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Similarity and heterogeneity of price dynamics across China's regional carbon markets: A visibility graph network approach

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HIGHLIGHTS

- Price dynamics of carbon pilots are studied as a whole by visibility graph networks.
- The networks are similar in topology properties but differ in degree of measures.
- Jaccard similarity coefficient shows a low similar in price dynamics of pilots.
- A price-dependence mode for the linkage of pilots is proposed.
- Visibility graph method is more reliable for measuring weak coupling of time series.

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ABSTRACT

Similarity and heterogeneity analysis of price dynamics across the region provide experiences for China's national carbon emission trading scheme. This study examines the dynamic behavior of carbon prices from the visibility graph network point of view, notably introducing the Jaccard coefficient to measure the similarity. By mapping daily carbon trading prices onto visibility graph networks, we analyze the characteristics of the carbon prices by topological measures of the networks. For the next step, we evaluate the similarity between pilots by the Jaccard similarity coefficient of the constructed visibility graph networks. Consequently, we cluster the pilots based on topology measures of the networks. Results show that the seven carbon markets in China have different patterns of similarity in visibility network properties: They are all small-world networks and are scale-free except for Chongqing pilot. Only Hubei and Shenzhen pilots are assortative, indicating a weak degree of market efficiency. At the same time, the two pilots have the highest value of Jaccard similarity coefficients and Shenzhen pilot presents the highest similarity to the supposed integrated market. According to the structure measures of the networks, the pilots are clustered into four groups which can be seen as sub-markets. Findings in this study indicate that inequalities across those groups should be sufficiently considered in the future national carbon market with particular emphasis on the Hubei pilot. Some sub-markets are suggested to be built according to the similarity in price dynamics.

1. Introduction

As a tool to curb emissions cost-effectively, Emission Trading Scheme (ETS) has expanded globally out of the Europe. The Chinese government approved the first branch of ETS pilots in its five most prominent cities (Beijing, Chongqing, Tianjin, Shanghai, and Shenzhen) as well as two provinces (Guangdong and Hubei) [1]. A national level ETS was launched at the end of 2017, however, the corresponding nationwide market has not been operated [2]. Since the initiation, the ETS pilots have been closely monitored, with varying success and have cumulated valuable experiences for the national scheme.

The ETS policy affects China's economic system mainly through the carbon market, where the carbon price fluctuates within a certain range [3]. Different system designs and subsequent policy adjustments of the seven ETS pilots have made their carbon prices vary considerably, resulting in the weak market vitality and liquidity [4]. Attempts have been made through investigation of carbon price time series to quantify the interdependencies across the pilots. Although it is natural for them to have some heterogeneity in price dynamics, more interesting questions are raised: Are there any similarities across the pilots? How to

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measure the similarity/heterogeneity? Which pilot might be more suitable to develop into a national ETS? Complex analysis of carbon price time series may provide a new perspective to answer those questions.

The motivation of the present work is threefold. First of all, knowledge of the carbon market in China remains insufficient despite of the maturing literature on the EU-ETS carbon market. Most of the existing studies are qualitative and focus primarily on policy recommendations. Second, related studies have not conducted a comparison of price dynamics for all the seven pilots. Chongqing and Tianjin are usually excluded because of their inactive trading activities and missing data in the trading volume [5]. Third, since a unified trading price is yet to be set in all markets, a more sophisticated and comprehensive assessment on all the ETS markets in China is required.

Network-based time series analysis has achieved considerable success in recent years. Complex network models many types of real systems that contain a large number of elements interacting with each other in a complex manner. Integrating the theory of complex network into time series analysis sheds us a new light on dealing with interdisciplinary problems in brain functions, climate dynamics, ECG dynamics, economics, multiphase flow and traffic systems [6]. Representing a time series through its corresponding complex network, one can investigate both its micro and macro behaviors from the topology properties of the network.

This study analyzes the similarity and heterogeneity of price dynamics across China's seven carbon pilot markets from a complex network point of view. We adopt the visibility graph algorithm [7] to convert the carbon price time series into visibility graph networks (VGNs). By such mapping, the dynamics of the carbon price are converted into the topology properties of the VGN, and vice versa. We analyze topological measures of the VGNs to show that there is some similarity among the pilots. Next, the similarity of two VGNs is quantified by the Jaccard similarity coefficient of neighbor sets of their nodes. Subsequently, seven pilots are clustered into four groups according to the characteristics of the VGNs.

Compared with existing researches, this study contributes to the literature mainly in three aspects. (1) This paper opens up new venues to address interdisciplinary challenges in carbon trading. Taking the carbon price as the temporal sample of the carbon trading system, dynamics of the carbon price in Chinese pilot markets as a whole are studied by applying visibility graph method. Forming a big picture, the general properties of the dynamics help avoid the blindness caused by the differences in the characteristics of different pilots. This kind of analysis angle is of great theoretical and application significance in carbon market researches. (2) A similarity measure, the Jaccard similarity coefficient of neighbor sets in visibility graph is proposed. This index measures the similarity in the whole dynamics rather than the linear relationship. The visibility graph method can deal with nonstationary time series and is more reliable for measuring weak couplings compared with the cross-correlation method [8]. (3) A price-dependence mode for the construction of sub-markets is proposed. It will provide insight into pilot ETS assessment and the national ETS development.

The rest of the study is organized as follows. Section 2 provides a literature review of China's ETS studies. The method and data employed in the study are given in Section 3. Sections 4 and 5 analyze the similarity in topological measures and the networks. Sections 6 presents policy suggestions and the last section concludes the paper.

2. Literature review

2.1. The determinants of the carbon price

As the supply of carbon emission allowance is relatively stable, carbon price is essentially affected by the demand side, such as energy prices, climate events, and economic activity. Energy price is usually regarded as the most vital factor of carbon price because power generators may switch between high-carbon and low-carbon fuels [9]. Climate condition is also an important cause for the instability of carbon spot price [10] because drastic weather change will influence energy demand and then perturb carbon market [11]. Meanwhile, macroeconomic variables are found to have some linkage with carbon prices. Experimental studies show that industrial sectors, such as production of combustion, steel, and paper, have significant influence on carbon price [12]. Other factors such as foreign direct investment may also affected the price [13].

2.2. The characteristics of carbon price movement

In general, the fluctuation of carbon price contains both linear and nonlinear patterns due to inherently high complexity. It is characterized by skewness, excess kurtosis and different phases of volatility in the returns. Econometrical methods and soft-computing models have been proposed to describe the dynamics of carbon prices as stochastic processes. The price does not have to follow any seasonal patterns. An adequate CO_2 price process should exhibit a time and price dependent volatility structure due to different phases of price and volatility behavior in the returns [14]. Geometric Brownian motion with jumps [15], Markov switching and AR-ARCH models [16] are suggested to model the stochastic movement of short-term spot price in EU ETS. Results of the ensemble empirical mode decomposition and variance ratio analysis show that the market mechanism and external environment are the dominant factors of carbon price volatility [17]. Carbon price also presents chaotic characteristics by complex analysis [18]. For carbon futures price, it moves divergently and is not predictable because it does not subject to the mean regression process [19]. The returns of carbon futures within the EU ETS can be estimated by the stable distribution with negative skewness and asymmetric characteristic [20]. The time scale of investment and the speculative expectations of returns have a dual impact on carbon price behavior [21].

2.3. Relevant studies on China's pilot markets

An increasing interest has been raised in the developing ETSs in China discussing the efficiency, effectiveness, and market performance of pilots ETSs. Compared with their European counterpart, Chinese carbon prices are closely related to coal [22], rather than oil or gas. The carbon price fundamentals of pilots are weak [5]. Market system design and policy adjustment have a significant impact on carbon price fluctuations [23], particularly in the early stage of the carbon market. The pilot markets are inefficiency regarding carbon prices, trading volume, market liquidity, information transparency [24], and a spot-only product system [25]. The reason lies in the deft modification of the trades of carbon emissions under China's unique context. Fortunately, the efficiency is likely to be improved with the expansions of market scale and trading volume. As Zhao et al. [26] point out, the market system is expected to converge from the state of inefficiency to weak-form efficiency gradually.

Some studies simulate the economic and environmental impacts of the pilots. Differences in the study area, as well as models, result in various, even contradictory conclusions. By applying a Chinese multiregional general equilibrium model, Liu et al. [27] point out that the Hubei ETS helps to change energy consumption structure and achieve emissions reductions at a lower cost. Wu et al. [28] evaluate the economic impacts of ETS-policy by using a static computable general equilibrium (CGE) model in Shanghai, concluding that carbon cap-and-trade can reduce the adverse effect on economic output and employment.

Comprehensive evaluation has been carried out both for a single [24] and multiple pilots [29]. Pilots are qualitatively evaluated and ranked by the Technique for Order Preference by Similarity to Ideal Solution TOPSIS model [30] and the Structure-Conduct Performance (SCP) framework [31]. Such researches provide valuable references for

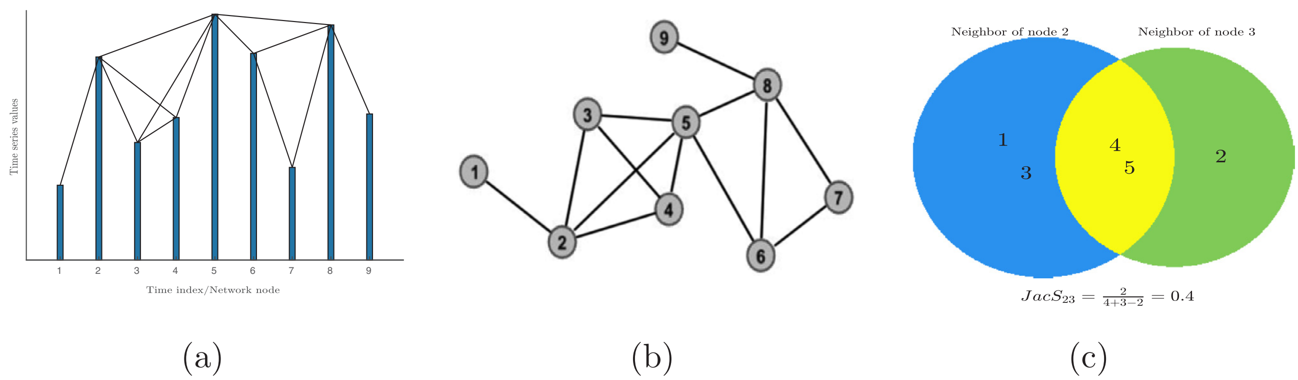

Fig. 1. Illustration of the network construction from a time series. (a) A simple time series represented by vertical bars. The lines indicate the network connection established according to the visibility criterion of Eq. (1). (b) The network emerging from the time series in (a). (c) Jaccard similarity coefficient between nodes 2 and 3 according to Eq. (2).

identifying the optimal linking opportunity. A comprehensive evaluation index system is designed and the maturity of the seven pilots are calculated in [32].

Scholars suggest three options on the development of national carbon market. The first option is a pilot-centered scheme. Each pilot (either the existing or new constructed one) is linked to a regional carbon market then extended nationwide [33] although such linkage may cause the uneven allocation of carbon emission among regions. The second is to set up and integrate regional sub-markets. It is suggested to build regional sub-markets in provinces or municipalities with close geographic and economic relationship such as Beijing-Tianjin-Hebei Area, Yangtze River Delta, and Pearl River Delta [34]. Unlike such a geography-dependence mode, Song et al. [35] propose an energy-dependence mode, where regional carbon markets are built based on the similarity among carbon intensity of different provinces. These two options indicate that China will continue to implement its national scheme in regional carbon pilots, but with expanding geographical and sectoral scope. The third scheme is to directly establish the unified market referring to only the current ETS mode [36]. Experiences from pilot schemes are vital in the implication of any of the three options.

2.4. Literature gap

Substantial progress has been made using a range of different approaches, data, and methods in the research of carbon markets. Nevertheless, complex network theory and methods have rarely been applied to carbon price time series. Understanding and quantifying the level of similarity and heterogeneity for all the pilots remains vague although there exist some comprehensive evaluation and comparison of pilots. Besides, proposals for inter-regional linkages of ETSs lack accurate quantitative method started from the dynamics of carbon price. We seek to fill this gap by including all seven markets in the first piloting phase and exploring both their similarity and heterogeneity from the perspective of complex networks. We give the exact value of similarity and heterogeneity among them then proposes a price-dependence mode based on the similarity for the development of sub-markets and the national market.

3. Method and data

3.1. Visibility graph

Converting a time series into a complex network allows the usage of the network's topological measures to infer the system's behaviors that are not explicitly visible in the time series. Time series can be mapped into networks with different methods [37], such as recurrence networks, correlation networks, cycle networks, transition networks, and visibility graphs. Among these methods, visibility graph algorithm [7] has advantages in maintaining time orders of the series in the sequence of the nodes, in presenting the straightforward geometric interpretation of the original time series. Moreover, the graph theory tools are immediately available because the extremely large number of nodes or links do not appear in application experiments. The visibility graphs also have a simple and fast speed in calculation without the need to create the state space which requires a large number of sampling points.

The Visibility Graph (VG) algorithm [7] maps a time series into a network according to the *visibility* criteria. Given a time series $\{y_i | i = 1, 2, ..., N\}$, an observation (t_i, y_i) of the time series, where t_i is the time, is represented by a segment on the plane from the point $(t_i, 0)$ to (t_i, y_i). The associated visibility graph network $G = (V, E)$ is constructed as follows: Each one of these observations (t_i, y_i) is assigned to a node $v_i \in V$ in the graph G. Two nodes, v_i and v_j, will be connected via a bidirectional edge in E if, and only if, two corresponding observations are *visible*, that is, two points (t_i, y_i) and (t_j, y_j) can be connected without crossing any segment joining $(t_k, 0)$ to (t_k, y_k) for any $1 \leqslant k \leqslant n, k \neq i, j$. Mathematically, v_i and v_j are connected when the following holds true

$$y_k < y_i + (y_j - y_i)\frac{k - i}{j - i}, \quad i < k < j. \tag{1}$$

Fig. 1 illustrates the procedure of converting time the series y (Fig. 1(a)) to its VG (Fig. 1(b)). The gray line between y_i and y_j in Fig. 1(a) indicates the two observations can see each other. The VG is always connected because each observation is certainly connected to its previous and next views except for the first and last observations. The *visibility* criteria ensure that VGNs are invariant under vertical (linear) rescaling, translation and superposition of a linear trend of a time series [7].

3.2. Topological measures of the VG

In general, average path lengths, clustering coefficients, degree distributions, and betweenness are most commonly used to measure complex networks.

Firstly, we evaluate the degree distribution of the networks $P(k)$, where k represents the node degree or its number of connections. If the degree distribution fits the power law $P(k) \sim k^{-\gamma}$, then the network is a scale-free network [38].

The degree assortativity is another commonly-studied network property. It is a Pearson correlation coefficient r of the degrees at both ends of the edges [39]. The network is argued to be assortative if $r > 0$, disassortative if $r < 0$, there are no correlation between vertex degrees if $r = 0$.

We use other fundamental conceptions, such as average degree, diameter, average path length, density, modularity, cluster coefficient, and eigenvector centrality distribution to depict the statistical

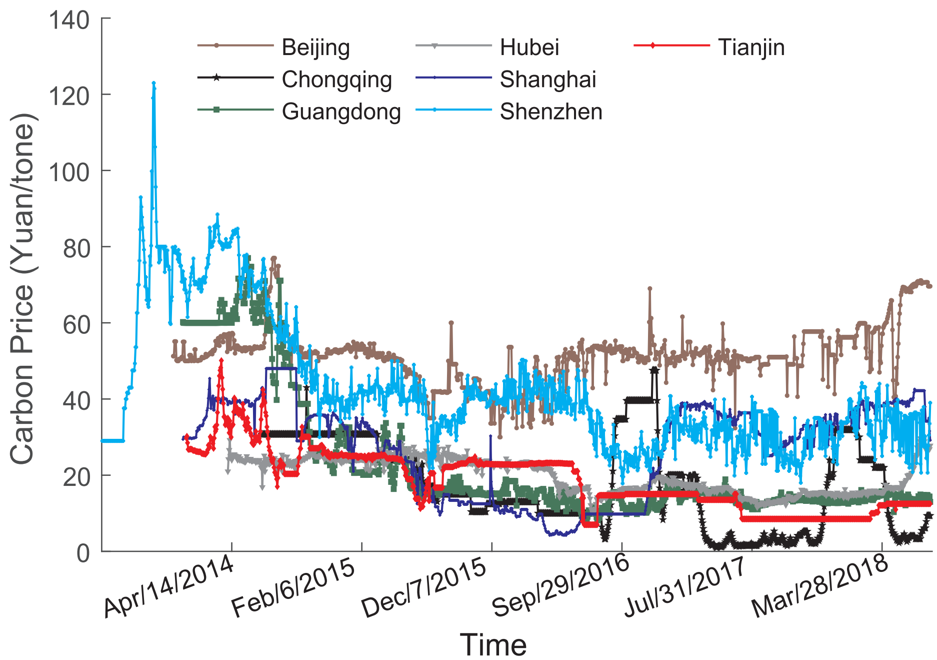

Fig. 2. Carbon price in Chinese ETS pilots.

characters of the associated network transferred from time series. Their definitions can be found in related references.

3.3. Jaccard similarity coefficient

In a given time span, two visibility graph networks share common features because their nodes stand for the time point and therefrom do correspond one-to-one. As the visibility graphs are unweighted, the similarity problem between the two visibility graph networks becomes the one-to-one node-matching networks [40]. However, the attributes of nodes which represents time points are trivial in visibility graphs. Node similarity has to be defined structurally, which is solely based on the network structure. There are many structural similarity indices [41] such as Salton Index, Jaccard similarity coefficient, Preferential Attachment Index, and Resource Allocation Index. They are based on the idea that nodes sharing more neighbors are considered to be more similar. Jaccard similarity coefficient is preferred in this study due to its clear set meaning and that neighbors form a set.

The Jaccard similarity coefficient [42], also known as Intersection over Union and the Jaccard index (originally coined coefficient de communauté by Paul Jaccard), is a statistical measure of similarity between sample sets. For two sets, it is defined as the cardinality of their intersection divided by the cardinality of their union.

We introduce the Jaccard similarity coefficient *JacS* of a node pair *i* and *j*:

$$JacS_{ij} = \frac{n_{ij}}{n_i + n_j - n_{ij}}, \tag{2}$$

where n_i is the number of neighbors of node i;n_j is the number of neighbors of node j; and n_{ij} is the number of nodes, which are neighbors of both the nodes i and j. The Jaccard similarity coefficient of two networks is defined as the average of *JacS* of their nodes.

The value of the Jaccard similarity coefficient ranges between 0 and 1, with 0 showing that there are no overlapping connections and 1 that the same pairs of dates are connected in the two networks.

3.4. Agglomerative hierarchical clustering

Clustering or cluster analysis is to group a set of objects in such a way that objects in the same group (called a cluster) are more similar to each other than to those in other clusters. Usually, the similarity is measured by distances. Among a variety of clustering approaches [43], such as k-means and expectation maximization hierarchical, Agglomerative Hierarchical Clustering (AHC) has the advantage in not requiring a prior specification of the number of clusters. AHC seeks to build a hierarchy tree of clusters in a “bottom-up” strategy. In the beginning, each object forms a cluster. Then, after calculating the distance matrix, the entire dataset is iteratively merged until obtaining one final group. At each iteration, the two closest clusters are merged. In this work, the AHC is preferred because there are totally only seven objects to be clustered and the number of clusters cannot be specified in advance

3.5. Data

The carbon prices are represented by transaction data collected from China’s Carbon Emissions Trading Network (http://k.tanjiaoyi.com/). Transaction prices are used for pilots except for Shenzhen which uses an average price. Since there are six allowances (SZA-2013 to SZA-2018) are traded in the Shenzhen market, the average emissions allowances prices, calculated the daily trading turnover divided by the daily trading volume, are selected as the representative carbon prices for Shenzhen pilot. The sample period covers from the first trading day when the first price observation is recorded to August 31, 2018. Weekend days and public holidays are excluded. Missing data are added by moving average in the previous week. Abnormal values are corrected according to the trading volumes.

Fig. 2 shows vast differences in prices across the markets with Guangdong, Shenzhen, Shanghai, and Chongqing being more volatile. The augmented Dickey-Fuller tests for unit roots confirm the non-stationarity of the prices. The Kolmogorov- Smirnov test for normality is rejected in all cases. We also observe that carbon prices are skewed. Only Hubei is negative skew. Guangdong has the largest abstract value of skewness. All prices have a pronounced excess kurtosis, which conforms to common characteristics of financial market series.

4. Similarity in VGNs’ measures

Table 1 shows the topology measures of the constructed visibility graph networks. The observed groups are likely to be heterogeneous

Table 1
Topology measures of the VSNs.

	Beijing	Chongqing	Guangdong	Hubei	Shanghai	Shenzhen	Tianjin
Edges	5501	10086	6340	7012	8345	4332	8087
Average degree	18.22	35.384	27.488	18.098	36.744	18.982	9.568
Diameter	9	11	7	9	52	9	8
Average path length	3.6418	2.6579	3.2451	4.3043	7.0812	4.0479	3.996
Density	0.014	0.027	0.021	0.014	0.028	0.014	0.011
Modularity	0.756	0.356	0.710	0.728	0.517	0.758	0.749
Number of communities	11	6	10	10	12	11	13
Cluster coefficient	0.776	0.737	0.754	0.749	0.695	0.757	0.752
Eigenvector centrality	0.0362	0.0128	0.0162	0.0469	0.0372	0.0274	0.0305

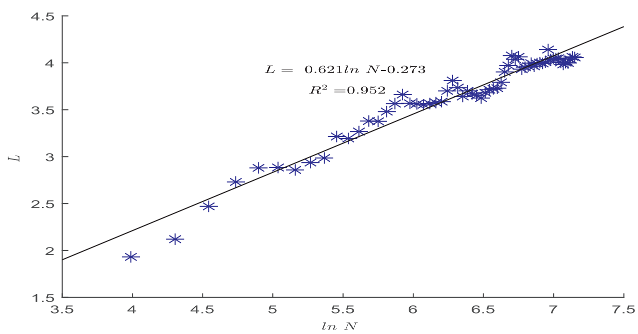

Fig. 3. Average shortest path length of the VGN of Shenzhen prices.

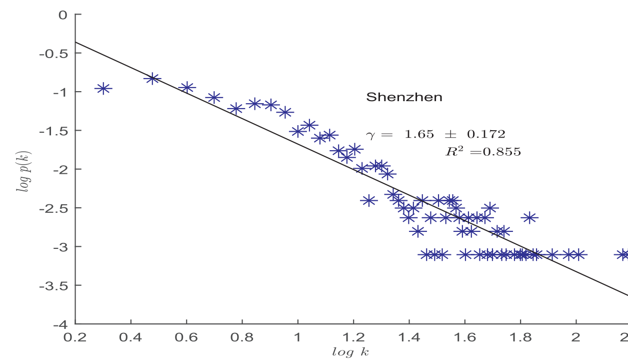

Fig. 4. Degree distribution of the VGN of Shenzhen.

concerning network structure and the interrelations between network dimensions. However, this section shows that the VGNs have some common aspects in the networks' properties.

4.1. Small world network: preferential attachment

Fig. 3 shows the average minimum path lengths of visibility networks for Shenzhen price series, where L is the average shortest path length, N is the number of nodes. If there is a linear relationship between L and the logarithm of N, that is, $L = \alpha + \beta lnN$, the network is of small-world properties. Table 2 shows that six networks out of all the pilots have the small world property (Chongqing pilot fails).

A small-world VGN means hub repulsion, that is, there are few hubs with high values while most nodes correspond to medium or low values. In the growth of the network, the small-world network indicates that the newly added nodes choose preferential attachment rather than random links [37]. The small-world characteristic of the VGNS indicates that fluctuations in the networks are not random. Instead, it is attracted, restricted or affected by previous prices. The newly added node will be affected by the history node and mainly affected by the hub.

4.2. Scale-free: long-range correlated fractal series

Fig. 4 shows the power-law degree distribution of the Shenzen VGN, where γ represents the exponent of power-law degree distribution which is 1.65 ± 0.172. The power-law distribution indicates that the VGN of the Shenzhen pilot is a scale-free network. Only a few nodes have large degrees, whereas the degrees of majority nodes are very low, which partly reflects the volatility of the original time series. In a certain range, nodes with high visibility are much affected by previous price fluctuations or have considerable influence on subsequent price fluctuations.

The degree distribution reveals that the carbon price series in the Shenzhen pilot is a fractal time series with long-range correlation. On the one hand, the price series is scale-invariance, that is, time series under different time scales, i.e., month, week, day, and so on have similarity in their statistics. On the other hand, there is a long-range correlation, that is, the carbon price fluctuations in the future are likely to be similar to a particular period in the past.

Similar scale-free properties are discovered for other pilots. We fit the power-law equation of the degree distribution in a log-log coordinate. All fitting equations are statistically significant by F-test at the 1% significance level. Table 3 shows the fitting results. The table shows that the Chongqing pilot has the lowest R^2, Guangdong and Tianjin have about seventy level, and others are all higher than 80%. The power γ is between 1 and 2, meaning that except for the Chongqing pilot, the constructed VGNs are scale-free and the original carbon price series are fractal time series with long-range correlation.

4.3. Assortativity: efficient market

The assortative mixing pattern is one of the critical properties of the complex network. The assortativity coefficients are calculated in Table 4. With an intuitive viewpoint, quantitative values are negative except for those of Hubei and the Shenzhen. Most of the constructed complex networks are disassortative. Hubs are likely to be discrete, not being linked together. In visibility graphs, the greater the data, the larger vertex degree. Generally, the spreading of information will cause

Table 2
Results of average shortest path length fitting $L = \alpha lnN + \beta$. The sign ∗ indicates that Chongqing pilot fails the regression fitting.

Item	Beijing	Chongqing	Guangdong	Hubei	Shanghai	Shenzhen	Tianjin
α	0.527	11.8	0.432	0.767	40.5	0.621	0.241
β	0.876	−1.29	0.593	−0.674	−5.11	−0.273	1.33
R^2	0.754	∗	0.844	0.903	0.928	0.952	0.545

Table 3
The exponent of power-law degree distribution and the fitting goodness.

	Beijing	Chongqing	Guangdong	Hubei	Shanghai	Shenzhen	Tianjin
γ	1.5	0.999	1.13	1.34	1.25	1.65	1.08
R^2	0.835	0.62	0.68	0.861	0.827	0.855	0.723

Table 4
Assortativity of VGNS of the pilots.

Beijing	Chongqing	Guangdong	Hubei	Shanghai	Shenzhen	Tianjin
−0.0696	−0.3763	−0.0605	0.0481	−0.1166	0.1104	−0.2369

the fluctuation of carbon prices. So it is inferred that assortative mixing represents there exists some links between a strong market information and another strong information, such as the investors' investment strategy, bad or good new. The disassortativity of the VGNs means those pilot markets are not efficient. The Hubei and the Shenzhen pilots perform better than them, which is partly consistent with the result in [4] that Shenzhen and Hubei performed more actively in seven ETS pilots.

5. Similarity of VGNs

5.1. Similarity of VGNs

This subsection calculates pairwise similarity and then for similarity between a network to the VGN of a supposed "integrated" market. Price of the "integrated" market is taken as the average of the prices in the existing seven pilots.

By calculating the Jaccard similarity coefficient for each pair of the seven networks, we get a 6 × 6 matrix of pairwise similarities as shown in Table 5. According to the table, Hubei-Shenzhen and Beijing-Shenzhen have a similarity in a medium level while very close to the lower limit. Similarity of other pairs is low. The greatest value occurs for Hubei-Shenzhen while the lowest for Chongqing-Guangdong.

Table 6 shows the Jaccard similarity coefficient between a network with the "integrated" market. The low value of the Jaccard similarity coefficient shows the existence of heterogeneity. Chongqing and Tianjin have a low Jaccard similarity coefficient far below others. Thus none of the VGNs can replace the "integrated" market. Among the seven pilots, the ETS in Hubei province exerts significant influences as it has the greatest Jaccard similarity coefficient. It may be caused by that Hubei's economic and social contexts are very similar to China as a whole [27].

5.2. Cluster results

We apply system cluster to group the seven pilots into groups using the topology measures as clustering factors. Clustering process is carried out on a PC by using MATLAB 2012(a) software.

The dendrogram (Fig. 5) presents the hierarchical evolution process of the clustering. Its vertical shape interprets cluster scattering and the overlap between them. Each node stands for a pairwise aggregation. The ordinate length between two nodes indicates the Euclidean distance between two merged clusters.

Table 5
Jaccard similarity coefficient between pairs of pilots.

	Beijing	Chongqing	Guangdong	Hubei	Shanghai	Shenzhen
Chongqing	0.2586					
Guangdong	0.3589	0.2580				
Hubei	0.3793	0.2703	0.3574			
Shanghai	0.3282	0.2603	0.3275	0.3423		
Shenzhen	0.4077	0.2890	0.3958	0.4165	0.3574	
Tianjin	0.3016	0.2188	0.2993	0.2918	0.2767	0.3230

Table 6
Jaccard similarity coefficient of a pilot and the supposed "integrated" market.

Beijing	Chongqing	Guangdong	Hubei	Shanghai	Shenzhen	Tianjin
0.3880	0.2763	0.3921	0.3953	0.3476	0.3983	0.3040

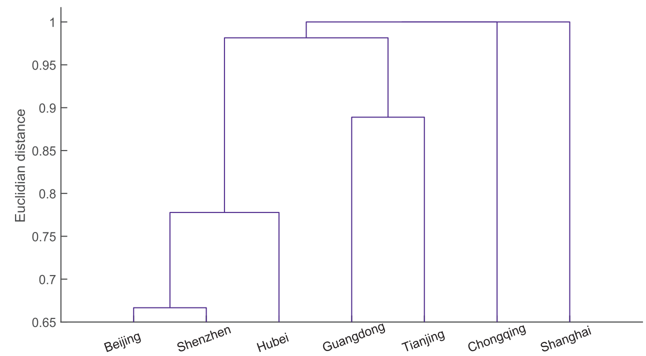

Fig. 5. Cluster tree. Cluster factors are topology measures of VGNs. The vertical axis is the distance.

It is preferable to choose four clusters by considering the ordinate length between nodes. The ordinate length distance from four clusters to three clusters is relatively considerable. At the top of the dendrogram, Chongqing and Shanghai each form a group separately with considerable distance. For real application, we name them as the stranger group and the vague acquaintance group. Accordingly, Guangdong and Tianjin make the good friend group as they have medium distances while Beijing, Hubei and Shenzhen are grouped as the family group with the shortest distance. The close relationship between the Shenzhen and Hubei pilots are also discussed by Fan et al. [5] who find their prices both have a positive relationship with the energy and materials sector indices, as materials companies are among the highest emitters in the greater Shenzhen region.

Each cluster can be seen as a sub-market. Thus pilots in the same sub-market are similar in price dynamics. We call this a price-dependence mode of the development of national carbon market.

5.3. Reasons behind the similarity and heterogeneity

Reasons for the similarity of the cluster members have something to do with the allocation mechanism. In the case of the Shanghai pilot, the allocation is determined by historical emissions, industrial benchmarks, an early abatement incentive, and a rolling baseline year. The early abatement incentive gives credits to entities that move early to reduce emissions, and the rolling baseline year allows firms to use emission data from the previous year if emissions increased by more than 50 percent from 2009 to 2011. In line with the Shanghai pilot, both the Guangdong pilot and the Hubei pilot have rolling baseline years and industrial benchmarks but do not provide early abatement incentives. Nearly 100 percent of the allowances in China are allocated free, except for Hubei (90%), Beijing (95%), and Shenzhen (95%) pilots [5]. The remaining allowances consist of competitive auctions and fixed-price sale. Those pilots do not have completely free allowances happen to form the family group. This finding confirms our assertion that allocation mechanism plays a role on the similarity of the cluster members.

The similarity of pilots also comes from the coverage of the sector. Apart from the allocation mechanism, energy price, climate events and economic activity are all determinants of the carbon price. Energy price is the most important determinant. While economic activities in Chinese carbon pilots are inactive and, unanticipated temperature changes have an immediate impact on carbon emissions, they contribute few to the similarity of pilots. This study seeks the reason why there exists a similarity among pilots rather than discussing how energy price decide the carbon price. Since different industrial sectors have different sensitivity to energy price, we find the similarity between pilots has a relation with the coverage of sectors.

Beijing and Shenzhen have something common in the coverage of the sector. Both Beijing and Shenzhen have required critical companies in the service sector to join the scheme as they have small industrial emissions and the flourishing service economy. Beijing is the only pilot requiring absolute yearly emission reductions for existing facilities in the manufacturing and service sectors. Companies in Shenzhen, unlikely, limiting their annual absolute emissions growth to less than 10 percent, using 2013 as a baseline, will need to reduce their carbon intensity per unit of Industrial Added Value (gross domestic product GDP due to industry) by 32 percent below 2010 levels over the next three years. Compared with other markets, Hubei pilot remains relatively liquid. This is caused by a regulation that surplus allowances would be canceled if they not from the secondary market. Hubei also tightens the CCER rule that only biogas and forest sink projects are eligible for compliance.

Varying economic contexts contribute to the heterogeneity among clusters. Guangdong is the largest ETS in China and the second largest in the world regarding emissions covered. Guangdong is the most transparent one in disclosing not only the number of allowances allocated but also those reserved for new entrants and government interventions to stabilize the market. Guangdong is also the only pilot requiring companies to buy a portion of their allowances through auction (3 percent of total in 2013, increasing to 10 percent by 2015). Only in Tianjin, financial penalties do not function when emitters did not meet their compliance requirements.

Chongqing pilot shows a “merciful” attitude towards participants. Allowances are allocated by the firms, while the government is responsible for controlling the allowance caps.

Shanghai stands out from the other pilots by regulating aviation emissions- a measure similar to the EU’s attempt to include aviation in the EU ETS. Six Shanghai-based airlines are required to submit emissions permits for their domestic commercial flights. Shanghai also shows its uniqueness by recognizing companies’ energy-saving efforts retrospectively. According to its allocation rule, companies can be awarded with extra carbon dioxide allowances for energy saving actions taken between 2006 and 2011.

6. Suggestions for the development of nationwide ETS

6.1. Constructing sub-national carbon markets

China can construct some sub-national carbon markets as a bridge from pilots to the national market. We suggest to adopt the price-dependence mode rather than the geography-dependence [44] or energy-dependence mode [35], considering that the regional ETS pilots are continuing to function in parallel to the established yet not full-fledged national ETS. Pilots sharing a greater similarity in price dynamics could be integrated to sub-national carbon markets. For example, Beijing, Hubei, and Shenzhen can become one sub-market while Guangdong and Tianjin can form another one. The price-dependence mode could smooth the transition by avoiding drastic changes in the market environment.

Hubei pilot should be paid more attention than other pilots in the development process of the nationwide ETS. Although Hubei and Shanghai have been appointed to leading the construction of two ETS systems separately, the former one has more successful experience and thus more potential experiences in emission trading. Its economic and social contexts are very similar to China as a whole. As a result of this study, Hubei pilot has the highest similarity degree which is another reason for its importance to an integrated ETS. Besides, Hubei pilot performs better compared with [4] or even the best among all the pilots [30] in terms of maturity evaluation, operational performance or comprehensive evaluation.

6.2. Optimizing the carbon trading market system

Market performance of the pilots should be noticed. The seven pilot regions are deliberately selected signifying varying stages of development. Each of the pilots is given the freedom to design its own scheme. Market performance evaluation and comparison is an important way to assess their achievements. Experience drew and lessons learned from the performance can help design implementation details in China’s national carbon market.

Information transparency should be improved for the upcoming long-term trading practice. Comprehensive information disclosure is the critical element of an efficient carbon market, where carbon price reflects emission reduction cost. Without information transparency and the availability of market information, traders cannot make optimized trading decisions, and the price discovery would fail. Although China has made considerable effort, there is still room for improvement in information transparency. Implementation of carbon trading schemes, management measures, and other policy tools can be found in the local Development and Reform Committee and emissions trading exchange platforms. The seven pilots also have compiled a dataset of transaction information, including trading volume, price and covered entities. However, some essential information is not disclosed such as the emissions measured at the enterprises, allowances attributed to the traders, typical traders, high-frequency trading data. Therefore, the government should set up an open information platform to publish the firm-level carbon emission data. Furthermore, a logbook of all transactions performed on the market should be established.

The government should make greater endeavor to stimulate market vitality. As the government interferes carbon trading markets strongly, regulations and market rules should maintain a certain degree of continuity to enhance investors’ confidence in the market. Since the covered entities trade quotas and meet compliance requirements passively, the total amount of quotas should be tightened, meanwhile avoiding insufficient emission allowances in Beijing pilot or excessive allowances in Shanghai. Although the pilots has been mainly based on carbon quota trading, diverse carbon financial instruments, such as carbon insurance, carbon funds, and carbon futures, can be introduced in the national market. Focusing on these issues would help to improve the market’s vitality and liquidity.

7. Conclusions

This paper investigates the similarity and dissimilarity of price dynamics among China’s regional carbon markets by applying the visibility network method. Results in this study suggest that the seven carbon markets in China share some similarity in terms of visibility network properties such as scale-free and small-world. Heterogeneity is also detected in these aspects of different degrees. Results also indicate that a low level of similarity exists between any pair of markets. Hubei and Shenzhen pilots have very weak efficiency due to the assortativity. Finally, based on topology measures of the constructed visibility graph networks, the results suggest that seven markets can be partitioned into four clusters: Shanghai is the stranger group, Chongqing the vague acquaintance, Guangdong and Tianjin the good friend group and others the family group. Each cluster can be seen as a sub-market in the view pint of price-dependence mode.

The findings presented in this study suggest that China is still in the early phases of ETS development. We can say that the implementation of seven pilots has provided valuable experience for constructing unified market at the national level since the different features of carbon price dynamics of them are discovered in this study.

The regional markets should be sufficiently considered when establishing a full national scale cap-and-trade system. With more regional markets joining the pilot system and providing richer data points, we hope that more researches on the similarity and heterogeneity of Chinese regional carbon markets can offer further suggestions for the construction of the national market.

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