A review of carbon trading based on an evolutionary perspective

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Abstract

Purpose – This paper aims to review the literature on carbon trading from the perspective of evolution, finds out the evolution path of these literatures and gives out the future research hotspots in this field.

Design/methodology/approach – Uses visualization tools (CiteSpace and HistCite) to systematically categorize the literature on carbon-trading schemes in the Web of Science core collection from 1998 to 2018, comprehensively analyzes carbon-trading schemes from four dimensions, namely, discipline evolution, keyword evolution, citation cluster evolution and citation path evolution.

Findings – Research on carbon-trading schemes has a specific development and evolution path along four dimensions, namely, in the discipline dimension, the largest change lies in the mathematics pointed to by at least four different disciplines; the keyword evolution dimension shows a gradual deepening emphasis on coordinated development; citation clusters identify three major clusters – carbon prices, China's carbon trading, carbon market and supply chain; and citation paths identify three major evolutionary paths, the most important of which shows that "What affects carbon price?" has changed to "What is the impact of carbon prices?"

Originality/value – Reveals the evolution path of carbon trading research studies and proposes four possible development directions for carbon-trading scheme research, which is helpful for future carbon trading-related research and serves as a reference for the promotion of and improvements in carbon-trading schemes.

Keywords Evolution, Systematic review, Carbon trading, Knowledge domain visualization

Paper type Literature review

1. Introduction

Increasing climate change is likely to hinder the steady and rapid development of the world economy. The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) states that extreme weather on the planet has increased since the 1950s, including heavy rainfall, heat waves, floods and droughts. The report predicts that the intensity and density of heavy rainfall will increase globally in the future, while some regions will experience more severe and frequent droughts and that the frequency of tropical storms in Categories 4 and 5 will also increase (IPCC, 2014). Greenhouse gas emissions, mainly carbon dioxide, are the main cause of climate change. Therefore, one of the key aspects of climate change governance is to reduce carbon dioxide emissions. National economic growth depends to a varying degree on fossil-fuel energy, which generates a large amount of carbon dioxide emissions. Reducing emissions means that fossil energy consumption must be

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controlled, which affects the economic development and production of all countries. There is a direct effect, meaning that the issue of emissions reduction is related to the development rights and spaces of all countries and closely related to their economic interests. To achieve sustainable economic and social development while managing and controlling climate risks, it is, therefore, necessary to coordinate and use all kinds of policy tools, promote energy conservation and low-carbon structures, promote technological innovation and institutional innovation, promote transformation in the patterns of economic development, achieve win-win situations of "emissions reduction" and "development" and turn actions that deal with climate change into new opportunities, and sources of growth to promote economic development. Among the many institutional arrangements available to reduce carbon dioxide emissions, a carbon-pricing mechanism is an important market-oriented solution that includes carbon trading and carbon taxes. Carbon taxes are difficult to implement due to various obstacles; therefore, carbon-trading mechanisms are more popular at present (Grubb *et al.*, 2017).

The research on carbon-trading schemes can be divided into three general categories (Figure 1). The first is research on the schemes themselves, such as studies conducted by Jiang *et al.* (2016) and Munnings *et al.* (2016). The most important uncertain variable in a carbon trading scheme is the carbon price, meaning that the research on carbon price is relatively rich, including research by Chevallier (2011a) and Fan and Todorova (2017). The second category is research on antecedent variables of the schemes and carbon price, i.e. what causes the fluctuation in carbon price; for example, research by Alberola *et al.* (2008). The third category is research on the consequence variables of the schemes and carbon price, namely, what social and economic effects are brought about by a carbon-trading schemes, such as research by Li and Lu (2015).

Because of the complexity of literature on carbon trading, many scholars have already reviewed this field. Hepburn (2007) reviewed the carbon-emissions trading system arrangements in the Kyoto mechanism; Duan *et al.* (2014) reviewed China's carbon emissions trading pilot; Yu and Xu (2017) used CiteSpace to conduct a co-citation visual analysis of a carbon-trading scheme; Narassimhan *et al.* (2018) comprehensively reviewed the implementation of carbon-trading schemes in eight regions. These literature reviews summarize the relevant research on carbon trading schemes locally and statically but lack a comprehensive understanding of the dynamic process of the development and evolution of carbon-trading schemes. This paper uses visualization tools, such as CiteSpace and HistCite, to analyze the literature and carry out a comprehensive review of the historical evolution of carbon trading from multiple angles. As shown in Figure 2, the paper summarizes the evolution of research on carbon trading along four evolutionary dimensions (discipline, keyword, citation cluster and citation path) and hopes to serve as a reference for future researchers and policymakers.

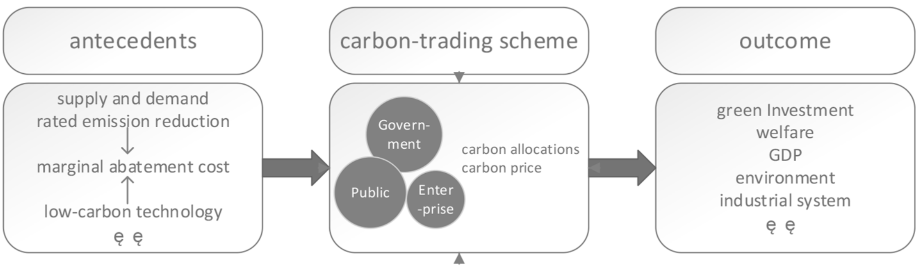

Figure 1.
Distribution of existing research on carbon-trading schemes

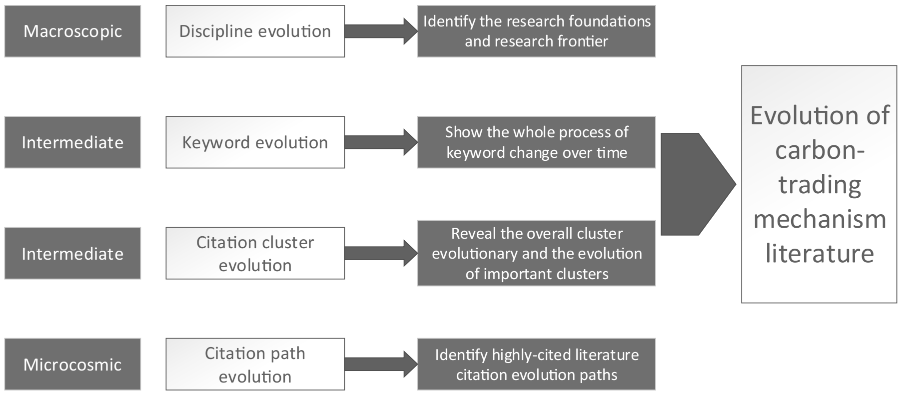

Figure 2.
Research framework

The novelty of this article can be displayed in the following four aspects: this paper provided a comprehensive understanding of the dynamic process of the development and evolution of carbon-trading schemes; this paper has mapped the first dual-map overlay figure of the carbon trading literature and demonstrated it by examples; for the first time, in strict accordance with the development of the timeline, this paper made a detailed and systematic analysis of keywords in a certain field, to describe the development of the whole field; this paper summarizes the evolution of research on carbon trading along four evolutionary dimensions, given and explained the Spiraling evolution of research on carbon-trading schemes.

The paper is organized as follows: the research methods and search strategies are presented in the second part; in the third part, the authors construct a systematic framework of the evolution of the literature on carbon trading along the four dimensions of discipline, keyword, citation cluster and citation path; the fourth part presents the research hotspots and future research trends; and the fifth part summarizes the whole paper.

2. Methodology and data

By applying mathematical statistics methods, a bibliometric analysis can quantitatively analyze specific research areas and discover the potential relationships between them through a series of text processing (Borner *et al.*, 2003). This analysis method can provide a relatively objective and scientific technical method that is not affected by a researcher's subjective thoughts (Yu and Xu, 2017). By using a multi-dimensional, time-sharing, dynamic visualization language and ingenious spatial layout, the evolution process of a certain field is displayed in a network knowledge map through the visualization of bibliometrics. In this paper, the authors use the dual-map overlay, the time zone view of keyword co-occurrence, the landscape view of the co-citation network and the co-citation path to analysis. Among them, the dual-map overlay analysis by classifying the subject distribution of literature itself and the references, form an evolutionary map from the research foundation to the research frontier. The keyword co-occurrence analysis counts the frequency of keywords and present their co-occurrence relationship, and then forms the evolution process of keywords in a certain field. It can clearly show which year, which keyword is the focus of attention. Citation clustering analysis gathers literature in a certain field into several sub-categories through co-citation between kinds of literature and shows the development and change of these clusters. Citation path analysis is used to find the "important links" in the research topic that is to answer the key path of the research topic in a certain period of time.

Through the use of the above analysis methods, the authors comprehensively categorize and analyze the research process of carbon trading along four dimensions, namely, discipline evolution, keyword evolution, citation cluster evolution and citation path evolution. This paper chooses CiteSpace and HistCite as visualization tools. CiteSpace is a very efficient and powerful scientometric method. It is designed for analyzing the co-citation networks through the visual form. CiteSpace has been received many attention from scholars in recent years (Yu and Xu, 2017). This paper takes it as the research tool to study the first three dimensions. HistCite is a very powerful citation analysis tool, which can quickly draw the development context of a certain research field, and quickly lock in the important literature in a certain research direction. Its advantage lies in path analysis, so the authors use it for the fourth dimension analysis. The discipline evolution uses overlay maps in CiteSpace to complete the visualization, showing the theoretical basis and research frontier of carbon trading; the keyword evolution uses a keyword cluster timeline in CiteSpace to describe the keyword's evolutionary process in this field; the citation cluster evolution uses the cocitation cluster in CiteSpace to visualize and analyze the historical evolution of the major topics in this field; and the citation path evolution uses the highly cited article citation path map in HistCite to present and study the evolutionary paths in the important literature in this field. By studying these four complementary dimensions, a comprehensive review of the evolution of carbon trading will be presented.

This paper uses the Web of Science (WOS) core collection as a database for data collection using the following queries (Table 1) for data retrieval:

Query #1 retrieves literature on carbon pricing, and, as carbon pricing includes both carbon taxes and emissions trading, studies on carbon taxes are removed. However, some literature may include comparative studies of carbon taxes and carbon trading, and these studies are retrieved using query #2. Query #3 is the literature on carbon trading. Query #4 constitutes the research object of this paper, including 2,282 papers. Following Chen (2017), who created CiteSpace, this paper did not perform artificial deletions.

3. Results and discussion

3.1 Discipline evolution

In Figure 3, the left side is the distribution of the citing journals, which represents the main categories of the carbon trading-related literature, and the right side is the distribution of the cited journals, which represents what categories are mainly cited in the carbon-trading literature. The former can be regarded as the research frontier of carbon trading, and the latter can be regarded as the knowledge base of carbon trading. The main areas of the research frontier include economics, economic, political, mathematics, systems, mathematical, ecology, earth and marine. The main areas of the knowledge base include economics, economic, political, environmental, toxicology, nutrition, systems, computing, computer, plant, ecology, zoology, earth, geology and geophysics.

Table 1.
Queries list

No.	Query
#1	TI = ((carbon OR CO2 OR GHG OR "greenhouse gas" OR emission*) AND price)NOT TI=tax
#2	TI = ((carbon OR CO2 OR GHG OR "greenhouse gas" OR emission*)AND "trading")AND TI = tax
#3	TI = ((carbon OR CO2 OR GHG OR "greenhouse gas" OR emission*)AND("trading" OR "cap and trade"OR "cap-and-trade"))
#4	#1 OR #2 OR #3

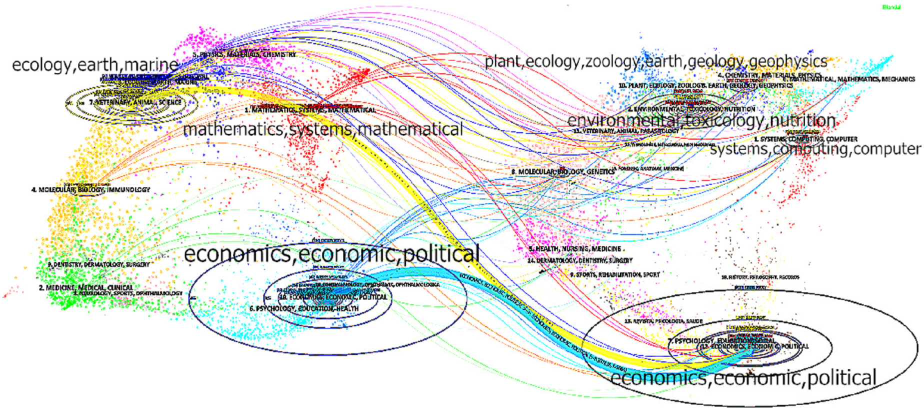

Figure 3.
A dual-map overlay of the carbon trading literature (make by CiteSpace)

For example, the authors find the category of "economics" under the classification of WOS journals. Given this classification, this paper chose the journal "Energy Policy" as the research object. The authors chose any paper related to carbon trading published on "energy policy" and observed the categories layout of the reference. The selected paper was temporal restrictions on emissions trading and the implications for the carbon futures market: Lessons from the EU emissions trading scheme (Daskalakis, 2018). There are 21 references in this article, of which 16 are journal articles. They are distributed as follows: *Journal of Political Economy (2), Journal of Economic Literature, Energy Journal, Energy Policy (2), Journal of Banking and Finance, Journal of Environmental Economics and Management (2), Journal of Finance, Review of Economic Studies, Journal of Public Economics, Journal of Economic Theory, Journal of Applied Corporate Finance, Climate Policy and the Journal of Farm Economics*. The research areas of all of the above journals include economic or environmental categories, which support the curve of economics, economic, political and environmental, toxicology, nutrition to economics, economic and political.

3.2 Keyword evolution

As shown in Figure 4, the keywords in the literature on carbon trading have been changing overtime. These changes can be roughly divided into three phases. The first phase was from 1998 to 2006, and most of this phase explored the design of carbon-trading schemes. The second phase was from 2007 to 2011 and focused on carbon price-related issues. The third stage was from 2012 to 2018 and focused on the issue of the interaction between carbon trading schemes and the economy.

In the first stage, the annual changes in keywords and the possible implications of these are as follows. Before 2000, the concept of a carbon-trading scheme had just caught the researchers' attention, and the keywords were "emission trading" (Godby *et al.*, 1998), "Kyoto protocol" (Sonneborn, 1999) and "climate change" (Madlener and Schlamadinger, 1999). In 2000, the words "energy" (Gabriel *et al.*, 2000), "greenhouse gas," "market" (Solomon and Lee, 2000), "permit" (Kruitwagen *et al.*, 2000) and "pollution" were introduced, and the research focused on the energy issues leading to greenhouse gas emissions and the synergistic relationship between greenhouse gases and pollution; the words "market" and "permit" are also mentioned to mark the beginning of the search for ways to control climate change. In 2003, "equity" appeared, which indicates that attention was being paid to the distribution effects of carbon-trading schemes. At this time, scholars were still enthusiastic

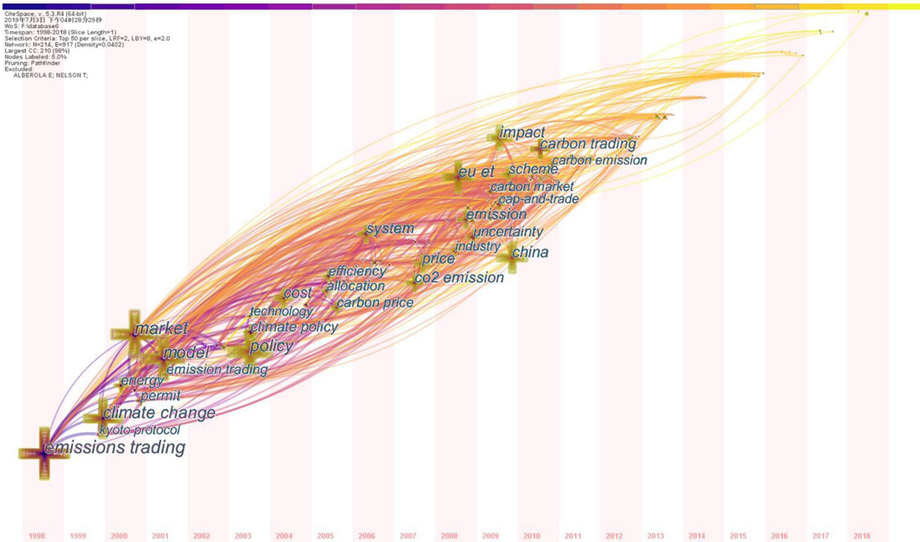

Figure 4.
A timezone view of keyword occurring more than 50 times: 1998-2018 (make by CiteSpace)

about the construction of a global carbon market, therefore, "international emissions trading" also appears as a keyword; "technology" (Sorrell and Sijm, 2003) means that scholars were beginning to pay attention to the relationship between technology and environmental regulation. The emergence of "transaction cost" means that the implementation cost of the carbon trading scheme began to receive attention. In 2004, "cost" (Choi, 2005) instead of "transaction cost" means that the overall socioeconomic cost of carbon trading schemes was considered. In 2005, "afforestation" and "sequestration" indicates that carbon sequestration became a research hotspot, and such words as "allocation" (Christiansen *et al.*, 2005), "carbon price" (Sajeewani *et al.*, 2015) and "optimal law enforcement" indicate that discussions of specific implementation issues, such as quota allocation and carbon price determination mechanisms, have begun. In 2006, researchers began to pay attention to the relationship between carbon-trading schemes and economic growth.

In the second stage, the annual change in keywords and their possible implications are as follows. In 2007, "aircraft emission," "deforestation" and "electricity" appearing as keywords means that aviation carbon emissions, forest degradation and the power sector become the research hotspots. The emergence of "price" (Higgins, 2013) indicates that the price change laws and determinants have become research hotspots. In 2008, the emergence of "carbon tax" may be because of the fact that scholars have begun to pay attention to the comparison of the two institutional arrangements of carbon taxes and carbon-emission trading. This era is also the hot period of the clean development mechanism. The emergence of the word "uncertainty" (Mandell, 2008) may indicate the uncertainty of the scheme itself and carbon price have received attention. The emergence of "innovation" and "welfare" may illustrate the impact of carbon trading schemes on innovation and social welfare was a concern. In 2009, "allowance" may refer to carbon emission permits or the carbon price mechanism or the comparison between market means and traditional subsidy policies. As carbon prices were a hot topic for these two years, econometric methods are frequently used, for example, cointegration, unit root and time series. Compared to the 2003 "international emissions trading," "domestic emissions trading" indicates that the research focus had shifted to the construction of the domestic carbon market. The emergence of "electricity price" shows the impact of carbon-trading schemes on electricity price and that the power sector shifting its cost to electricity prices in response to carbon emissions became research hotspots. The word "impact" (Bailey, 2010) has a frequency of 122 times, indicating that after the 2008 financial crisis, the world economy is recovering slowly, and people are beginning to pay attention to the impact of carbon-trading schemes. "Risk" may be referring to the risks that carbon trading schemes bring to the social economy, the risks brought about by the rising costs to enterprises or the risks of institutional uncertainty and price uncertainty. "Storage" becoming a keyword may indicates that carbon sequestration technology has become a research hotspot. In 2010, the emergence of "carbon leakage" indicates that the impact of carbon-trading schemes on international competition has begun to receive attention. The co-occurrence of "consumption," "demand" and "cost pass through" indicates that the research focus is on the impact of cost shifts on consumption. "Personal carbon trading (PCT)" shows that carbon trading has begun to flatten. "Transport" may indicate that scholars are paying attention to carbon emissions in the transportation sector. "Windfall profit" indicates the unexpected profits that enterprises obtain from the carbon-emissions trading scheme. In 2011, "energy price" became a keyword, which can affect carbon emissions by affecting energy consumption and energy structure. The emergence of "optimization" means that scholars begin to comprehensively consider such factors as cost, effect and impact to seek the optimal path.

In the third stage, the annual keyword changes and possible implications are as follows. In 2012, "life cycle assessment" indicated that the carbon cost of the whole life cycle has been considered. In 2013, "footprint" may refer to the carbon footprint, which is related to PCT and life cycle assessment. The emergence of "supply chain" may also be related to the emergence of the life cycle assessment idea; it indicates that scholars try to open the black box to observe, which link in the supply chain has high emissions, and thus, find the right way to reduce them. In 2015, the emergence of "air pollution" may indicate the beginning of research on the coordinated management of carbon emissions and air pollution. The emergence of "politics" may because the climate politics and climate game during the economic downturn, and "shadow price" refers to the carbon price determined according to the marginal abatement cost. In 2017, the emergence of "computable general equilibrium (CGE) model" as the keyword in the representative method indicates that scholars have started to embed climate governance into the development of economic society, considering a series of issues such as the interaction between carbon-trading schemes and economic society. The foothold of 2018 is "coordination," which can be regarded as an emphasis on coordinated development.

3.3 Citation cluster evolution

As shown in Figure 5, the overall evolution path of the citation cluster is as follows (Figure 6).

Beyond the overall evolutionary path, the authors select three typical Clusters #0/#4/#7 (#0 is the largest Cluster, #4 and #7 are the latest clusters) (Figure 5) and study the internal evolution paths of these three main topics. The label of Cluster #0 is "carbon price interaction," and this is a cluster, which mainly includes the study of carbon prices, focusing on the modeling of dynamic carbon prices. Specifically, they determine the factors related to the fluctuation of carbon prices, and then use the regression equation to fit the carbon price. Christiansen *et al.* (2005) analyzed some of the key factors affecting EU carbon prices during 2005–2007, including policy and regulatory issues, weather, production levels and technical indicators. Sijm *et al.* (2006) analyzes the impact of free allocation of CO_2 emission allowances

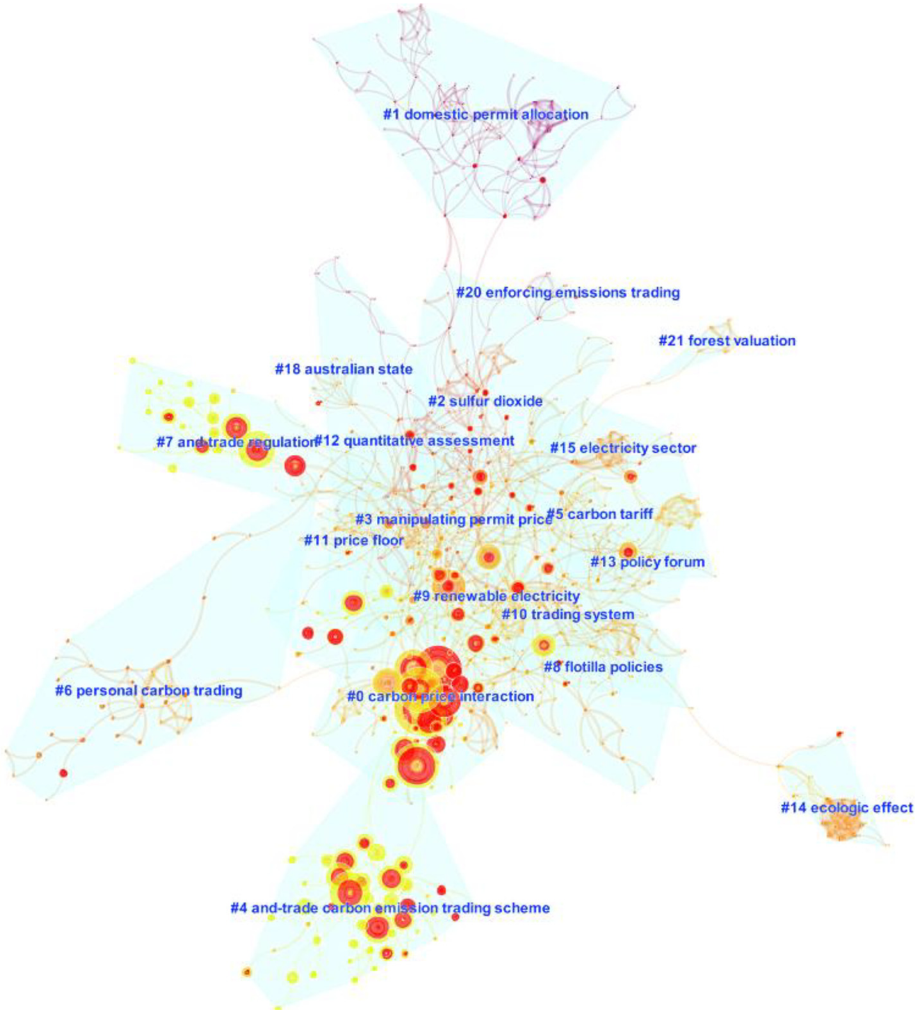

Figure 5.
A landscape view of the co-citation network (make by CiteSpace)

on the price of electricity and the profitability of power generation, indicated that the power companies realize substantial windfall profits. Mansanet-Bataller *et al.* (2007) focus on the daily price changes during 2005 in an attempt to examine the underlying rationality of pricing behavior and find out that the energy sources are the principal factors in the determination of CO_2 price levels. Seifert *et al.* (2008) presented a tractable stochastic equilibrium model reflecting stylized features of the European Union Emission Trading Scheme (EUETS) and analyze the resulting CO_2 spot price dynamics, find that CO_2 prices do not have to follow any seasonal patterns. Daskalakis *et al.* (2009) studied the three main markets for emission allowances within the EUETS and suggests that the prohibition of banking of emission allowances between distinct phases of the EUETS has significant implications in terms of futures pricing. Chevallier (2011b) first attempted a non-parametric model for the carbon

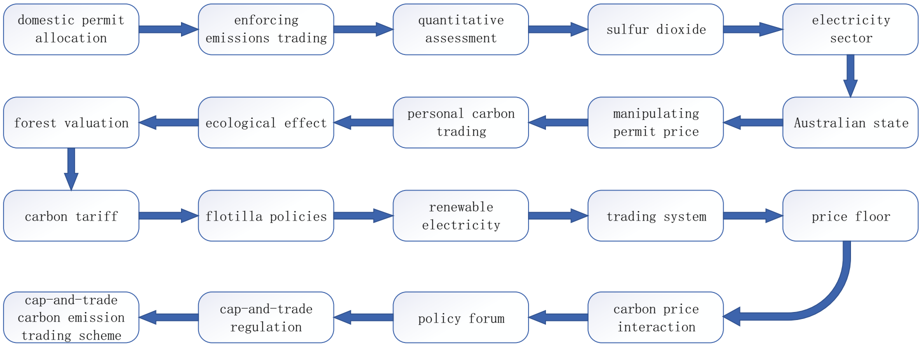

Figure 6.
Citation cluster evolution path

market and found that the non-parametric model reduced the prediction error by 15% compared to the linear autoregressive model. Hammoudeh *et al.* (2014) analyzed the response of short-term carbon dioxide dynamic prices to oil, coal, natural gas and electricity prices using a Bayesian Structural vector auto-regression (VAR) model. Sousa *et al.* (2014) used multi-variate wavelet analysis to describe the interaction between carbon dioxide prices and energy prices (electricity, natural gas and coal) and economic activity. Fan and Todorova (2017) explored the relationship between the carbon prices of China's carbon trading pilot and macro-risks from an empirical perspective. The results show that energy, utilities, industrial and materials industry indices are positively correlated with quota prices in Shenzhen and Guangdong.

The label of Cluster #4 is "cap-and-trade/carbon emission trading (CET) scheme," and the research frontiers given by CiteSpace are mainly about China's carbon-trading scheme. Cong and Wei (2010) establish an agent-based model to study the potential impact of the introduction of CET on China's power sector and discusses the impact of different allocation options of allowances. Zhou *et al.* (2013) estimated the marginal abatement cost curve of each province in China, and then evaluate the economic performance of interprovincial emission reduction quota trading. The results show that China's total emission abatement cost could decrease by over 40% through implementing such an interprovincial emission reduction quota trading scheme. Hubler *et al.* (2014) assess Chinese climate policy proposals in a multi-region, multi-sector CGE model, find out that when the emissions intensity per gross domestic product in 2020 is required to be 45% lower than in 2005, the climate policy induced welfare loss in 2020 is about 1%. Yang *et al.* (2016) used an online questionnaire survey of seven carbon trading pilots from May to November 2015 and determined the factors affecting the awareness and perception of emissions trading schemes. Munnings *et al.* (2016) evaluated how the three most developed emission trading scheme pilots (Guangdong, Shanghai and Shenzhen) adjusted according to China's economic and political background, show that a broader reform of China's political and economic system may be needed to make carbon trading work successfully. Wu *et al.* (2016) used the CGE model to assess the economic impact of emissions trading scheme (ETS) policies in Shanghai. The study concluded that carbon trading can reduce the negative impact on economic output and employment. Zhao *et al.* (2016) conducted an empirical investigation of seven ETS pilots in China and analyzed the market efficiency of ETS pilots from four aspects, namely, carbon price, trading volume, market liquidity and information transparency. The results show that the market efficiency of the carbon trading scheme was not satisfactory. Lin and Jia (2018) used a dynamic recursive CGE model, to establish six different scenarios for the diminishing schemes of carbon emission rights, and the effects of these scenarios on the energy, economy and the environment were discussed. Wang *et al.* (2018) using a case study of 1,867 industrial enterprises in China, find that monitoring, reporting, verification cost is the main cause of the decline in ETS efficiency and that there seems to be no intrinsic link between market structure and an effective coverage of the quota market.

The label of Cluster #7 is "cap-and-trade regulation," which mainly discusses the impact of carbon emissions regulations on industry, supply chain and enterprise production decisions. Dobos (2005) deals with the effect of the introduction of tradable permits on the production–inventory strategy of a firm, and compare the optimal production–inventory strategy before tradable permits and thereafter based on the dynamic Arrow–Karlin model. Ellerman and Buchner (2007) discuss various aspects of the allocation of European Union Allowances, including the lack of readily available installation-level data, the participants in the process, the use of projections, etc. Wrake *et al.* (2010) describe an experimental investigation into price determination under a cap-and-trade program with different allocation methods and find that subjects learn to consider the opportunity cost of permits and overall behavior moves toward the economic prediction. Hua *et al.* (2011) investigates how firms manage carbon footprints in inventory management under the CET mechanism. Li and Gu (2012) used the arrow-Karlin dynamic production-inventory model to study the impact of trading emissions permits in the banking industry on the production inventory strategy of enterprises. Fahimnia *et al.* (2013) established a closed-loop supply chain unified optimization model for carbon cost characterization of carbon emissions in US dollars, assessing the impact of forward and reverse supply chains on the carbon footprint. Zhang and Xu (2013) analyzed the optimal strategy of production and carbon trading decision-making and its impact on carbon prices, production decisions, carbon emissions and total profits. Cao *et al.* (2017) studied the impact of carbon trading policies and low carbon subsidy policies on manufacturers' production and carbon emissions reduction levels. The results show that the carbon trading price does not always have a negative impact on the profits of the manufacturer and the carbon trading cap does not always have a positive impact on the profit of the manufacturer. Ji *et al.* (2017) take the online to offline (O2O) retail supply chain in a low-carbon environment as the research object and establish the decision-making model in three cases, the results show that carbon allowance plays a decisive role in enterprise decision-making. Wang *et al.* (2017) developed an optimal production model of new products and remanufactured products with maximum profit under three different carbon trading regulations, the results show that capital constraints can encourage manufacturers to remanufacture old products at a higher quality level and significantly reduce carbon emissions.

3.4 Citation path evolution

The HistCite is used to display the citation paths of the first 30 highly cited papers, as shown in Figure 7. Overall, except for the number 306, 976 and 1,175, which are isolated points, the other points are connected. The citation network originated in Sorrell and Sijm (2003) and ended in Liu *et al.* (2015) and Li and Lu (2015). The important documents passed through included 266, 392, 393, 465, 534, 837, 839, 892, 973, 1220, 1425, etc. Based on the importance of these papers and the cited relationships, this paper summarizes three main evolutionary paths as follows: the first one: 266–465-837–1220-1425–1592; the second one: 214–1576; and the third one: 392–465-534–892.

Path 1 evolved from literature No. 266 to literature No. 1592, which is the longest and most complex of the three paths. The path started from two papers on the driving factors of carbon prices and, after two papers on the cost of carbon trading, evolved into one paper on the impact of the carbon trading mechanism. In short, this path is an evolution path from

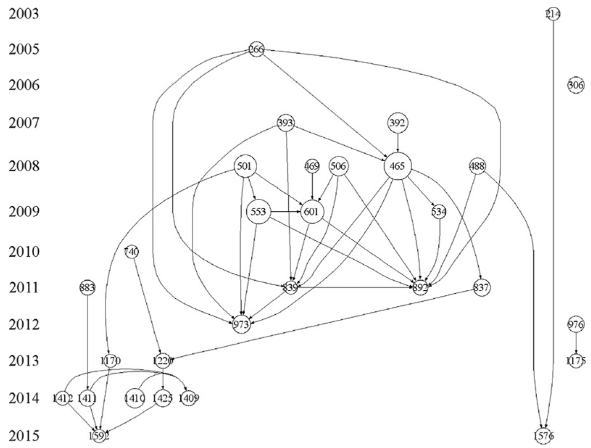

Figure 7. The research main paths of carbon-trading literature from 1998 to 2018 (make by HistCite)

"What affects carbon price?" to "What does carbon price affect?" Paper 266 is an article published by Christiansen *et al.* (2005), this paper provides a starting point for understanding the dynamic changes of carbon-emissions trading. Paper 465 (Alberola *et al.*, 2008) studied the drivers and structural changes of EU carbon prices from 2005 to 2007, shown that carbon spot prices are not only related to energy prices but also to unpredicted temperature changes during coarser events. Paper 837 (Feng *et al.*, 2011) studies the fluctuation of EU carbon prices from the perspective of non-linear dynamics and shows that carbon price is not random walk and the historical information on carbon prices is not fully reflected in the current carbon prices. Paper 1220 (Zhou *et al.*, 2013) models the economic performance of China's interprovincial carbon-trading scheme. The simulation results show that by implementing such an interprovincial emissions reduction allocation, the total cost of emissions reduction in China can be reduced by more than 40%. Paper 1425 (Cui *et al.*, 2014) established China's interprovincial emissions trading model, and then designed three policy options, including carbon-free trading, pilot-only carbon trading and unified carbon trading market and studied the cost-saving effect of carbon trading in China. Paper 1592 (Li and Lu, 2015) explores the effects of carbon prices on China's macroeconomic, environmental and energy needs in eight different models using a recursive dynamic general equilibrium model. It is suggested that the benchmark range of carbon price in the national unified carbon trading market should be 30 yuan/TCO_2 to 50 yuan/TCO_2.

Path 2 evolved directly from paper No. 214 to paper No. 1576. This path is the most direct, simplest and longest-spanning of the three evolutionary paths. It can be seen that this path represents the discussion on the optimization of carbon-trading schemes. The path from general literature to a study of China shows that China's carbon market is receiving increasing attention. Paper 214 is an article published by Sorrell and Sijm (2003), and the purpose of this article is to provide an understanding of policy interactions by assessing the effectiveness of carbon-emissions trading policies in conjunction with carbon/energy taxes, new energy generation support mechanisms and annual energy efficiency improvement policies. The article argues that each of these tools is acceptable and the goals and costs of the policy mix must be weighed when choose them. Paper 1,576 is an article published by Liu *et al.* (2015), this paper argues that China's carbon-trading market is facing challenges, such as a lack of a functional carbon-trading market, inaccurate quota allocation, imperfect trading mechanism and lagging legislation. At present, due to poor real-time carbon prices and dominant spot trading, China's carbon-trading market is not a functional system, and more effective measures are needed to integrate and develop China's carbon market.

Path 3 evolves from paper No. 392 to paper No. 892. This path is still a research path on carbon prices. Paper 392 (Ellerman and Buchner, 2007) focuses on how EUETS allocates the carbon allowance, discusses the latest emissions data from 2005 and the information that they indicate about overallocation, trade patterns and emissions reduction. Paper 465 (Alberola *et al.*, 2008) studies the driving factors and structural changes of EU carbon prices from 2005 to 2007. The results show that spot carbon prices are not only related to energy prices but also to unpredictable temperature changes during colder events. Paper 534 (Alberola and Chevallier, 2009) indicates that the banking restrictions from 2007 to 2008 could also explain the lower-than-expected carbon price, demonstrated that the carry-over cost relationship between the EU spot and h-period delivery futures prices was not established after the implementation of the inter period bank restriction. Paper 892 by Chevallier (2011a) established a carbon pricing model to capture the interaction between the macroeconomy and the energy sector in a Markov-switching VAR model, shows that industrial production has a positive (negative) impact on the carbon market during economic expansion (recession), thereby confirming the link between the macroeconomy and carbon prices.

4. Topics for future research

Through a systematic review of the literature in the field of carbon trading, the authors find that the development of carbon trading shows a spiral upward trend (Figure 8). Specifically, in the early stage of drafting and establishing carbon-trading schemes, the literature mostly discusses how to design a scheme itself and how to gain experience from the implementation of previous relevant mechanisms (e.g. the USA sulfur dioxide emissions trading system); thus, at this stage, most of the keywords (1998–2005) are "climate change," "carbon-trading scheme," "Kyoto Protocol," "sulfur dioxide." When a scheme is established, scholars tend to explore the antecedent and outcome variables of the important variables in the scheme. In a carbon-trading scheme, the important and uncertain variable is carbon price, which also leads to a series of antecedents and consequences, such as energy, technology, innovation and welfare. Cluster 0 (2005-2014) is mostly about the research in this area. When the

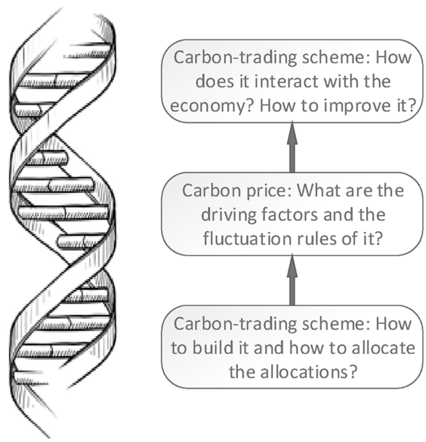

Figure 8.
Spiraling evolution of research on carbon-trading schemes

scheme fails or is not effective for some reason, when the economy suffers a major blow or when the technological development is facing bottlenecks (or, perhaps, an interaction of the two or three), scholars return to explore the scheme itself. Therefore, after the 2008 financial crisis, for a long time, it was difficult for the world economy to recover, and the research on a carbon trading scheme in itself gradually increased; this cluster (Cluster 4) has lasted since 2010. At present, the development of the world economy is still not optimistic, and a carbon-trading scheme is almost an overhead. The research on carbon-trading schemes is in an important stage of restructuring the scheme itself. The duration of this stage will depend on the speed of economic recovery, major institutional breakthroughs or major technological breakthroughs. The authors find that the keywords of 2017 and 2018 are rooted in a grand method of linking the whole economic system, and in the impact of a carbon-trading scheme on the economy. Therefore, the development trend of the carbon-trading scheme can be summarized as: find the most effective way, which has the least cost and the least impact on the economy.

Based on the above comprehensive review of the evolution of carbon trading, this paper identified several potential hot spots for future research on carbon-trading schemes, specifically as follows.

4.1 Marginal costs and benefits of carbon trading

Zhou *et al.* (2013) estimated the marginal cost and revenue curve of a carbon-trading scheme and then established the economic performance model of a carbon-trading scheme to simulate the cost-saving utility of different quota allocation methods. Cui *et al.* (2014) established a model of China's interprovincial emission trading and then designed three policy models to study the cost-saving effect of China's carbon-emissions trading under different models. A carbon-trading scheme will bring some costs and benefits to society. In the section on keyword evolution, it can be seen that such words as "cost" and "impact" appear repeatedly. Studies on the marginal cost and shadow price of emissions reduction are also attracting more attention. Literature on the impact of emissions reduction on the social economy, industrial development, innovation and welfare are emerging in an endless stream. In the context of a sluggish global economic development, the analysis of the costs and benefits of a carbon-trading scheme will be more eye-catching. The authors believe that future studies on the costs and effects of carbon trading are still worthy of attention.

4.2 Improvements in carbon-trading schemes

At present, the improvement of China's carbon market is a research hotspot: Liu *et al.* (2015) discussed the policy process and development status of China's carbon market to date and analyzed the obstacles hindering the development of China's carbon market. The paper points out that China's carbon market is faced with such challenges as the lack of a functional carbon market, inaccurate quota allocation, imperfect trading mechanism and lagging legislation and that more effective measures are needed to integrate and develop China's carbon market. Jiang *et al.* (2016) systematically reviewed and evaluated the research progress in recent years on China's carbon trading mechanism from three aspects, including mechanism design, policy and regional contact and finally put forward five urgent issues to be further studied over the next few years: including the limits set, quota allocation between departments and enterprises, carbon pricing, package design and the construction of a unified carbon market and *ex ante* and *ex post* impact assessment. It should be noted that not only China's carbon market but also the carbon-trading scheme itself has many problems that need to be addressed: for example, which greenhouse gases should be included in the emission trading scheme, as there are many kinds of greenhouse gases and the current emissions-trading scheme only includes CO_2; which sectors should be involved in carbon trading, as many sectors contribute to greenhouse gas emissions, but a carbon-trading scheme only includes a few departments; how to allocate carbon allowance, given the selection and combination of "grandfather" allocations, national allocations and auctions; how to balance the game between governments, vested interests and the public, given that in the EUETS carbon allowances are excessive, carbon prices are far from the expected level and the electricity sector is profiting profitably from ETS (vested interest groups gain benefits and the public interest is impaired).

4.3 Criticisms of carbon-trading schemes

First, the theoretical basis for a carbon-trading scheme is the idealized pollution control theory in economic theory, which assumes that the marginal cost and benefit function are complete, continuous and known. However, the real world does not meet this assumption, which means that it is disconnected from the actual situation to a certain extent. Second, in the process of moving from theory to practice, carbon-trading mechanisms have oversimplified and complicated the real world, and have difficulties in balancing the market, power and vested interests. A carbon-trading mechanism has a series of irrationalities in its greenhouse gas accounting, quota allocation and emissions compensation (Spash, 2010). A carbon-trading scheme is an institutional arrangement adopted by the EU after it failed to seek a unified carbon tax; due to its strong marketization degree and great elasticity to economic impact, it has been supported and promoted to a certain extent in the world. However, it should also be aware that the carbon price is lower than expected worldwide and that the emissions reduction effect of the carbon-trading scheme is not satisfactory. Instead, it has brought benefits to some vested interests and increased unfair distribution. The institutional and operational costs of a carbon-trading scheme are relatively high, and if other policies are implemented, will they achieve better results at a lower cost? If a carbon-trading scheme can be supported, it means that the polluters do not think it will harm their interests, but if the polluters do not pay for the pollution, then who will pay for the carbon-trading scheme? Is this mechanism a vanity or a comfort?

4.4 Personal carbon trading

With the deepening trend of social flattening, PCT has become an important development prospect of in carbon-trading scheme. PCT can turn the trader of carbon trading into the most basic unit (the individual) of the society and make this scheme completely reasonable. However, current PCT is still at the stage of building a vision and faces huge problems. Fawcett and Parag (2010) present an introduction and a literature review of PCT that reminds us of the following questions: how to balance the responsibility of reducing emissions between national and local governments, organizations, communities and individuals? Can certain features of PCT be implemented without the whole scheme? What is its most executive aspect? Fawcett (2010) questioned the British government's announcement that PCT is an "advanced idea": they reviewed the relevant literature and found that most studies showed that PCT was at least as socially acceptable as alternate tax policies that were considered fair and effective. Eyre (2010) analyzed the feasibility of PCT from the mechanism design level and believed that it was difficult to implement. The authors believe that although it is difficult to implement PCT given the current social situation and technology level, it is consistent with the flattening trends in social development; therefore, it is one of the directions for future emissions reduction work, and its institutional arrangement and system of construction will also be a research hotspot for future scholars.

5. Conclusions

This paper reviewed the evolution of carbon-trading research and conducted a quantitative analysis of 2,282 papers. First, the authors obtained the literature on carbon trading published between 1998 to 2018 in the WOS core collection using an advanced search. Next, the current research status is analyzed by the evolution of the discipline, keywords, citations and citation paths. Based on the above analysis, the evolutionary process of the 20-year literature on carbon trading is clearly demonstrated.

This paper finds that the research on carbon-trading schemes has developed and evolved along four dimensions. The macroscopic disciplinary dimension shows that the research frontiers of carbon trading include economics, economic, political, mathematics, systems, mathematical, ecology, earth and marine. The knowledge base is mainly distributed in such fields as economics, economic, political, environmental, toxicology, nutrition, systems, computing, computer, plant, ecology, zoology, earth, geology and geophysics. The biggest change is that at least four different disciplines point to mathematics. The evolution of the keywords can be roughly divided into three stages. The first stage is from 1998 to 2006, during which the design of carbon-trading schemes is mostly discussed. The second phase is from 2007 to 2011, which focuses on carbon price issues. The third stage is from 2012 to 2018, and mainly discusses the interaction between a carbon-trading scheme and the economy, showing a deepening emphasis on coordinated development. Citation clusters identified 19 research topics and their evolution processes, the most important of which are carbon prices, China's carbon-trading scheme, the carbon market and the supply chain. The citation path identifies three main evolutionary paths, the most important of which shows a change from "What affects carbon price?" to "What does carbon price affect?" Based on the above results, the authors indicate several future research directions for carbon-trading schemes, including four topics, namely, marginal costs and benefits of a carbon-trading scheme, improvements in carbon-trading schemes, criticisms of carbon-trading schemes and PCT. There are still the following points that can be improved or further explored: because of the difficulty in eliminating duplicate documents between different databases, the inconsistency caused by different retrieval algorithms and the requirements of the analysis software used in this paper, this paper only use WOS database for literature collection. The analysis and discussion are based on the results given by the software, from which the authors select representative keywords, clusters or paths to analysis, which may cause the omission of some important issues, such as the consequences of carbon trading, especially its impact on climate change.

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