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The dilemma for China's national carbon trading market: minimizing carbon abatement costs or maximizing net social benefits?

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Abstract

After a decade of planning and trials, China officially launched a national carbon trading in July 2021. Using a standard economic model, this study shows that an unconstrained carbon trading market would face a dilemma between minimizing pollution control costs and maximizing social benefits. We further show that this would be a significant challenge in China. Our results show that areas with higher population densities also would have higher costs for carbon reduction, and hence the polluters in those areas would be net buyers in the national market. Moreover, our analysis indicates a significantly high correlation between carbon dioxide emissions and other local pollutants. Therefore, cross-regional transactions may result in more emission of other pollutants in areas with higher population density under the unconstrained national cap-and-trade system and cause larger losses in social benefits. We call for more studies to address the issue.

Keywords: Carbon trading, Abatement costs, Carbon flows, Net social benefits

1 Introduction

On July 16, 2021, China kicked off the long-awaited national carbon trading market in its power industry, a precursor for a more comprehensive carbon market that will cover eight carbon-intensive industries soon. Efforts to establish a carbon cap-and-trade market started in 2011 in China. In 2013, seven provinces and cities—including Shenzhen, Shanghai, Beijing, Tianjin, Chongqing, Hubei, and Guangdong— started pilot programs for carbon trading. The plan that President Xi Jinping committed to at the Paris Conference 2015 is to establish a comprehensive carbon market that will span the entire nation and cover all carbon-intensive sectors. This market would serve as the key policy powertrain for China to meet its climate pledge: achieving peak emissions in 2030 and carbon neutrality in 2060.

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In this march toward a national market, few appear to be concerned about possible welfare loss due to the cross-regional carbon transaction. The carbon cap-and-trade system aims to reduce total carbon abatement costs under the constraint of achieving the targeted total carbon abatement. However, these two goals are not necessarily aligned with each other. Therefore, the questions that need to be addressed are: Would China's nationwide unified market lead to socially optimal outcomes while reducing pollution control costs? And: What could policymakers do if the answer were NO?

Our paper is a modest step toward answering these questions. We began with a stylized model to illustrate the dilemma between minimizing pollution control costs and maximizing social benefits. Provided that flows of carbon permits would be determined by the relative cost of carbon abatement across different areas, we empirically analyze the correlation of carbon dioxide (CO_2) abatement costs and population intensity. We find areas with higher population density also have higher costs for carbon reduction, and hence might be net buyers in the

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national market if no trading constraints were imposed. This may be problematic from the perspective of maximizing social benefits from pollution reduction. We discuss policy implications based on our results.

This research adds to the literature on evaluating the effect of the nationwide cap-and-trade system. Previous studies have considered topics such as market design [1–4], effects on pollution reduction [5–7], green technology innovation [8–10] and regional economic development [5]. However, the possible conflict between the goal of maximizing social benefit and the cap-and-trade system has not been sufficiently discussed. More specifically, the possibility of resulting in a higher level of air pollution in more populated areas under an unrestricted permit trading system has been relatively unexplored. Our study highlights the importance for policymakers to take this into consideration in future improvement of the cap-and-trade system.

The remainder of this paper is organized as follows. We briefly review the existing literature on carbon markets. Section 3 outlines the theoretical model of the emissions permit market. The empirical analysis is presented in Sect. 4. We provide a discussion of policy implications in Sect. 5, and Sect. 6 concludes this article.

2 Literature review

Based on the Coase Theorem, Hass and Dales [11] first proposed emissions trading as a policy instrument to drive pollution abatement. This market-based approach has become prevalent in recent years. Examples include sulfur dioxide (SO_2) cap-and-trade in the United States (US), the Carbon Emission Trading System in Europe, as well as carbon cap-and-trade systems in developing countries such as China and Korea [12]. Research on carbon and cap system has focused on two separate yet related questions.

First, is a market-based trade system an effective policy instrument for pollution reduction? For instance, Fowlie et al. [13] investigated pollution reduction in the context of Southern California's Regional Clean Air Incentives Market (RECLAIM) program by matching RECLAIM facilities with similar California facilities in non-RECLAIM areas. Their empirical results indicated that average emissions fell 20 percent at RECLAIM facilities. Analyzing the Ozone Transport Commission (OTC) nitrogen oxides (NOx) Budget Program, Swift [14] proved emission reductions in most states were about 11 percent, on average. Burtraw et al. [15] suggested that, by 2003, the emissions cap would represent a reduction of approximately 70 percent from the five-month summer emissions of 490,000 tons in 1990 from affected sources under the US SO_2 trading program.

In recent years, more studies began to pay close attention to China's carbon market. In spite of the previous frustration with the SO_2 emission trading [16–18], scholars have found that the carbon emission trading system works well and documented the positive effect of the trading system on carbon reduction. For instance, Based on a data envelopment analysis (DEA), Zhang et al. [6] found that the carbon trading system could reduce the carbon emissions (24.2%) of the pilot provinces. Cao et al. [8] provide retrospective firm-level evidence on the effectiveness of the cap-and-trade system in reducing emissions in China's electricity sector. Zhou et al. [19] and Wang et al. [20, 21] found a similar effect on carbon reduction. In a more recent paper, Wang et al. [22] showed that carbon trading policy has a significant and sustainable effect on carbon neutrality.

The second question is whether cap-and-trade systems can help achieve cost savings, which is the goal of efficiency. Consistent with the theoretical prediction, most empirical work has found a positive cost-saving effect. Burtraw et al. [15] proved that SO_2 and NO_x cap-and-trade programs have generated sizable cost savings over command-and-control (CAC) approaches and there is evidence that they have also induced technological improvements. Keohane [23] used an econometric model of the decision whether to install a scrubber under different policy regimes in the context of Title IV of the 1990 Clean Air Act. She showed that the use of the market-based instrument resulted in cost savings of between 16 and 25 percent. Popp [24] found that a cap-and-trade system could lead to dynamic efficiency,that is, companies tend to install scrubbers with higher sulfate removal efficiencies under a trading system. Carlson et al. [25] demonstrated that using low-sulfur coal and technical changes decreased marginal abatement cost curves by over 50 percent since 1985 within the SO_2 trading system in the US. In the long run, allowance trading would achieve cost savings of 700–800 million dollars per year compared to CAC regulation.

Studies on the China's carbon trading system have found mixed effects. Based on provincial panel data and industrial enterprise panel data in China, Zhang et al. [9] show that the carbon emission trading scheme significantly improves green development efficiency and regional carbon equality. Zhu et al. [10] showed that the carbon trading system has a positive effect on green development efficiency. However, according to Cao et al. [8], the carbon emission trading system has no effect on changing the coal efficiency of regulated coal-fired power plants. The reduction in carbon emissions was achieved by reducing electricity production.

Apparently, cap-and-trade systems are not free from criticism. A primary concern is that permits would flood into areas with high pollution abatement costs but poor economic conditions, causing hotspots of local pollutants and concerns about environmental justice [13, 26–29]. The empirical evidence is mixed. Fowlie et al. [13] found that the impact of RECLAIM on facility-level emissions does not vary systematically with neighborhood demographic characteristics, and therefore may not cause environmental injustice. However, Lejano & Hirose [26] identified that NO_x did concentrate in the Wilmington area of greater Los Angeles due to RECLAIM. A study from the US General Accounting Office [27] also provides a critical view, projecting that although total emissions of NO_X and SO_2 will decrease by about 100 thousand tons and two million tons, respectively, by 2020, while in some parts of the US there could be an increase due to emission trading. Shadbegian et al. [28] compared the market-based system to a CAC alternative and found that low-income populations received slightly lower benefits on average from Title IV. Therefore, they concluded that any environmental justice concerns are small, and concentrated on the poor, rather than on the black or Hispanic communities. A similar conclusion has been reported by a recent paper by Shapiro and Reed [29].

In spite of this mixed evidence, we note that the flow of emission permits, and therefore pollutant discharge, does not matter as long as the health or economic damages from pollution do not vary geographically. One could argue that this may be the case for carbon emissions since climate change would be global in nature. However, carbon emissions often share the same source as other pollutants (e.g., particulate matter, NO_x, and SO_2) that affect local atmospheric conditions significantly. The social damages from these local pollutants would vary significantly across regions depending upon population density, precipitation, and many other factors. Aggregate social welfare would be endangered if these local pollutants flowed from areas with low marginal social damages to areas with higher marginal damages.

The purpose of this paper is to investigate the potential impact of the national carbon trading system in China at the level of aggregate social welfare. The next section presents a stylized model to elaborate on the nature of the conflict between minimizing pollution abatement costs and maximizing social benefits within a cap-and-trade system. A discussion on whether these two goals could be simultaneously served in China's national carbon cap-and-trade system will follow.

3 Theoretical model

The purpose of this section is to theoretically illustrate the conflict between maximizing social benefits and minimizing pollution control costs.

3.1 Net social benefits maximization

Without the loss of generalizability, we start with a highly universal prototype planning problem. We assume that a certain pollutant could be reduced in K location, with cost $C(q_i)$ and potential benefits $B(q_i)$, in which q_i is the quantity of carbon abatement of facility i. Following the existing literature [3, 4], we assume that $C(q_i)$ is an increasing and convex function, while $B(q_i)$ is increasing and concave.

The problem of social benefit maximization is to find the value of q_i^* of q_i to maximize

$$\max_{q_i} \sum_{i=1}^{K} (B(q_i) - C(q_i)) \tag{1}$$

which means the solution of q^* must satisfy

$$\frac{\partial B(q)}{\partial q}|_{q=q*} = \frac{\partial C(q)}{\partial q}|_{q=q*} \tag{2}$$

namely, for any location i, the marginal benefit of carbon abatement $MB_i\left(q_i^*\right)$ must be equal to the marginal cost $MC_i(q_i)$.

when the marginal benefit exceeds the marginal cost, the location would continue to increase CO_2 abatement until the net benefits are optimized. On the other hand, CO_2 abatement will decrease if the marginal benefit is smaller than the marginal cost. In order to obtain the greatest aggregate social benefit, the above solution implies that the optimal level of pollution abatement at various locations could be very different, provided that the benefit and cost function are geographically specific.

3.2 Carbon abatement cost minimization

Assume that a central planner with authority over K locations aims to minimize the total social cost under the constraint of achieving a certain amount (Q) of CO_2 abatement. The planning problem is to find the $q_i^{'}$ of q_i that minimizes the total costs, so that

$$\begin{aligned} &\min_{q_i} \sum_{i=1}^{K} C(q_i) \\ &s.t. \sum_{i=1}^{K} q_i = Q \end{aligned} \tag{3}$$

The first-order conditions for the above cost minimization problem are:

$$MC_1\left(q_1^{'}\right) = MC_2\left(q_2^{'}\right) = \cdots = MC_K(q_K^{'}) \tag{4}$$

This realization occurs when the marginal abatement costs across all facilities are equal to each other.

Figure 1 illustrates the equilibrium condition using two locations, A and B, as an example. Suppose the marginal abatement cost of location B is higher than

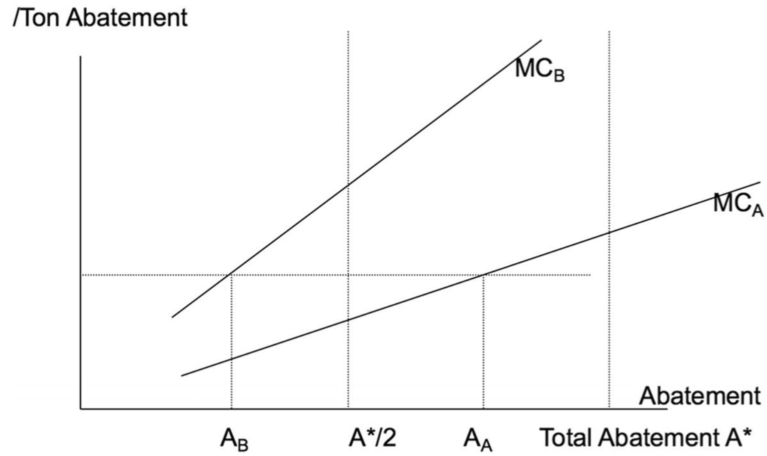

Fig. 1 The marginal cost curve for two locations

the marginal abatement cost of location A. There exists some price that location B would be willing to pay location A to increase its abatement so that location B can lower its abatement while keeping total abatement constant. Location B is better off because the price it pays is less than the cost of abatement. Location A is also better off because the cost of the additional abatement is lower than the trading price.

In the presence of a trading system, this cooperation can be easily achieved by trading emission permits. To reduce abatement costs, facilities can buy or sell emission allowances. This incentive to trade allowances exists between the two locations and would continue until their marginal abatement costs are equal.

As discussed earlier, net social benefits maximization means $MB_i\left(q_i^*\right) = MC_i\left(q_i^*\right)$, and carbon abatement cost minimization indicates an equivalent abatement cost of carbon across all regions. The only situation in which these two goals—minimizing total carbon abatement costs and maximizing net social benefits—could be simultaneously achieved is when marginal benefits from carbon abatement are the same across all regions.

For most pollutants, this condition is hard to achieve since regions differ in their population densities and geographic features. One may argue that this condition might hold for carbon emission. But when we realize that carbon emission often shares the same source with other local pollutants (e.g., particulate matter, NO_x, and SO_2) that affect local atmospheric conditions significantly, it immediately follows those marginal benefits from carbon abatement at different regions could be very dissimilar.

3.2.1 This raises a dilemma

To what extent should China allow carbon permits to flow across regions? The goal of minimizing pollution abatement costs cannot be fully achieved if cross-region trading is restricted; while the goal of maximizing net social benefits could be endangered if the flow of carbon permits is completely free. If trading constraints are desired, what kind of constraints should be imposed? The answers to these questions require a close look into the marginal benefits and costs of carbon abatement across different regions in China.

4 The benefits and costs of carbon abatement in China

The cost of CO_2 abatement in China at the province level has been studied in recent years [30–34]. The results of these studies vary due to the different time periods examined and the different estimation methods used. Wang et al. [33] only reported the average provincial marginal abatement cost in 2007, which was about 475.3 *yuan*/ton (68.9 *USD*/ton). Choi et al. [30] utilized the Slacks-Based DEA to estimate the shadow price of CO_2 in 30 provinces between 2001 and 2010. They reported the average marginal abatement cost of CO_2 emissions was about 7.2 USD per ton. Wei et al. [34] also used an extended Slacks-Based Measure model and estimated marginal abatement costs for 29 provinces over the earlier period of 1995–2007. The estimated abatement cost ranged from the lowest of 17.6 *yuan*/ton (2.6 *USD*/ton)[1] in Guizhou from 2002 to 2007, to the highest of 275.2 *yuan*/ton (39.9 *USD*/ton) in Beijing during the same period.

However, these models are built upon the assumption that all provinces have the same production functions. The estimation can be biased when this assumption is violated. To address this issue, Wang et al. [32] combined

[1] We use the average exchange rate (1 USD = 6.894 Yuan) in 2020.

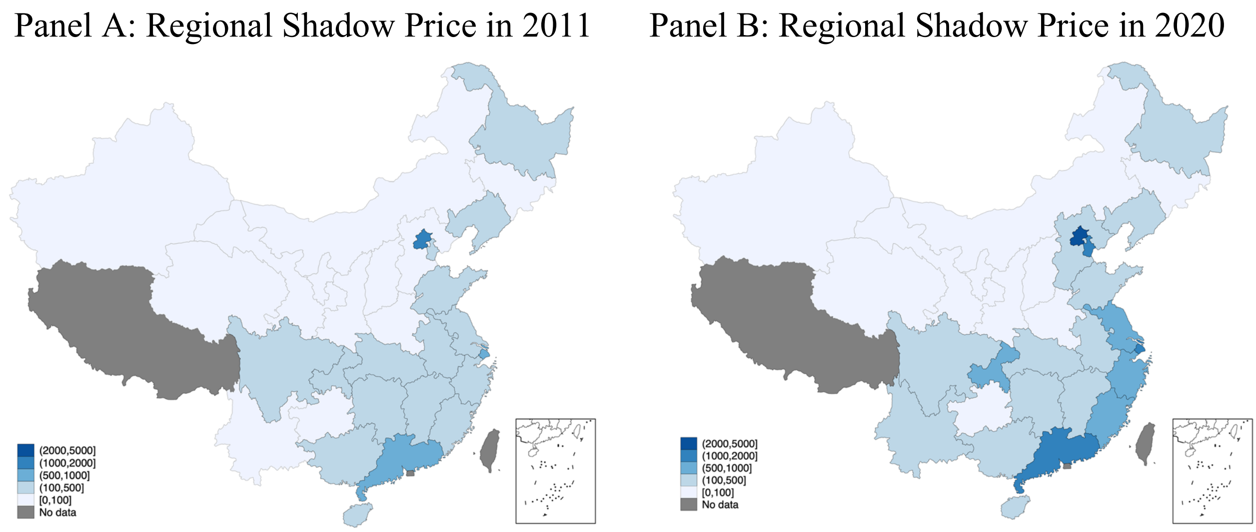

Fig. 2 Regional Shadow Price of CO_2 Emissions (*USD*/ton). Source: Wang et al. [32]

directional distance function and linear programming to calculate the shadow price in 30 provinces over the period 2011–2020, to account for the large differences in both technology efficiency and industry structure across China. This parametric approach is believed to provide more accurate estimates because of its advantageous accounting for provincial heterogeneity.

Therefore, in this study, we used the estimated shadow price of CO_2 by Wang et al. [32] in our analysis. Their result shows that the overall abatement cost of the country from 2015 to 2020 is increasing [32]. Meanwhile, the abatement costs show a clear spatial pattern in these years. Panels A and B of Fig. 2 summarize the results and illustrate the geographic distribution of shadow prices for carbon reduction in 2011 and 2020, respectively. It shows that eastern and southern coastal provinces have significantly higher abatement costs than middle and western ones.

The empirical results are driven by the fact that eastern and southern provinces are more economically developed than those in the middle and western parts of China and reducing carbon emissions requires sacrificing more domestic priorities. Furthermore, eastern and southern provinces already have been targeted by environmental enforcement, and therefore abatement does not look that easy to implement anymore. As Wang et al. [35] demonstrated, energy efficiency is already very high in East China, while it remains at a low level in comparison with the west. Yao et al. [36] provided detailed information showing significant heterogeneity across regions in China in terms of energy efficiency and carbon emissions performance. This indicates that significant carbon emissions reductions can be made by helping regions with low energy efficiencies and carbon emissions performances improve. The abatement costs will be low in these regions.

Cost differences across provinces would determine the flow of carbon permits when the nationwide and unified carbon market is functioning. Specifically, carbon permits would travel from the provinces with lower costs to those with higher costs. This predicts that co-pollution would flow from the west to the east. Now the question concerns the implications of this carbon emission flow on the goal of maximizing social benefits, which requires an investigation into the extent to which the marginal benefit of carbon reduction from the west and the east are comparable to each other.

In answering this question, we note two facts. First, it could be argued that CO_2 emissions are a global issue, and the marginal benefit of carbon abatement should not be geographically dependent. However, CO_2 does not enter the air in isolation from other pollutants [37]. The combustion process that generates CO_2 also produces a range of harmful co-pollutants including criteria pollutants such as particulates, SO_2, NOx, ozone precursors,

Table 1 The Correlation of CO_2, SO_2, Soot and Dust in 2016

Correlation Coefficient	CO_2	SO_2	NO_x	Soot and Dust
CO_2	1.0000	-	-	-
SO_2	0.8028***	1.0000	-	-
NO_x	0.8839***	0.8595***	1.0000	-
Soot and Dust	0.8025***	0.8898***	0.9034***	1.0000

Source: Wang et al. [21] and National Statistics Bureau 2016. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

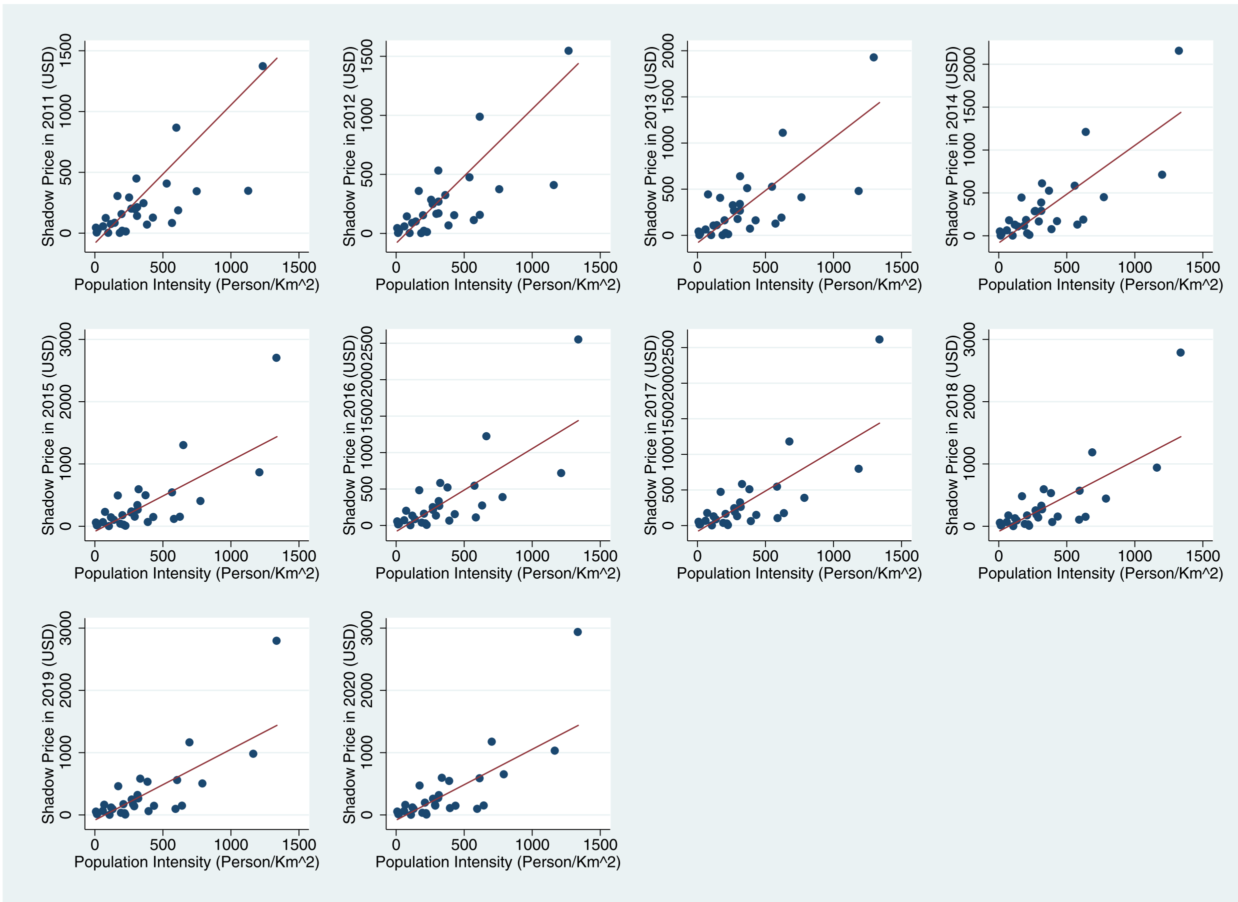

Fig. 3 The correlation between the shadow price (USD/ton) and population intensity (Person/Km^2)(Shanghai is dropped in Fig. 3 and Table 2 because its population density is so high that including it would easily dwarf the variation among other areas.)

and carbon monoxide (CO); as well as a wide range of toxic pollutants including many volatile organic compounds (VOCs), benzene, and other toxins. As Table 1 shows, the emissions of CO_2, SO_2, NOx, and soot and dust are highly correlated (correlation coefficients are larger than 0.80), suggesting they tend to stay together. All the correlation coefficients are positive at the 1% significant level.

The positive correlation demonstrates that excessive emissions of CO_2 will also contribute to the concentration of other toxic pollutants. The impact of these co-pollutants can be local or regional. It is a legitimate concern that these co-pollutants may also travel to regions with higher marginal costs of carbon abatement, along with carbon permits. Research on the trading system of NOx in the US found evidence that the trading system generated new externalities, such as the possibility that other air pollutants (e.g., volatile organics) are essentially traded along with it [26]. Therefore, when facilities take advantage of carbon trading systems to initiate or increase production, the emissions of co-pollutants are likely to increase in regions where the net buyers of carbon permits are located. This suggests the need to consider the local impacts of carbon emissions.

Second, because of the local health and economic impacts of the co-pollutants that are generated along with carbon emission, we need to determine whether the marginal damages of these co-pollutants are varied across regions in a significant manner. A full-fledged analysis of regional vulnerability to co-pollutant emissions is beyond the scope of this paper. However, a glance at the decisive factors for marginal benefits offers insightful information. Population density is of interest because one unit of pollution would arguably lead to a higher benefit loss if it occurs in a more populated area compared to a less populated one. Figure 3 graphs the correlation between the shadow price of CO_2 and population intensity from 2011 to 2020. We further calculated the correlation between the shadow price of CO_2 abatement in 2020 and population intensity at the province level, and found

Table 2 The Correlation Coefficient between Shadow Price and Population Intensity in 2020

Correlation Coefficient	Shadow Price	Population Intensity
Shadow Price (USD/ton)	1.0000	-
Population Intensity (Person/Km^2)	0.8082***	1.0000

Source: Wang et al. [32] and National Statistics Bureau 2021. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

a significant positive correlation (0.8082) between them (see Table 2). This demonstrates that more populated areas in China also tend to have higher marginal costs of pollution abatement. Hence, we predict that with the national trade system, carbon emission permits will flow into eastern and southern coastal provinces with denser population intensity from middle or western provinces with lower population density. It is reasonable to argue that the marginal social loss from one unit of increasing co-pollutants in more populated areas is larger than the marginal social benefit from one unit of decreasing the same pollutants in less populated areas. As such, the nationwide and unified carbon cap-and-trade system may risk endangering aggregate social welfare in the pursuit of minimizing pollution abatement costs.

Apart from human health, the cross-region transaction of carbon permit could lead to other changes that have an important implication on social welfare. For instance, the heterogeneous industrial structure across regions, when coupled with cap-and-trade systems, can bring a technique effect on the inland regions [38]. Over the past decade, the western regions undertook pollution-intensive factories which were transferred from the eastern coastal areas to seek economic development. According to a report from Moody's analytics,[2] large investments in manufacturing, infrastructure and resource extraction helped narrow inland provinces' overall gap with the coastal provinces. However, with the increase of the awareness of environmental protection, the urge for a healthy environment calls for a transformation towards a cleaner environment in these inland regions. The nationwide carbon trading system provides these regions additional financial incentives to reform their economic structure, encouraging low-carbon technology innovation. Therefore, we would observe the faster dynamic technology diffusion and industrial transfer in the west and north regions with lower shadow prices for carbon.

In addition, another focus of the market-based carbon control policy is to achieve optimal allocation through free competition and the free exchange of resources in the trading market. This could have important implications on the flow of labor and capital. On the one hand, labor, and capital experience gradual flows from low efficiency to high efficiency in pursuit of profit maximization. On the other hand, the carbon trading market also helps to correctly price the energy. The prices of energy have been relatively underestimated for a long time, resulting in excessive use of energy [39]. Through market-based adjustment, the trading market helps to internalize the social cost of carbon emission, balance the demand and supply of energy, and therefore bring more benefits to the economic development [40].

5 Discussion

We find that China's nationwide cap-and-trade system could endanger the goal of maximizing social benefits if the flow of carbon permits is not restricted. This echoes earlier studies on cap-and-trade systems. Shadbegian et al. [28] found that many facilities where emission reductions produced larger net benefits had bought allowances, thus, they emitted more than their initial allocation. The trading system led to sizable savings (16.8%) in abatement costs, but permit buyers tended to have higher-impact emissions than sellers, offsetting the cost savings. Solomon and Lee [41] argue that unfettered trading in a single national market is a mistake because it fails to adequately protect sensitive areas in the Northeast, particularly in New York State. Antweiler [42] pointed out that conventional emission permit markets are inefficient for non-uniformly mixed pollutants that create geographic "hot spots" of different ambient emission concentrations and environmental damage. This flow may also lead to concerns about social justice because the areas that buy permits are populated with disadvantaged people. According to Kaswan [43], there is a potential shift of the spatial distribution of dirty industries toward communities with less economic and political resources to resist the increase of net social welfare under cap-and-trade systems.

The question remains: How should China reconcile the potential conflict between minimizing carbon control costs and maximizing net social benefits? An immediate conclusion is that we need a careful assessment of the marginal benefits of carbon control in different regions. The assessment should recognize co-pollutants from carbon emissions and consider restricted trading between regions with substantial difference in marginal benefits. For some highly environmentally sensitive areas, restrictions should be enacted to limit their procurement of permits from other regions. Liu et al. [44] compared scenarios depicting separated provincial markets and a linked inter-provincial market. They showed that the

[2] https://www.moodysanalytics.com/-/media/article/2019/China-Provincial-Economies.pdf

combined system distributes welfare more unevenly and thus increases social inequity.

Another solution is to consider additional instruments to cope with carbon's co-pollutants. It seems to be a promising way to decrease the negative effect of carbon emission flows. However, in that case, we immediately encounter another challenging issue: the instruments controlling these co-pollutants will lead to a reduction of carbon, no matter how carbon control costs appear relative to other regions or market prices. This will lead to an excessive supply of carbon permits and a potential collapse of the carbon market. A similar policy coordination issue has been blamed for the failure of the SO_2 cap-and-trade system in China [45]. Wang et al. [45] argued that large companies are ordered to reduce SO_2 emissions through various types of CAC regulations, even when a sulfate trading market exists. Efforts to comply with these CAC regulations result in excess permits from large companies even when their pollution abatement costs are higher than the market price. Therefore, we also need to be very careful to carry out any additional policies to regulate the emission of co-pollutants.

Besides, we should not ignore the benefits of the carbon trading market on dynamic technology diffusion, industrial transformation, and allocation of resources, as discussed above. Health and economic impacts caused by the cross-regional carbon transaction are both important for the sustainable development of society. Taking these into account in future design for cap-and-trade markets would help to reconcile the conflict between minimizing carbon control costs and maximizing net social benefits.

6 Conclusion

China is determined to play a more significant role in combating global warming, and it is now clear that the government will rely on a cap-and-trade system as its primary policy instrument to achieve "carbon neutrality" by 2060. This paper calls for concern over the flow of carbon emission permits, and therefore, co-pollutants that are often tied to carbon. This would potentially lead to local health risks from co-pollutants and a decrease in aggregate social welfare. This concern has received relatively less attention from the policymakers in China who have focused on carbon abatement and cost control.

We found that with a nationwide cap-and-trade system, emission allowances likely would flow from the western provinces with sparse populations to the eastern and southern ones with dense populations. Although the environmental impact of carbon does not depend on where CO_2 is emitted, some poisonous gases that accompany carbon (such as SO_2, soot, dust, etc.) could have larger local health and environmental impacts and cause a deterioration of net social benefits. To alleviate this concern, some restrictions on cross-region carbon trading should be imposed, for instance, carbon permits that travel from the west to the east should be imposed a surcharge on the top of the market price.

This paper is by no means conclusive. It is written more in the spirit of raising questions. We call for additional studies on how to mitigate multiple pollutants from the same sources, how to coordinate diverse policy goals, and how to coordinate policies that target different pollutants that share common origins. These issues have been somewhat neglected in the existing literature [46].

Abbreviations

CO_2: Carbon dioxide; SO_2: Sulfur dioxide; US: United States; RECLAIM: Regional Clean Air Incentives Market; OTC: Ozone Transport Commission; NOx: Nitrogen oxides; CAC: Command-and-control; CO: Carbon monoxide; VOCs: Volatile organic compounds; DEA: Data envelopment analysis.

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Authors' contributions

YH, HY and FW conceived of the study; YH collected, processed, and analyzed the data; YH and HY interpreted the results; all authors drafted and edited the article. The author(s) read and approved the final manuscript.

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Availability of data and material

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

Haitao Yin is an editorial board member for Carbon Neutrality and was not involved in the editorial review, or the decision to publish this article. All authors declare that there are no competing interests.

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