consumption in conversion of the primary energy into the secondary energy and the loss in the process of conversion.
[4] Including raw coal, cleaned coal, other washed coal, briquettes, coke, coke oven gas, other gas, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas, refinery gas, and natural gas.

carbon emissions permits to be traded not only across regions but also across period. In other words, the permits for carbon emissions are both tradable and allowed to be deposited and borrowed. The summation of Type II and III potentials gains from the trade of carbon emissions constitute the upper limit on the potential cost of transaction of the permits.

Furthermore, the carbon emissions reduction potentials ($b_l^t - \tilde{b}_l^t$, $\sum_{l=1}^{30} b_l^t - \sum_{l=1}^{30} \tilde{b}_l^t$ and $\sum_{t=1}^{5}\sum_{l=1}^{30} b_l^t - \sum_{t=1}^{5}\sum_{l=1}^{30} \tilde{b}_l^t$) from spatial and temporal trading also can be calculated based on the optimal solutions of Models (1), (4) and (7), respectively, and the total amount of carbon emissions reduction potential also represents the effectiveness of carbon emissions control caused by introducing carbon emissions trading scheme in China.

Table 2 first reports the percentage of annual potential gains from trade of carbon emissions in China. The second column is the percentage of Type I potential gains over the observed GRP production, the third column shows the percentage of Type II potential gains over the maximized GRP with command and control estimations, and the fourth columns shows the percentage of Type III potential gains over the maximized GRP with spatial tradable permits. In addition, Table 2 also reports the percentage of annual carbon emissions reduction potentials from trade of carbon emissions in China. The fifth and sixth column respectively represents the percentage of carbon emissions reduction associated with the realization of Type II and III potential gains when spatial trading and spatial-temporal trading scheme is implemented.

[Insert Table 2 here]

The percentage of annual Type I potential gains ranges from 4.37% to 7.60% during 2006-2010 which indicates a considerable amount of theoretical GDP loss associated with technical inefficiency of China, i.e., the theoretical GDP loss due to the fact that not all the provinces were operating on the efficiency frontier. During the same period, the annual Type II and III potential gains represent the differences in maximal GDP production between the no tradable permit or command and control GDP estimations and the tradable permit GDP estimations in China. The percentage of annual Type II potential gains ranges from 8.32% to 13.50% and the percentage of annual Type III potential gains ranges from 2.74% to 8.33%, which respectively represent the theoretical magnitude of GDP loss associated with the spatial regulatory rigidity and the temporal regulatory rigidity of China, i.e., the theoretical GDP losses due to the suboptimal allocation of carbon emissions permits among provinces and over years.

For the observed inputs of energy, labor and capital unchanged, and the technology fixed during the study period, the positive Type II to Type III potential gains support our expectation that less flexibility on regulations (or high rigidity on regulations) would lead to reduction on GDP production, and thus the introduction of carbon emissions trading system would help to realize the potential GDP production in China, or in other words, to implement carbon emissions trading scheme would help to reduce the GDP loss due to the command and control policies on carbon emissions in which the carbon emissions permits are not able to be optimally reallocated among provinces in China.

The results reported in Table 2 also respectively reveal an average increase potential on GDP of 5.87%, 10.78% and 5.96% for China over the period of 2006-2010 if the technical inefficiency, the intra-period carbon emissions allocation inefficiency, and the inter-period carbon emissions allocation inefficiency could be eliminated. This result indicates that the GDP loss caused by carbon emissions control in China during 2006-2010 can be recovered by approximate 17% (summation of Type II and III potential gains) through implementing interprovincial and additionally intertemporal carbon emissions trading schemes.

Fig. 1 illustrates three types of annual potential gains from carbon emissions permits trade of China during 2006-2010. It can be found that, on average, the Type II and III potential gains together account for approximate 75% of total GDP increase potentials or GDP loss recoveries in China, in which, 46% of the potential gains (Type II) could be realized through eliminating the rigidity of spatial trading, and 29% of the potential gains (Type III) could be achieved by eliminating the temporal trading rigidity. The remaining 25% of total GDP increase potential comes from reducing technical inefficiency.

[Insert Figure 1 here]

Table 2 also reports the potentials on carbon emissions reduction in China from the trade of carbon emissions permits over 2006-2010. When the spatial tradable emissions permits are implemented, an average carbon emissions reduction percentage of 10.97% compared with the observed or command and control carbon emissions can be identified. And if the additional spatial-temporal tradable emissions permits are implemented, an average carbon emissions reduction percentage of 2.36% compared with the spatial tradable carbon emissions can be additionally realized. Note that, for each single year under estimation, China's carbon emissions could be reduced from spatial and spatial-temporal permits trading. There is only one exception that, in 2006, carbon emissions increased 1%. This indicates that if spatial-temporal permits trading are allowed, some provinces may borrow additional permits from themselves or other provinces in the remaining years and emit more CO_2 than observed values in 2006 so as to achieve more GRP outputs.

Fig. 2 further illustrates the difference between the observed carbon emissions and the carbon emissions with spatial and temporal tradable permits of China from 2006 to 2010. It is notable that, the introduction of carbon emissions permits trading scheme will not only lead to potential GDP increase or reduce GDP loss caused by command and control policies, but also help to reduce total carbon emissions in China, and on average, most of the reduction potentials come from spatial trading (84%) with a small amount of potentials come from additional spatial-temporal trading (16%).

[Insert Figure 2 here]

The realization of Type II and III potential gains or GDP loss recoveries from carbon emissions trading, and the realization of associated carbon emissions reduction potentials in China during 2006-2010 should be explained by the reallocation of carbon emissions reduction burdens from the provinces with high carbon emissions inefficiencies and high abatement costs to those provinces with low inefficiencies and low costs. In this study, we have 150 observations, i.e., 30 provinces with 5 years, under estimation, and the five years average of potential gains and carbon emissions reduction potentials of these 30 provinces are reported (both in percentages) in Table 3. It can be seen that Qinghai, Jilin and Ningxia respectively present the highest percentages on Type I, II and III potential gains.

[Insert Table 3 here]

According to the percentages of Type I potential gains, which account the GRP increase percentages from eliminating technical inefficiencies of specific provinces in China, we could find that the efficiency difference in the production process of desirable and undesirable outputs in China among different regions is substantial, since the economic well-developed regions, such as Beijing, Shanghai, and Guangdong etc., always produced on the efficiency frontier and show no Type I potential gains, but the underdeveloped regions like Qinghai, Gansu and Yunnan etc. kept suffering from high technical inefficiencies in their production processes and show high percentages on Type I potential gains (24-36%).

According to the combined percentages of Type II and III potential gains, which account the GRP increase percentages from spatial and temporal trading of carbon emissions permits, Jilin shows the highest gains (51%) followed by Ningxia (42%) and Hebei (36%). Guangdong presents the lowest gains (0.04%) followed by Inner Mongolia (0.6%) and Shanghai (1.9%). Although the deviation on the percentage of potential gains is relatively large, all provinces shows positive potential gains from carbon emissions trading. Furthermore, among all 30 provinces, 26 provinces present carbon emissions reduction potentials, in which Hainan has the highest average reduction percentage (32%), followed by Jilin (31%) and Hebei (31%), and Inner Mongolia has the lowest average reduction percentage (0.8%). The remaining four provinces (Guangdong, Chongqing, Shanghai and Xinjiang) which have negative reduction percentage values may increase their carbon emissions after trading. This indicates that if the spatial and temporal permit trading is allowed, in aggregate, Guangdong, Chongqing, Shanghai and Xinjiang will be the buyers of carbon emissions permits over the entire study period of 2006-2010. Although, these four provinces may increase their emissions, the total amount is just 23.39 million tonnes which is quite lower than the total amount of carbon emissions reduction potentials of the other 26 provinces (981.1 million tonnes). Fig. 3 further illustrates the cluster map of China's provinces with different percentages of combined Type II and III potential gains from carbon emissions trading.

[Insert Figure 3 here]

We further compare the observed carbon emissions intensity reduction during 2006-2010 (11^{th} FYP period) with the estimated carbon emissions intensity if the technical inefficiency and the inefficiency of suboptimal allocation of emissions permits are eliminated, i.e., three types of potential gains from trade are realized, so as to highlight the effectiveness of introducing carbon emissions trading programs from the perspective of reducing China's carbon emissions intensity.

[Insert Table 4 here]

The results in column 2 of Table 4 report the observed carbon intensity reduction percentage of China and its 30 province of 2010 compared with 2006, which revels a 19.7 percent decrease at the national level. This reduction is due to Chinese government's effort on implementing energy conservation and emissions reduction policies and regulations during the 11th FYP period (Wang et al., 2013a). If the technical inefficiency of the province, which is not located on the production frontier, is eliminated, the estimation results in column 3 revel that there will be another 5% carbon intensity reduction potential would be realized at the national level, and the reduction percentages for those inefficient provinces range from 1% (Zhejiang) to 27% (Qinghai). The last two columns of Table 4 report the estimated carbon intensity reduction percentages from spatial trading and spatial-temporal trading, respectively. It is obvious that, at the national level, approximate 20% of the potential reduction could be realized through eliminating spatial rigidity and another 7% reduction potential could be realized through eliminating temporal rigidity. Both of the carbon intensity reduction potentials caused by emissions trading are higher than that due to improving technical inefficiency. Among all China's 30 provinces, there are respectively 21 provinces and 27 provinces show carbon intensity reduction potentials from spatial trading and spatial-temporal trading, and their reduction percentages range from 1%-53% and 1%-30%, respectively. These results imply that, the elimination of trading rigidity of carbon emissions permits will help to release more carbon intensity reduction potentials than command and control or no tradable permit policies on carbon emissions for all provinces in China that participated in the trading system. These estimation results are further illustrated in Fig. 4.

[Insert Figure 4 here]

As discussed above, the major attraction of provincial carbon emissions permits trading in China is its potential to achieve stated emissions control target (e.g. 17% decrease in carbon emissions intensity during 2010-2015), and to achieve this target at lower cost than that if each province faces individual carbon emission reduction burden. This study indicates that, in a spatial and temporal permits trading system, provinces that face relatively high emissions reduction costs (e.g. Shanghai and Guangdong) could purchase additional emissions permits from other provinces rather than incur the high costs, and correspondingly, provinces that are capable to reduce carbon emissions at relatively low costs (e.g. Hebei and Shandong) could have choices to purchase fewer permits or sell excess permits. Although these choices oblige these provinces to reduce carbon emissions further, their avoided abatement costs or permits sale revenues will compensate the costs associated with extra emissions reductions. This will provide a constant incentive of each province to identify cost minimizing abatement opportunities.

Moreover, the carbon emissions permits trading system provide Chinese government, the environmental regulation authority, considerable flexibility to distribute net carbon abatement compliance costs across covered regions (30 provinces in mainland China except for Tibet which was not assigned energy and carbon intensity reduction targets during 11th and 12th FYP periods). Since the emissions permits become valuable assets, the government will have the ability to reduce or even offset the cost of emissions permits trading program through using the value of permits to benefit those provinces that have purchased them, and the government also can use this value to achieve development goals such as protect the jobs of coal miners and coal-fired power industry workers in provinces with rich coal endowments (e.g. Shanxi and Shaanxi), to provide additional protections for China's western low-income provinces (e.g. Yunnan and Guizhou), and to incentive high-income provinces (e.g. Jiangsu and Zhejiang) to investment more in abatement technology and procedure. Furthermore, the cost saving effect of carbon emissions permits trading identified in this study could additionally strengthen the case for marketable permits trading for controlling other pollutants (through pollutant trading) and energy consumptions (through energy saving quantity trading) in China.

6 Conclusions

Carbon emissions permit trading is known as a market based regulatory scheme for reducing greenhouse gas emissions cost-effectively. China has just recently launched its carbon trading markers in seven pilot regions. In this study, we try to answer the question that what will be the abatement cost savings or GDP loss recoveries from carbon emissions trading in China from the perspective of estimating the potential gains from carbon emissions trading. Through an ex post analysis based on China's provincial data over 2006-2010 and by applying a DEA based optimization model with several trading schemes, this study estimates three types (Type I, II and III) of potential gains from (i) eliminating technical inefficiency under the no tradable permit scheme or command and control regulation, (ii) implementing spatial tradable permit scheme on carbon emissions, and (iii) implementing spatial-temporal tradable permit scheme on carbon emissions in China. The Type I potential gains calculate the potential GDP increase associated with eliminating technical inefficiency on GDP production and carbon emissions under the carbon emissions command and control or no tradable permit scheme. If a spatial tradable carbon emissions permit system exists in China, the Type II potential gains identifies the potential GDP increase or GDP loss recovery associated with reducing spatial regulatory rigidity by eliminating intra-period carbon emissions allocation inefficiency. In addition, the Type III potential gains identifies, if a spatial-temporal tradable carbon emissions permits system exists in China, the additional potential GDP increase or GDP loss recovery associated with reducing temporal regulatory rigidity by eliminating inter-period carbon emissions allocation inefficiency. Type II and III potential gains together identify the potential increase in GDP production, or in other words, the recovery in GDP loss, if an efficient spatial and temporal tradable carbon emissions permits scheme is implemented instead of the carbon emissions command and control policies in China. Our estimation results can be concluded as follows.

i) China's 30 provinces have various economic growth modes, natural resource endowments, energy consumption patterns, industrial structures, and technological levels, and this heterogeneity gives rise to diversified carbon emissions abatement costs in different provinces. The difference in carbon abatement cost determines the efficiency advantage of market based instruments as carbon emissions trading over command and control policies and this advantage is realized in the form of potential gains or potential cost savings from emissions permits trading. This study indicates substantial potential cost savings from carbon emissions permits trading in China.

ii) The average percentage on potential gains of Type I, II and III is 5.87%, 10.78% and 5.96%, respectively, in China over the period of 2006-2010. The considerable large magnitude of potential gains identified in this study supports the expectation that less flexibility on emission trading regulations leads to reduction on GDP output. Therefore, the implementation of carbon emissions permit trading program in China will contribute to realize the potential gains, or in other words, the carbon emissions control leaded GDP loss in China can be recovered through implementing interprovincial and intertemporal carbon emissions trading schemes.

iii) About 75% of the theoretical GDP loss in China during 2006-2010 is due to the regulation rigidity of not allowing spatial and temporal trading of carbon emissions permits, and in which, 46% and 26% of the potential gains could be realized through eliminating the spatial trading rigidity and temporal trading rigidity, respectively. The remaining 25% GDP loss is due to technical inefficiency of GDP production and carbon emissions of specific provinces in China.

iv) The implementation of carbon emissions permit trading program will also help to reduce total carbon emissions in China. The average carbon emissions reduction percentages are 10.97% and 2.36% if the interprovincial trading scheme and the additional intertemporal trading scheme are implemented, respectively.

iv) All China's 30 provinces under estimation could have potential gains or benefit from reducing GDP loss through carbon emissions trading, and according to the combination of Type II and III potential gains, Jilin shows the highest percentage on GDP loss recovery (50%). In addition, 26 out of 30 provinces present carbon emissions reduction potentials from trading, and in which, Hainan has the highest percentage on carbon emissions reduction potential (34%).

v) The elimination of rigidity on carbon emissions permit trading will also release additional carbon emissions intensity reduction potentials in China, and all China's provinces that participate in the trading scheme will benefit from additionally reducing their carbon emissions intensities by 8%-56%.

vi) A marketable carbon permits trading would provide the entities covered a constant incentive to identify cost minimizing abatement opportunities, and provide Chinese government the flexibility in determining the distribution of abatement cost savings for achieving further economic and social development goals.

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Appendix

The variable returns to scale DEA models for identifying potential gains from trade are presented as follows in Models (A1) to (A4), in which the abatement factor θ_j and θ_{jl} are applied to keep the reductions of desirable and undesirable outputs proportionally. The explanations of other parameters and variables in Models (A1) to (A4) are same with Models

(1), (4) and (7) is Section 3.

$$\begin{aligned}
& R_l^{NTt}(VRS) = \max \tilde{y}_l^{NTt} \\
& s.t.\ \sum_{j=1}^{30} \theta_j \lambda_j^t y_j^t \ge \tilde{y}_l^{NTt} \\
& \quad \sum_{j=1}^{30} \theta_j \lambda_j^t b_j^t = b_l^t \\
& \quad \sum_{j=1}^{30} \lambda_j^t x_{ij}^t \le x_{il}^t \quad i = 1,\ldots,3 \\
& \quad \sum_{j=1}^{n} \lambda_j = 1 \\
& \quad \lambda_j^t \ge 0, 0 \le \theta_j \le 1 \quad j = 1,\ldots,30
\end{aligned} \tag{A1}$$

Model (A1) can be linearized by setting $\theta_j \lambda_j^t = \delta_j^t$, $(1-\theta_j)\lambda_j^t = \eta_j^t$, and $\lambda_j^t = \delta_j^t + \eta_j^t$. Then Model (A1) can be rewritten as Model (A2).

$$\begin{aligned}
& R_l^{NTt}(VRS) = \max \tilde{y}_l^{NTt} \\
& s.t.\ \sum_{j=1}^{30} \delta_j^t y_j^t \ge \tilde{y}_l^{NTt} \\
& \quad \sum_{j=1}^{30} \delta_j^t b_j^t = b_l^t \\
& \quad \sum_{j=1}^{30} \left(\delta_j^t + \eta_j^t\right) x_{ij}^t \le x_{il}^t \quad i = 1,\ldots,3 \\
& \quad \sum_{j=1}^{n} \left(\delta_j^t + \eta_j^t\right) = 1 \\
& \quad \delta_j^t, \eta_j^t \ge 0 \quad j = 1,\ldots,30
\end{aligned} \tag{A2}$$

Model (A1) is the VRS counterpart of Model (1), and the VRS counterparts of Models (4) and (7) are as follows.

$$\begin{aligned}
& TR^{STt}(VRS) = \max \sum_{l=1}^{30} \tilde{y}_l^{STt} \\
& s.t.\ \sum_{j=1}^{30} \theta_{jl} \lambda_{jl}^t y_j^t \ge \tilde{y}_l^{STt} \quad l = 1,\ldots,30 \\
& \quad \sum_{j=1}^{30} \theta_{jl} \lambda_{jl}^t b_j^t = \tilde{b}_l^t \quad l = 1,\ldots,30 \\
& \quad \sum_{j=1}^{30} \lambda_{jl}^t x_{ij}^t \le x_{il}^t \quad i = 1,\ldots,3 \quad l = 1,\ldots,30 \\
& \quad \sum_{l=1}^{30} \tilde{b}_l^t \le \sum_{l=1}^{30} b_l^t \\
& \quad \sum_{j=1}^{30} \lambda_{jl}^t = 1 \quad l = 1,\ldots,30 \\
& \quad \lambda_{jl}^t \ge 0, 0 \le \theta_{jl} \le 1 \quad j = 1,\ldots,n \quad l = 1,\ldots,30
\end{aligned} \tag{A3}$$

$$
\begin{aligned}
& TTR^{STT}(VRS) = \max \sum\nolimits_{t=1}^{5} \sum\nolimits_{l=1}^{30} \tilde{y}_l^{STTt} \\
& s.t.\ \ \sum\nolimits_{j=1}^{30} \theta_{jl} \lambda_{jl}^t y_j^t \geq \tilde{y}_l^{STTt} \\
& \qquad \sum\nolimits_{j=1}^{30} \theta_{jl} \lambda_{jl}^t b_j^t = \tilde{b}_l^t \quad l = 1,\dots,30 \quad t = 1,\dots,5 \\
& \qquad \sum\nolimits_{j=1}^{30} \lambda_{jl}^t x_{ij}^t \leq x_{il}^t \quad i = 1,\dots,3 \quad l = 1,\dots,30 \quad t = 1,\dots,5 \qquad\qquad (A4) \\
& \qquad \sum\nolimits_{t=1}^{5} \sum\nolimits_{l=1}^{30} \tilde{b}_l^t \leq \sum\nolimits_{t=1}^{5} \sum\nolimits_{l=1}^{30} b_l^t \\
& \qquad \sum\nolimits_{j=1}^{30} \lambda_{jl}^t = 1 \quad l = 1,\dots,30 \\
& \qquad \lambda_{jl}^t \geq 0, 0 \leq \theta_{jl} \leq 1 \quad j = 1,\dots,30 \quad l = 1,\dots,30 \quad t = 1,\dots,5
\end{aligned}
$$

The linearization of Models (A3) and (A4) are similar with Model (A2) and are omitted here.

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Figures and Tables

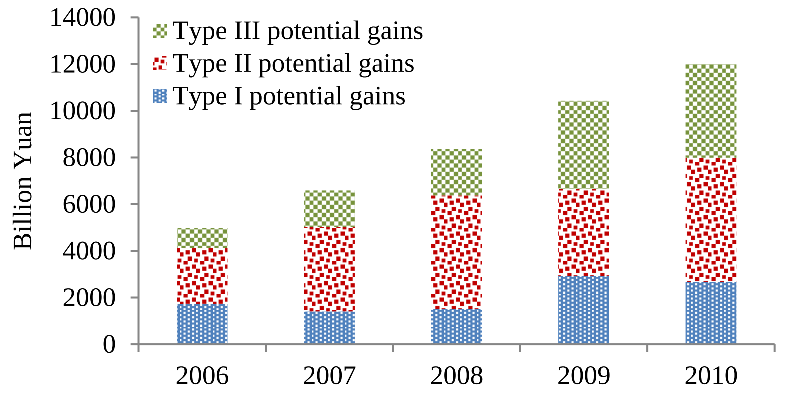

Fig. 1 Potential gains from trade of China

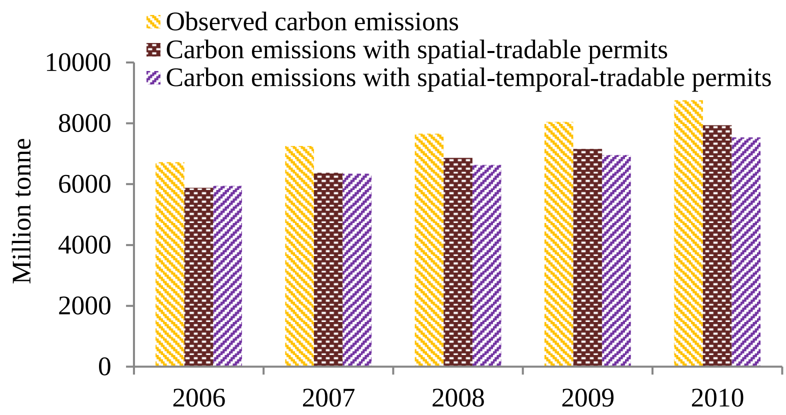

Fig. 2 Carbon emissions reduction potentials from trade of China

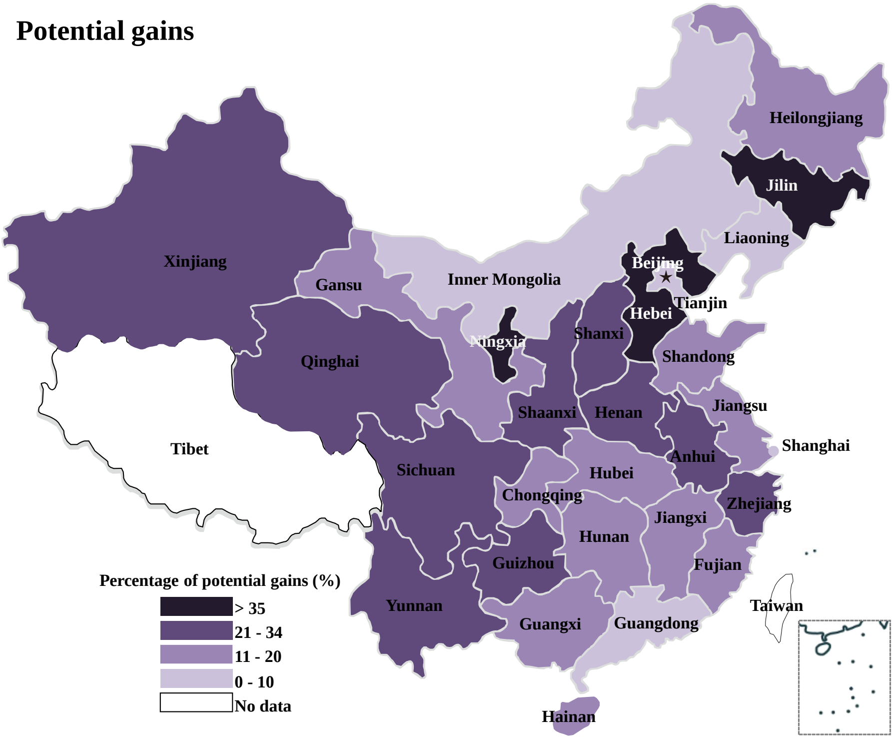

Fig. 3 China's cluster map of regional potential gains from trade

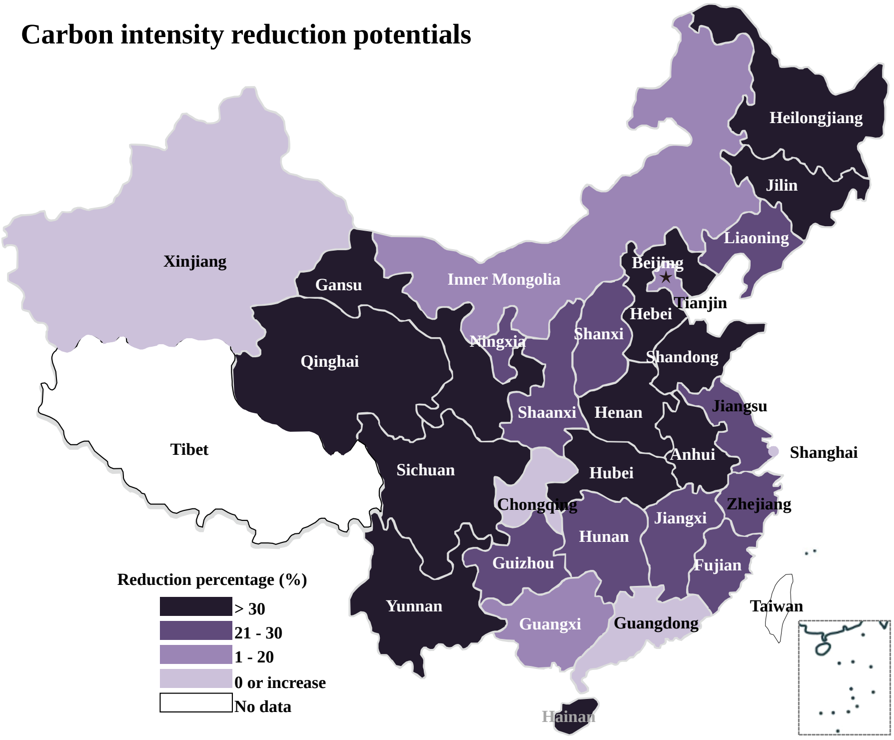

Fig. 4 China's cluster map of carbon intensity reduction potentials from trade

Table 1 Summary statistics of input and output data

		GDP (billion yuan in 2010 price)	CO_2 (million tonnes)	Energy (million tce)	Labor (million person)	Capital (billion yuan in 2010 price)
2006	Total	26912.52	6720.66	2660.12	748.23	53041.54
	Mean	897.08	224.02	88.67	24.94	1768.05
	Std. Dev.	714.61	148.82	57.30	16.64	1295.06
	Maximum	2941.84	616.58	246.93	62.41	5185.70
	Minimum	82.58	18.55	9.19	2.95	241.34
2007	Total	30853.43	7253.97	2903.30	751.59	62170.80
	Mean	1028.45	241.80	96.78	25.05	2072.36
	Std. Dev.	819.46	161.46	63.48	16.76	1496.66
	Maximum	3380.17	679.10	272.95	60.94	5997.97
	Minimum	93.73	20.80	10.17	2.92	273.77
2008	Total	34553.83	7658.18	3063.15	753.98	72630.24
	Mean	1151.79	255.27	102.11	25.13	2421.01
	Std. Dev.	910.24	170.98	67.01	16.78	1716.33
	Maximum	3731.71	725.09	291.49	60.44	6902.69
	Minimum	106.38	24.14	11.99	2.87	308.59
2009	Total	38585.88	8046.34	3226.59	756.57	85699.79
	Mean	1286.20	268.21	107.55	25.22	2856.66
	Std. Dev.	1008.11	175.31	70.19	16.81	1999.04
	Maximum	4093.69	740.30	300.78	60.18	8041.24
	Minimum	117.12	25.54	12.37	2.89	361.17
2010	Total	43653.51	8757.33	3527.57	759.32	100850.41
	Mean	1455.12	291.91	117.59	25.31	3361.68
	Std. Dev.	1130.89	188.88	75.18	16.85	2316.75
	Maximum	4601.31	795.37	321.64	59.84	9340.19
	Minimum	135.04	33.29	13.95	2.91	432.28

Table 2 Potential gains and carbon emissions reduction potentials from trade of China

	Percentage of potential gains			**Percentage of carbon emissions reductions**	
	From eliminating inefficiency	From spatial trading	From spatial and temporal trading	From spatial trading	From spatial and temporal trading
2006	6.45%	8.32%	2.74%	12.47%	-1.00%
2007	4.56%	11.18%	4.38%	12.13%	0.49%
2008	4.37%	13.50%	4.86%	10.34%	3.39%
2009	7.60%	8.99%	8.33%	11.01%	2.84%
2010	6.10%	11.51%	7.77%	9.37%	5.02%
Mean	5.87%	10.78%	5.96%	10.97%	2.36%

Table 3 Average potential gains and carbon emissions reduction potentials from trade of China's provinces

	Percentage of potential gains			Percentage of carbon emissions reductions	
	From eliminating inefficiency	From spatial trading	From spatial and temporal trading	From spatial trading	From spatial and temporal trading
Beijing	0.00%	0.00%	5.16%	0.00%	2.64%
Tianjin	0.00%	2.71%	2.61%	12.52%	-0.88%
Hebei	0.31%	28.98%	5.79%	26.69%	6.12%
Shanxi	0.00%	0.00%	21.25%	0.00%	18.49%
Inner Mongolia	0.00%	0.00%	0.65%	0.00%	0.82%
Liaoning	17.65%	1.95%	4.39%	2.19%	9.35%
Jilin	0.00%	46.53%	3.67%	31.46%	-0.06%
Heilongjiang	12.46%	17.04%	2.58%	19.36%	7.40%
Shanghai	0.00%	0.00%	1.88%	0.00%	-4.47%
Jiangsu	1.91%	13.10%	3.94%	12.18%	-5.25%
Zhejiang	1.70%	15.35%	4.80%	11.06%	-0.06%
Anhui	1.84%	24.28%	6.94%	28.76%	-1.62%
Fujian	5.09%	14.70%	3.12%	10.13%	-0.60%
Jiangxi	4.01%	8.72%	8.81%	5.54%	1.08%
Shandong	11.94%	13.79%	2.08%	13.96%	4.18%
Henan	11.52%	22.94%	7.51%	19.43%	-0.52%
Hubei	21.81%	10.20%	4.29%	19.89%	-1.50%
Hunan	14.45%	3.54%	7.60%	7.18%	0.96%
Guangdong	0.00%	0.00%	0.04%	0.00%	-0.36%
Guangxi	0.00%	0.00%	14.46%	0.00%	3.24%
Hainan	0.00%	12.19%	5.95%	31.89%	1.34%
Chongqing	0.00%	1.30%	15.99%	-2.22%	0.09%
Sichuan	8.11%	14.10%	10.15%	8.96%	1.20%
Guizhou	0.00%	0.00%	25.73%	0.00%	5.03%
Yunnan	24.30%	21.15%	9.11%	27.24%	-0.53%
Shaanxi	0.00%	12.24%	13.81%	13.20%	-2.04%
Gansu	28.29%	1.43%	12.89%	6.67%	0.60%
Qinghai	36.89%	2.19%	18.76%	1.51%	-0.14%
Ningxia	0.00%	0.00%	42.81%	0.00%	8.84%
Xinjiang	10.47%	6.01%	24.87%	-4.91%	-2.48%
China	5.87%	10.78%	5.96%	10.97%	2.36%

Table 4 Carbon intensity reduction from trade of China's provinces

	Observed carbon intensity reduction percentage (2010/2006)	Potential carbon intensity reduction percentages		
		From eliminating inefficiency	From spatial trading	From spatial and temporal trading
Beijing	29.8%	0%	0%	8%
Tianjin	23.8%	0%	15%	1%
Hebei	17.2%	0%	43%	10%
Shanxi	17.2%	0%	0%	29%
Inner Mongolia	19.5%	0%	0%	2%
Liaoning	18.4%	15%	4%	12%
Jilin	33.6%	0%	53%	3%
Heilongjiang	22.4%	10%	32%	9%
Shanghai	18.9%	0%	0%	-3%
Jiangsu	21.6%	2%	22%	-1%
Zhejiang	19.5%	1%	23%	5%
Anhui	13.6%	2%	42%	4%
Fujian	16.7%	4%	22%	3%
Jiangxi	17.0%	4%	13%	9%
Shandong	20.0%	11%	24%	6%
Henan	29.2%	8%	35%	5%
Hubei	15.7%	18%	26%	2%
Hunan	32.8%	12%	11%	7%
Guangdong	16.7%	0%	0%	0%
Guangxi	15.2%	0%	0%	13%
Hainan	-8.4%	0%	37%	8%
Chongqing	6.3%	0%	1%	12%
Sichuan	19.5%	6%	21%	10%
Guizhou	33.5%	0%	0%	21%
Yunnan	19.9%	20%	40%	7%
Shaanxi	14.0%	0%	22%	9%
Gansu	9.8%	22%	8%	10%
Qinghai	19.3%	27%	3%	13%
Ningxia	10.8%	0%	0%	30%
Xinjiang	2.7%	9%	1%	16%
China	19.7%	5%	20%	7%