Time-varying spillovers among pilot carbon emission trading markets in China

Zumian Xiao · Shiqun Ma · Hanwen Sun · Jiameng Ren · Chao Feng · Shihao Cui

Abstract
Clarifying the time-varying spillovers among pilot carbon emission permit trading markets in China is an important foundation for building the national carbon emission trading market. We calculate the dynamic spillover of carbon price return among the pilot carbon emission permit trading markets in China with the time-varying connectedness approach. The dataset is constructed from transaction data from seven pilot carbon markets in China during the period of June 23, 2014, to December 31, 2020. The quantitative analysis suggests that (i) Beijing and Chongqing carbon emission trading markets are the main spillover markets of carbon price returns, with strong pricing power, while the Guangdong and Tianjin markets are the main receivers of the price return spillover in other pilot carbon emission trading markets. (ii) The spillover effect among China’s carbon markets has a strong policy orientation. The improvement and development of the carbon market driven by macroeconomic regulation and control policies can effectively improve the spillover ability of the carbon market, and the market trading activity, namely the volatility of the carbon price return rate, can amplify the spillover ability of the carbon market in the short term. (iii) There exist three types of price return spillover among China’s pilot carbon emission trading markets, including central divergence, one-way chain transmission, and circular spillover. Along with the improvement of market operation efficiency, the central divergent type of spillover shifts to the pattern of circular spillover. It is necessary for the government to improve market efficiency and ensure the coordinated development of China’s pilot carbon emission trading market and national carbon emission trading market.

Keywords Carbon emission permit trading · Climate change · Time-varying connectedness · TVP-VAR model · Cross-market spillover

Introduction
Global climate change is triggered by greenhouse gas emissions (mainly carbon dioxide) as the global economy continues to develop rapidly, threatening human survival and development (Martin et al. 2014; Zhao et al. 2017; Han et al. 2019). In order to handle the problems of climate change effectively, fulfill the Paris Agreement commitments, and ensure the realization of global carbon reduction targets, China proposed a carbon emission permit trading market framework in 2011 and officially launched its first pilot carbon emission permit trading market in 2013. In 2020, China had established pilot carbon emission trading markets in Shenzhen, Beijing, Shanghai, Guangdong, Tianjin, Hubei, Chongqing, Sichuan, and Fujian; these markets are essential part of solutions for carbon emission control and environmental management tool for mitigating climate change (Oberndorfer 2009;
During the exploratory period of China’s pilot carbon emission permit trading market, each market operated independently, and aspects of policy implementation and institutional design differed (Zhang et al. 2017; Zhao et al. 2017; Zhu et al. 2020), having policy-oriented characteristics (Zhao et al. 2020; Chang et al. 2018a, 2018b). Enterprises in different regions are impacted by how completely different the environment and climate can be due to geographical factors, so there is a strong heterogeneity in their demand for carbon permit. Therefore, there are obvious differences in carbon price and price growth among the pilot markets (Jiang et al. 2014; Qi et al. 2014; Jotzo and Löschel 2014; Munnings et al. 2016). This, the price gap, however, will provide strong potential energy for the price linkage spillover of the pilot carbon market, in which market participants are important components of the spillover. For example, the carbon price in a certain market rises due to the electricity consumption policy or the impact of climate change, and the subjective expectations and investment behaviors of other market traders (e.g., financial institutions, individual investors) could be impacted by the change of the carbon price growth rate in the market. The impact will continue to be transmitted to other markets, forcing them to undertake and digest carbon transaction costs caused by non-local shocks, which will cause local carbon prices to rise and form the directional spillover of carbon price between the pilot carbon emission trading markets (Song et al. 2019; Zhu et al. 2020).

Additionally, the pilot carbon emission permit trading market will also be affected by some common factors and national macroeconomic policies. This implies potential economic relations and interactions. And, spillover effect must exist among the pilot emission trading markets with separated locations (Cong and Lo 2017; Chang et al. 2018a, 2018b, 2018a; Han et al. 2019; Zhu et al. 2020; Fan and Todorova 2017; Zhu et al. 2020). At the same time, the spillover of price return among China’s pilot carbon emission permit trading markets also has time-varying characteristics due to the dynamic trend of the above impact factors. However, what is the degree of integration of China’s pilot carbon emission trading market? What is the trend of price correlation among carbon markets? Which pilot carbon market has pricing power? Is there a tendency for price spillovers in each carbon market? These problems are urgent to optimize the pilot carbon market and promote the steady development of the national carbon market. Therefore, it is necessary to model the price return spillover between China’s pilot carbon emission trading markets to clarify the heterogeneity between China’s pilot regions and identify China’s major carbon emission pricing markets, so as to provide theoretical support for improving the system construction of the national carbon market launched on July 16, 2021.

We aim to deepen the study on the price return time-varying spillover of the pilot carbon emission permit trading markets in China. The time-varying connectedness approach based on the time-varying parameter vector autoregressive (TVP-VAR) model is adopted to investigate the return spillover among pilot carbon emission trading markets in China, which is the main contribution of this Paper. This methodology overcomes the shortcomings of the constant disturbance coefficient and variance in the vector autoregressive (VAR) model (Lundgren et al. 2018; Ji et al. 2018; Wang and Guo 2018; Song et al. 2019). This approach builds on the work of Antonakakis et al. (2018, 2020) and Gabauer and Gupta (2018, 2020) who advance the time-varying connectedness approach proposed by Diebold and Yilmaz (2009, 2012, 2014). This overcomes the burden of the often arbitrarily chosen rolling window size that can lead to erratic or flattened parameters and the loss of valuable observations; instead, it is possible to examine the dynamic connectedness at lower frequencies and with limited time series data. Time-varying connectedness can be used to examine correlation effects of one-to-many, many-to-one, and one-to-one among variables (Antonakakis and Gabauer 2017; Zhang and Hamori 2021; Jebabli et al. 2014; Liu et al. 2021) and is introduced here for the purpose of studying the dynamic spillover effect of the carbon price among pilot markets so as to broaden the research of the return dynamic spillover of the pilot markets in China.

**Literature review**

Currently, scholars attach great importance to ecology and environmental issues (Tao et al. 2021; Su et al. 2021a, b; Wang et al. 2021); more specifically, considerable attention has also been devoted to the study of the dynamic spillover effect of the carbon emission permit trading market. A large body of literature focuses on the correlation spillover effect between the carbon emission trading pilot market and the energy and financial markets (Oberndorfer, 2009; Chevalier 2009, 2011, 2012; Kumar et al. 2012; Hammoudeh et al. 2014, 2015; Yu et al. 2015; Fan and Todorova 2017; Chang et al. 2018a, 2018b; Ji et al. 2018; Wang and Guo 2018; Han et al. 2019; Jiménez-Rodríguez 2019; Lin and Chen 2019). For example, Jiang et al. (2018) demonstrated that the Shanghai Composite Index has a negative spillover effect on the carbon price of China’s pilot carbon emission permit markets, and there is a strong spillover effect between the carbon emission permit trading market and stock market, especially in energy-intensive and clean-energy industries (Tan et al. 2020; Wen et al. 2020; Dutta et al. 2018; Lin and Chen 2019). Meanwhile, Ji et al. (2018) used social network...
analysis to study the information spillover between carbon price returns and stock returns of 18 top European power companies. Outside the stock market, there is a spillover connectedness between the price of carbon emission and energy derivatives, especially the prices of oil, coal, and natural gas (Boersen and Scholtens 2014; Yu et al. 2015; Balcilar et al. 2016; Chang et al. 2018a, b, c; Ma et al. 2020).

Researches have focused on spillover effects between European and American carbon emission permit trading markets in their early stages (Oberndorfer 2009; Kumar et al. 2012; Jiménez-Rodríguez 2019). For example, Wang and Guo (2018) constructed a spillover index through the variance decomposition of prediction errors to study the dynamic spillover effects between the EU carbon market and energy markets. Along with the rapid development of China’s economy and the advance of China’s pilot carbon emission permit trading markets, the domestic emission reduction work has been completed effectively. The research perspective of scholars around the world has gradually been focused on the spillover effect among China’s pilot carbon emission permit trading markets (Jiang et al. 2014; Qi et al. 2014; Fan and Todorova 2017; Zhang et al. 2017; Han et al. 2019). Currently, the research on the spillover effect between the pilot carbon emission trading markets in China can be mainly divided into price return spillover effect and volatility spillover effect. The price return spillover effect refers to the influence of the change of the price return of one market on other markets, while the volatility spillover effect refers to the influence of the volatility of the carbon price of one carbon market on other carbon markets, which has no direction but scale. As far as the research methods are concerned, the VAR model and vector error correction (VEC) model are used frequently for studying carbon price return spillover. For example, Zhu et al. (2020) used the VAR model and conditional VAR model to evaluate the risk of China’s carbon emission trading market; the study indicates that there is a risk spillover effect between the Guangdong and Shenzhen carbon emission trading markets, while there is no risk spillover effect between the Hubei and Guangdong markets. Lv et al. (2020) used the VAR model and the time-varying parameter state space model to analyze the trend of the return spillover effects across the seven pilot carbon markets in China, finding that there is a network of the return spillover among China’s seven pilot carbon markets. Zhao et al. (2020) used the HJ test, DP test, and TVP-SVAR model to study the market nonlinear Granger causality and time-varying effect of carbon emission permit trading markets in Guangdong, Hubei, and Shenzhen, and found that there is a time-varying synergy between the three carbon emission trading markets; furthermore over time, there is a significant negative correlation or positive correlation between the three, which means that there is a deep foundation for the construction of China’s carbon emission trading market.

In addition, most of the literature on the spillover effect of price volatility is based on one or more GARCH models, such as E-GARCH, GARCH, MS-DCC-GARCH, STR-EGARCH, MVGARCH, BEKK-GARCH, and DCC-GARCH (Nicola et al. 2016; Bashier and Sadorsky 2016; Boubaker and Raza 2017; Tsuji 2018; Engle and Kroner 1995; Engle et al. 2013).

Several scholars have studied the spillover effect between carbon markets from the perspective of term structure (Baruník and Křehlík, 2018; Toyoshima and Hamori 2018; Ferrer et al. 2018; Wang and Wang 2019; Lovcha and Perez-Laborda 2020). For example, Guo and Feng (2021) used a generalized forecast error variance decomposition as well as a spectral decomposition in the VAR process to decompose the spillovers into short-term, medium-term, and long-term effects, for researching the return and volatility spillover among the carbon emission trading market in China.

The most relevant studies are lack of discussion for the dynamic evolution of spillover patterns among the pilot emission trading markets in China. These pilot carbon emission trading markets adapt for changing local economic development and variation in industrial carbon emission intensity, which form the time-varying characteristics of carbon price return spillover among them. Clarifying the dynamic process is the key areas for improving how pertinent government policy and enhancing the pilot and the national carbon emission market. In addition, the characteristics of the constant disturbance coefficient and variance of the VAR model are hard to effectively capture and explain the dynamic spillover effect between carbon markets, while the time-varying connectedness approach is able to solve the problem.

Thus, this study aims to characterize the time-varying spillover patterns of China’s pilot carbon emission trading markets by utilizing the time-varying connectedness approach based on the TVP-VAR model. The time-varying connectedness approach enable us to identify the time-varying spillover status of each carbon market and the dominant market of price discovery and its dynamic changes, and to clarify the spillover tendency of each market to understand the dynamic interaction of carbon emission trading markets in China.

Methodology and data

Methodology

To characterize the return dynamic spillover of the pilot markets in China, we use the time-varying connectedness approach. The quantitative analysis proceeds as follows:
The GIRFs represent the responses of all pilot carbon price return among carbon emission trading markets following a change of carbon price return in pilot carbon emission trading market. We compute the differences between a J-step-ahead forecast once the carbon price return of pilot carbon emission trading market shocked and once the carbon price return of pilot carbon emission trading market did not shocked. The differences can be accounted for to measure the magnitude of the return spillover of pilot carbon emission trading market, which can be calculated by the following:

\[
GIR_t(J, \delta_{j,t}, F_{t-1}) = E(Y_{t+j}|\varepsilon_j, F_{t-1}) - E(Y_{t+j}|F_{t-1})
\]  

(7)

\[
\psi^g_{j,t}(J) = \frac{A_{j,t}S_{j,t}\delta_{j,t}}{\sqrt{S_{j,t}}}, \quad \delta_{j,t} = \sqrt{S_{j,t}}
\]

(8)

\[
\psi^g_{j,t}(J) = S_{j,t}^{-1}A_{j,t}S_{j,t}\varepsilon_{j,t}
\]

(9)

where \( J \) represents the forecast horizon, \( \delta_{j,t} \) represents the selection vector with one on the \( j \)th position and zero otherwise, and \( F_{t-1} \) represents the information set until \( t-1 \).

The construction of the dynamic total connectedness index

Subsequently, we compute the GFEVD, which can be interpreted as the variance share one pilot market has on others. These shares are then normalized, so that each row sums up to 1, meaning that all markets together explain 100\% of the return of carbon price in pilot carbon emission trading market. This is calculated as follows:

\[
\phi^g_{ij,t}(J) = \frac{\sum_{i=1}^{J-1} \sum_{j=1}^{N} \phi^g_{ij,t}}{\sum_{i=1}^{J-1} \sum_{j=1}^{N} \phi^g_{ij,t}}
\]

(10)

with \( \sum_{i=1}^{J-1} \phi^g_{ij,t}(J) = 1 \) and \( \sum_{i,j=1}^{N} \phi^g_{ij,t}(J) = N \). Using the GFEVD, we construct the total connectedness index (TCI), which is as follows:

\[
C_T^g(J) = \frac{\sum_{i,j=1,\neq}^{N} \phi^g_{ij,t}(J)}{N} \times 100
\]

(11)

\[
= \frac{\sum_{i,j=1,\neq}^{N} \phi^g_{ij,t}(J)}{N} \times 100
\]

(12)

The TCI means the average impact one variable has on all others. If this measure is relatively high, it implies that the interconnectedness of the network is high.
The construction of the dynamic net pairwise connectedness index

At the same time, we construct the pairwise pilot markets’ return spillover connectedness index, including the mean level \( (C^g_{i \rightarrow j}(J)) \) of spillover from pilot market \( i \) to market \( j \), which is calculated as follows:

\[
C^g_{i \rightarrow j}(J) = \frac{\phi^g_{j,i}(J)}{\sum_{i=1}^{N} \phi^g_{j,i}(J)} \times 100
\]  \hspace{1cm} (13)

The mean level \( (C^g_{i \rightarrow j}(J)) \) of spillover from pilot carbon emission trading market \( j \) to pilot carbon emission trading market \( i \) can be calculated as follows:

\[
C^g_{i \rightarrow j}(J) = \frac{\phi^g_{i,j}(J)}{\sum_{i=1}^{N} \phi^g_{i,j}(J)} \times 100
\]  \hspace{1cm} (14)

We extracted Formulas (13) and (14) and defined the net pairwise spillover of the carbon price from pilot market \( i \) to pilot market \( j \) as the return spillover from market \( i \) to market \( j \) minus the return spillover from market \( j \) to market \( i \). This is calculated as follows:

\[
C^g_{i,t} = C^g_{i \rightarrow j}(J) - C^g_{i \rightarrow j}(J)
\]  \hspace{1cm} (15)

The construction of the dynamic directional connectedness index

Based on the above study, we can calculate the magnitude of the return spillover effects between a pilot market and other pilot markets, such as the aggregated impact that a shock in variable \( i \) has on all other variables (To, spillover). The expression is as follows:

\[
To_i = \sum_{j=1,j \neq i}^{N} C^g_{i \rightarrow j}(J)
\]  \hspace{1cm} (16)

For the aggregated impact received by pilot market \( i \) from all other pilot markets (From, spillover), the expression is as follows:

\[
From_i = \sum_{i=1,j \neq i}^{N} C^g_{i \rightarrow j}(J)
\]  \hspace{1cm} (17)

According to Formulas (16) and (17), the net spillover denotes the difference between To, spillover and From, spillover, such as from Formula (18):

\[
Net_i = To_i - From_i
\]  \hspace{1cm} (18)

As shown in Formulas (15) and (18), if \( C^g_{i,t} \) and \( Net_i \) are positive, it means that the impact of pilot market \( i \) on all other markets in the network is greater than the reaction of all other markets in the network. On the contrary, if \( C^g_{i,t} \) and \( Net_i \) are negative, pilot market \( i \) is impacted by other markets in the network and accepts their net return spillover.

Data

There are nine pilot carbon trading markets in China, including Beijing, Shanghai, Chongqing, Hubei, Tianjin, Guangdong, Shenzhen, Fujian, and Sichuan. In this paper, we choose seven of the pilot carbon market as the research samples. Trading data from Fujian market has a short sample period, and Sichuan market trades Chinese certified emission reduction (CCER); hence, these markets are removed from the analysis. It is worth noting that our sample data contain price data corresponding to zero trading volume, which is related to the fact that local enterprises do not carry out carbon emission trading. Additional reasons why the trading demand of the enterprises may be constrained are that the local government has relaxed the carbon emission restrictions and that the carbon emissions of enterprises have not reached the upper limit of their own carbon permit. However, the dynamic changes of market effective demand and ineffective demand can also be reflected truly by the sample data of zero volume which is an important basis for the measurement of inter-market spillover, providing effective economic information for the analysis of inter-market spillover.

Subsequently, the first-order logarithmic difference of the closing price data of each pilot market is used to measure the carbon price return; this, in turn, is used to study the spillover effect between markets. The daily closing carbon price series are fetched from the China’s carbon emissions trading network (http://www.tanpaifang.com). Considering the availability of permit price data in each pilot market, our weekly sample data span from June 23, 2014, to December 31, 2020.

Notably, the carbon permit quota in the Shenzhen pilot carbon market is different from that in other markets. The Shenzhen market assigns a new name with year label to the carbon emission permits that are listed and traded each year and implements differentiated pricing for them; this means that as long as a new product is listed, traders can keep trading in the following years. Thus, there are many types of carbon permit products available to traders in the Shenzhen market such as SZA-2016, which can be used for compliance in 2016 and later years and is still in a tradable state in 2020. Based on the above discussion, we cannot take the new products coming to market every year as the main product to represent the true state of the transaction due to the fact that
it may not necessarily be the most active. Hence, following the criteria proposed by Guo and Feng (2021), we divide the sample time span into eight parts according to the time when the new product is launched, and select the product with the largest average daily volume every year as the more concerned and preferred product in the market, connecting their prices into a time series in chronological order as a representative of the Shenzhen market, as shown in Table 1. It is worth noting that from July 2019 to December 2020, this paper still takes 1 year as a sample span period and chooses June 30, 2020, as the time dividing point.

**Empirical results**

In order to ensure the robustness of the results, we determine the lag period of the time-varying connectedness approach based on the TVP-VAR model process according to the information criterion, as shown in Table 2. Notably, according to the HQIC and SBIC criteria, the lag order we select is 0, and according to the FPE criteria and AIC, the lag order we select is 2. Thus, a one-lag connectedness approach based on the TVP-VAR model has been selected on the return series of the carbon emission trading markets in China after compromise consideration.

At the same time, the sample data is tested for stability. The results in Table 3 show that the carbon price returns of each pilot carbon market are stationary sequences.

**Static analysis of the return spillover of pilot markets in China**

The magnitude of the return spillover among the pilot markets is shown in Table 4. The spillover of carbon price return of the sample markets is as high as 53.86% overall, and the average spillover effect in a single market is as high as 7.69%, which indicates that the pilot markets’ carbon price returns have a slightly significant spillover effect, and Zhao et al. (2020) found the same conclusion. The carbon price returns of the Beijing carbon market, Chongqing carbon market, and Shenzhen carbon market have high spillover levels, which reach 2.23%, 4.9%, and 0.98%, respectively. Among these three markets, the magnitude of carbon price return spillover in Chongqing carbon market is the highest, indicating that the market’s carbon price guidance ability is significantly higher than that of other pilot carbon markets, which is related to the high activity of carbon prices, that is, high volatility. The strong ability of carbon price return spillover in Beijing and Shenzhen pilot carbon markets benefits from the advantages of its establishment time. For example, the Shenzhen carbon market is the first pilot carbon market in China, which started on June 18, 2013, and the Beijing carbon market followed, which started on November 2013.

### Table 1 Price return series construction for the Shenzhen market

| Time interval     | Selected products |
|-------------------|-------------------|
| 2014.06.23–2014.08.05 | SZA-2013          |
| 2014.08.06–2015.07.13 | SZA-2014          |
| 2015.07.14–2016.08.31 | SZA-2015          |
| 2016.09.01–2017.07.28 | SZA-2016          |
| 2017.07.31–2018.07.03 | SZA-2016          |
| 2018.07.04–2019.07.07 | SZA-2016          |
| 2019.07.08–2020.06.30 | SZA-2015          |
| 2020.07.01–2020.12.31 | SZA-2017          |

In eight different time periods, the representative products chosen are SZA-2013, SZA-2014, SZA-2015, SZA-2016, SZA-2016, SZA-2016, SZA-2015, and SZA-2017.

### Table 2 Lag and information criteria of the time-varying connectedness approach based on the TVP-VAR model

| Lag | LL      | LR    | df | p    | FPE  | AIC    | HQIC   | SBIC  |
|-----|---------|-------|----|------|------|--------|--------|-------|
| 0   | 3529.17 | 113.810 | 49 | 0.000 | 1.1e–18 | –21.477 | –21.444* | –21.396* |
| 1   | 3586.08 | 147.730 | 49 | 0.000 | 9.1e–19* | –21.677* | –21.192 | –20.462 |
| 2   | 3659.95 | 52.801  | 49 | 0.329 | 1.0e–18 | –21.539 | –20.828 | –19.758 |
| 3   | 3686.35 | 93.099* | 49 | 0.000 | 1.1e–18 | –21.524 | –20.587 | –19.176 |
| 4   | 3732.90 | 57.962  | 49 | 0.178 | 1.2e–18 | –21.402 | –20.239 | –18.488 |

*Significant at the 5% significance level

**Significant at the 1% significance level**
Beijing carbon market and Shenzhen Carbon market belong to the early pilot markets in China, owning the advantage of development time gap. At the same time, the ability of carbon price return spillover is also related to the abundant experience of market construction and relatively the complete market mechanism of Beijing carbon market and Shenzhen carbon market. The Guangdong carbon market, Tianjin carbon market, and Hubei carbon market mainly play the roles of receiver of net spillover. Among these, the Guangdong and Tianjin carbon emission trading markets are the most significantly affected by external spillover due to the lower participation of traders in Guangdong and Tianjin carbon markets compared to other pilot carbon markets.

The research conclusion is clarified in Table 4, which shows the data on the magnitude of the net return spillover of the pilot carbon emission permit trading markets. The results are illustrated in Fig. 1.

### Dynamic analysis of the return spillover of the pilot markets in China

The dynamic change of the total return spillover level in China’s pilot carbon emission trading markets is shown in Fig. 2. The level of total spillover is at a relatively high stage at the beginning of the establishment of each pilot carbon market. The main reasons for this are that China’s pilot carbon market has a short running time, the market is in the exploratory stage, the carbon price is in an inefficient state, and the price mechanism that can reflect the external cost of carbon emissions has not yet been formed. Therefore, the trend of the carbon price of each market is affected by market information (Liu et al. 2015; Zhao et al. 2016; Ren and Lo 2017). For example, the information channels can be provided by the trading expectations of traders among the pilot markets for establishing price spillover linkages between pilot carbon markets, which increases the magnitude of cross-market spillover of carbon price return. Along with the development of each pilot carbon market, the mechanism of the market is gradually established. At the same time, China’s carbon trading markets have gradually changed from an inefficient state to a weak effective state.

The overall spillover level between markets has been declining, and the carbon price independence of the pilot market has increased (Zhao et al. 2017). The pace of economic transformation of China and the strength of the strict control of carbon emissions have accelerated in 2017, which has forced carbon-intensive enterprises to increase the frequency and volume of carbon market transactions. For example, the

### Table 4 The return spillover of the pilot markets in China

|       | BJ  | GD  | HB  | SH  | TJ  | CQ  | SZ  | From others |
|-------|-----|-----|-----|-----|-----|-----|-----|-------------|
| BJ    | 93.69 | 1.35 | 0.46 | 2.03 | 0.56 | 0.87 | 1.05 | 6.31        |
| GD    | 1.55 | 91.33 | 0.51 | 1.85 | 2.57 | 1.28 | 0.91 | 8.67        |
| HB    | 1.37 | 0.44 | 92.61 | 1.09 | 2.69 | 1.23 | 0.58 | 7.39        |
| SH    | 2.84 | 1.24 | 1.4 | 91.73 | 0.68 | 1.07 | 1.04 | 8.27        |
| TJ    | 0.98 | 0.91 | 2.35 | 2.44 | 87.57 | 1.95 | 3.81 | 12.43       |
| CQ    | 0.58 | 0.37 | 0.65 | 0.32 | 0.14 | 96.45 | 1.49 | 3.55        |
| SZ    | 0.91 | 0.87 | 0.58 | 1.29 | 2.04 | 1.95 | 92.07 | 7.93        |
| To others | 8.24 | 5.18 | 5.95 | 9.02 | 8.67 | 8.62 | 8.88 | 54.56       |
| Net   | 1.92 | −3.49 | −1.44 | 0.75 | −3.76 | 5.07 | 0.95 | 7.79        |

The data in the table is the static spillover level between the pilot carbon emission permit trading markets. The names of the pilot markets in the table are expressed as Chinese pinyin alphabetical abbreviations.

### Fig. 1 Directed weighted network for the return spillover of the pilot carbon markets in China

Blue (yellow) nodes illustrate the net transmitter (receiver) of spillover. Vertices are weighted by averaged net pairwise directional connectedness measures. The size of nodes represents weighted, averaged net total directional connectedness. Meanwhile, the return spillover index between pilot markets is taken as the edge weighting, and the net spillover between markets is expressed by the thickness of the edge.
amount of permit declaration of the Chongqing enterprises exceeded the total amount, and the carbon price began to rise significantly during this period, which means that the magnitude of total return spillover was pushed to a relatively high level. The optimization and development of the carbon market is a dynamic process. In the later stage, along with the formation of a unique mechanism structure and the enhancement of the pricing power of each pilot market, carbon price tends to be stable. Therefore, the level of inter-market spillover began to decline again in 2019. Subsequently, when the COVID-19 pandemic broke out, the Chinese government advocated a policy of “not going out unless necessary” (despite the Spring Festival holiday in China at that time) in an effort to control the spread of the virus. As a result, the output of enterprises and factories decreased, which caused the demand for carbon emission permits to shrink, and the spillover effects among carbon markets to maintain a steady state.

In summary, the total return spillover level of China’s pilot carbon emission permit trading market shows a trend of “decrease-increase-decrease,” which confirms that the spillover effect between China’s pilot carbon markets has obvious dynamic characteristics.

From and To connectedness indexes

In order to clarify the dynamic spillover status of each pilot market in China and the changes in carbon pricing power among pilot markets, it is particularly necessary to measure the dynamic directional spillover of carbon price return in pilot emission permit trading markets in China. We measure the magnitude of the return spillover effects of one market on other markets (“To spillover”) and other markets on one market (“From spillover”) and the net spillover of seven pilot carbon emission permit trading markets, as shown in Fig. 3.

Return spillover effects between markets are mainly concentrated in the early stage of market establishment, and we can clearly find that there are strong spillover effects in Beijing, Chongqing, Shenzhen, and Shanghai. Among them, the high level of the carbon price return spillover in the Beijing carbon market, Shenzhen carbon market, and Shanghai carbon market may be related to the improvement and development of the basic system and infrastructure of the carbon markets driven by policies, which is consistent with the conclusions of Lv et al. (2020). For example, at the end of 2014, the Beijing carbon market opened the opening limit of individual traders and completed the first transaction. At the same time, Beijing created the first cross-regional carbon trading market in China with Chengde and expanded the coverage of the Beijing carbon market. In April 2016, Beijing officially launched the cross-regional carbon emissions trading with Inner Mongolia, and the capacity of the Beijing carbon emission trading pilot market was expanding. In May 2016, the Beijing carbon market formed a “1 + 1 + N” policy system and a monitoring report certification system (MRV) and established an electronic reporting system for carbon emission data, showing the function of the national carbon trading hub. As far as the Shenzhen carbon market is concerned, in June 2014, the Shenzhen carbon market launched a carbon quota auction to promote the transition of carbon rights from free quotas to paid quotas. In August 2014, the foreign investors were incorporated into the Shenzhen carbon market and the Shenzhen carbon market became China’s first carbon market open to foreign investors. In November 2014, the carbon quota trusteeship mechanism was launched by the Shenzhen carbon market. Subsequently, the Shenzhen carbon market quickly promoted the development of carbon finance. For example, in May 2015, the first domestic private carbon fund was launched by the Shenzhen carbon market. The Shanghai carbon market opened to domestic investors in September 2014 and steadily expanded the coverage of the market. Therefore, the spillover effects among China’s pilot carbon markets have a strong policy orientation, and the improvement and development of the carbon market under the macro-control policy can effectively improve the external spillover level of the market. The economic growth of Chongqing relies mainly on the secondary industry. In the early stage of establishing the Chongqing carbon emission trading market, the government’s supply of carbon permit is quite sufficient to coordinate the relationship between carbon emissions and economic growth, resulting in low enthusiasm for carbon market transactions. Subsequently, challenges have emerged to the development of the secondary industry in Chongqing due to China’s economic transformation. The participants crowd in, and carbon price volatility
has risen to a high level, which has promoted the spillover level of Chongqing’s carbon market. However, the carbon emission trading markets in Guangdong, Hubei, and Tianjin are seriously affected by external spillover, especially in Guangdong, which has set a new mode for distributing the carbon permits. For example, the proportion of free permit electricity is set to 95%; the free permit ratio of steel, petrochemical, cement, and paper enterprises is 97%, and the free permit ratio of aviation enterprises is 100%, which imposes a binding force on carbon price fluctuations and enhances the stability of carbon price returns. This is one of the important factors that the Guangdong carbon market becomes the main receiver of external spillovers. It is worth noting that the industries included in the pilot areas such as Guangdong and Hubei are mainly high-emission industries—for example the electric power, steel, cement industry, and chemical

Fig. 3 The dynamic directional connectedness of the pilot markets’ carbon prices. The dash line represents the “To Spillover” of carbon price return in pilot market \( i \) to other pilot markets, and the solid line represents the “From Spillover” of the carbon price return in pilot market \( i \) from other pilot markets; the directions of the “To Spillover” and “From spillover” are indicated by plus and minus signs, respectively, while the dotted line represents the sum of the two, which is the “Net spillover” of pilot market \( i \).
industries, and the cumulative carbon trading volume of the two markets has long been among the highest. Thus, the magnitude of the market spillover is not correlated with the trading volume but is mainly related to volatility of the carbon price return. Chongqing market, of which trading volume is low, is the best evidence, as detailed later.

Spillover levels of pilot markets have continued to decline as the pilot carbon markets in China matured; moreover, it is worth noting that the Beijing carbon market plays a dominant role in relation to the other markets during the whole sample period, showing the capacity of strong spillover. The reason for this is that the coercive force of the policy implementation of Beijing, the capital of China, is the guarantee of its carbon market spillover status. The spillover indices of other pilot areas fluctuate around the 0-scale line, and the magnitude of the spillovers among the carbon markets is similar, which again reflects that the spillover effects between pilot carbon markets in China are policy-oriented.

Net pairwise dynamic directional connectedness

It is meaningful to further analyze the return spillover microstructure of pilot carbon emission permit trading markets in China based on research on the spillover “from one market to other markets” and “from other markets to one market” to clarify the return spillover connectedness between two countries. Thus, we will capture and identify the microscopic structure of the spillover among pilot markets and then clarify the dynamic characteristics of the spillover. In this paper, the network analysis method is used to conduct a visual dynamic analysis of the microscopic spillover structure between the pilot carbon markets in China.

Beijing is China’s capital and policy center; thus, the policies of Beijing have strong binding force. Therefore, the Beijing pilot carbon emission trading market is gradually maturing driven by the policy force (Hu et al. 2017; Jotzo and Loschel, 2014; Zhang et al. 2014), which will impact other pilot markets, such as the Tianjin, Shanghai, and Shenzhen pilot markets, as shown in Fig. 4. Tianjin is geographically adjacent to Beijing, so geographical conditions provide convenience for the policy spillover of the Beijing carbon market to affect the Tianjin carbon market. Therefore, the carbon market in Beijing has a significant spillover impact on the carbon market in Tianjin, which highlights the policy-driven spillover effect between markets and also shows that the level of spillover between markets is often associated with policy performance effects. In addition, the relatively perfect market system and policy enforcement of Beijing are also a vital reason for its spillover to Shanghai and the Shenzhen carbon markets.

The positive impact of the gradual development of the pilot carbon markets in China and the continuous improvement of the market efficiency are also reflected in the Guangdong and Hubei carbon markets, as shown in Fig. 5.

In the early stage of establishing pilot carbon markets, the Guangdong and Hubei carbon markets played the role of spillover receiver and were impacted by the return spillover of the Beijing, Shanghai, Chongqing, and Shenzhen carbon markets. Subsequently, the Guangdong and Hubei carbon markets gradually developed. For example, in August 2014, in order to accelerate the transformation from free quota mode to paid quota mode, the Guangdong carbon market increased the proportion of paid quota in power industry to 5%. In September 2014, the Hubei carbon market launched carbon asset pledge loan financing business; in June 2015, the Hubei carbon market was allowed to introduce qualified foreign investors; in July 2019, the Hubei carbon market launched spot forward trading products, which enriched the trading targets of the market.

Thus, the market spillover status of Guangdong carbon market and Hubei carbon market has improved, and

![Fig. 4](https://example.com/fig4)

The dynamic net pairwise connectedness of pilot markets (part 1). The results are based on the time-varying connectedness approach based on the TVP-VAR model, and the solid line represents the change trend of the net return spillover from one market to another.
the spillover effects among the pilot carbon markets have declined sharply.

The micro-spillover structure characteristics between the Chongqing carbon market and other carbon markets are the best evidence to demonstrate that market participation and the carbon price volatility are positively correlated with the magnitude of the volatility of the carbon price return, as shown in Fig. 6. The trading volume of the Chongqing carbon market is at an absolute low level, and the market maturity is relatively insufficient. The Chongqing carbon market is still the main transmitter of the return spillover before 2017, and the level of spillover has exceeded the Beijing carbon market. The main reason is the high volatility of carbon price return. Along with the continuous improvement of market efficiency, the carbon pricing power of each market increases and the magnitude of the return spillover decreases again.

Cross-market spillover tendency of the carbon price return in pilot markets

This paper is based on research on the micro-structure of the return dynamic spillover of pilot markets in China. According to the spillover of the carbon price return between two markets, we rank the main “From” markets and “To” markets of the single pilot market, recording the top two markets. This effectively depicts the tendency of the spillover in seven pilot markets and measures the “spillover distance” so as to provide a decision-making reference point for the carbon emission market system in China to establish, modify, and improve.

As shown in Fig. 7, the Beijing and Chongqing markets during the period 2014 to 2017 were the main transmitter of the spillover to most pilot carbon markets; the spillover level ranks at the forefront, maintaining a close “spillover distance” for most pilot carbon markets. Guangdong and Tianjin are the spillover tendency markets and main spillover objects of other carbon markets. It is worth noting that the level of spillover in Chongqing, which is the primary transmitter of spillover to Beijing, is higher than that in Beijing in the stage. During the period of 2018 to 2020, Beijing still maintains a high spillover status and a close spillover distance with some carbon markets, such as Hubei and Shanghai; Moreover, the spillover level of Beijing, which becomes the primary transmitter of spillover to the Chongqing market, is higher than that of Chongqing. Thus, the roles of

![Fig. 5 The dynamic net pairwise connectedness of pilot markets (part 2). The results are based on the time-varying connectedness approach based on the TVP-VAR model, and the solid line represents the change trend of the net return spillover from one market to another.](image-url)
Beijing and Chongqing are reversed, and the carbon pricing power of the Beijing carbon market improves. Additionally, the Guangdong and Hubei markets have also become the main transmitters of spillover to other pilot areas, and the spillover levels of each market are gradually similar.

Based on the study of spillover tendency between the pilot carbon markets in China, the following interesting conclusion can be identified: From 2014 to 2017, there are three patterns of dynamic spillover of carbon price returns between pilot markets, including central divergent spillover, one-way chain conduction spillover, and circular spillover, as shown in Fig. 8. For example, the Chongqing carbon market is the center of divergence spillover, and the spillover of carbon price return is transmitted through the Hubei, Shanghai, and Tianjin chain, which finally brings a spillover impact on the Guangdong carbon market (Fig. 9).

In addition, the Hubei, Shanghai, and Tianjin carbon markets formed a spillover closed loop, which is also one of the important spillover patterns of the pilot carbon market in China. From 2018 to 2020, the pattern of spillover has changed from a central divergent path to a circular spillover path. The main reason for this is that the ability of each pilot carbon market to resist external spillover shocks has been enhanced by the improvement of the market structure and the maturity of the mechanism. Thus, the correlation of spillovers among pilot markets has decreased, the spillover level of each pilot market has gradually converged, and the number of spillover closed loops has increased, such as the closed loops between the following: Hubei, Shanghai, Tianjin, Guangdong, and Beijing; Tianjin, Hubei, and Shanghai; and Guangdong, Beijing, Shanghai, and Tianjin.

Therefore, it is particularly critical to clarify the spillover structure between the pilot carbon markets, the spillover status, and spillover tendency of each market and to identify the spillover patterns and path between markets, which provides an important theoretical guarantee for the mechanism design and policy formulation of the national carbon market.

Conclusions and policy implications

In this article, the time-varying connectedness approach based on the TVP-VAR model is used to construct a dynamic spillover index to analyze time-varying connectedness among pilot carbon emission permit trading markets in China. The main conclusions of this paper are as follows:
(1) The coercive force of the policy promotes the continuous development and improvement of the carbon emission trading market in Beijing which is the policy center in China, and the carbon market of Beijing carbon market has a high spillover status and strong pricing power, maintaining a high spillover level during the whole sample period. At the same time, the Guangdong and Tianjin carbon emission trading markets are the main receivers of the external spillover.
The magnitude of the spillover among pilot carbon emission trading markets is time-varying due to some factors. In the short term, the spillover level of carbon market is related to the volatility of carbon price return; for example, along with the volatility of carbon price return gradually stabilized, the spillover level of the Chongqing carbon emission trading market decreased. Additionally, with the development of pilot carbon emission trading market, the pricing independence of carbon emission trading market is also gradually enhanced, which improves the capacity of the spillover of carbon emission trading markets, and the Guangdong and Hubei carbon emission trading markets are powerful evidences.

There are three patterns of spillover connectedness between China’s pilot carbon markets: central divergence spillover, one-way chain conduction spillover, and circular spillover. However, along with the improvement of market operation efficiency and the improvement of market mechanism, the spillover level between markets also shows a trend of gradual convergence, and the pattern of central divergent spillover shifts to the pattern of circular spillover.

Some policy implications can be drawn from the above conclusions. First, the government should promote the coordinated development of the pilot carbon emission trading market and the national carbon emission trading market, give full play to the regional carbon reduction advantages of the pilot carbon emission trading market to fill the blank area of carbon reduction in the national carbon emission trading market, and establish a dynamic adjustment mechanism for the coverage of carbon emission between the pilot carbon emission trading market and the national carbon emission trading market, ensuring that as the national carbon emission trading market continues to mature and improve, the coverage ratio between the two can be adjusted flexibly dynamically. Second, in the process of continuous promotion of the national carbon emission trading market, it is necessary to fully consider the dynamic changes in the spillover status and pricing power of the pilot carbon emission trading market so as to realize the gradual substitution of the national carbon market on the pilot carbon market in the order of weak spillover to strong spillover, ensuring the efficient operation of the carbon market, and effectively cover the national carbon emissions to prevent the breeding of carbon leakage. Third, based on the full consideration of regional carbon emission status, and carbon market development and pricing power, the government should establish an institutional continuous optimization mechanism and compatibility mechanism to promote the rapid development of national carbon emission trading market, giving full play to its price guidance.

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Data availability The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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