Economic Growth and Carbon Emission Nexus: A Survey

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2 **A Survey**

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8

9 **Abstract**

10 Developing better mitigation strategy requires a comprehensive understanding the

11 relationship between economic growth and carbon emission. Through a literature

12 review, we summarized the following five relationship reported in existing studies: (i)

13 a single causal from economic growth to carbon emission, (ii) a single causal from

14 carbon emissions to economic growth, (iii) a bidirectional causality, (iv) the

15 Environmental Kuznets Curve, (v) no obvious relationship. And then, we further

16 quantify contribution of countries, institutes, authors, investigate research hotspot, and

17 explore future research directions of carbon emissions and economic growth nexus

18 using web of science data from 2001-2019. We find regardless of the total number of

19 publications, institutions and highly cited papers, China research on carbon emissions

20 and economic growth has always been among the best. By analyzing the cooperation

21 relationship between countries and institutions, more than half of the institutions are

more inclined to cooperate with institutions in their own countries rather than abroad. Through keyword hotspot analysis and keyword trend analysis, we uncovered the future research directions and hotspots of carbon emissions and economic growth: ①What is the relationship between carbon emissions, economic growth and energy consumption. ②The efforts of China in carbon reduction and economic growth. ③How to reduce carbon dioxide emissions while ensuring stable economic growth. ④The research on carbon emissions and economic growth in the fields of urbanization, financial development, renewable energy, and climate change.

Keywords: Carbon emissions; economic growth; research profile; research outlook;

1. Introduction

With the growing conflict between economic development and environmental protection, the issue of carbon emissions has received increasing attention from countries(Saidi and Hammami 2015). According to the " Global Energy and CO₂ Status Report 2018" published by the International Energy Agency, global carbon dioxide emissions reached 33.1 billion tons, and it will continue to rise in the future. Faced with this challenge, countries around the world have begun to respond. The United Nations Framework Convention on Climate Change was proposed in 1992, the Kyoto Protocol adopted in 1997, and the national independent contribution mechanism introduced by the Paris Agreement in 2015. The Paris Agreement requires all parties to assume

44 emission reduction obligations and set their own emission reduction targets. This not
45 only guarantees the wide range of participants, but also dilutes the game and opposition
46 between all parties in the allocation of emission reduction obligations, and enhances
47 the enthusiasm of countries to participate in voluntary contributions. All these indicate
48 that countries around the world have acted to actively reduce carbon emissions.

49 Studying the relationship between carbon emissions and economic growth is of
50 great significance for promoting low-carbon green development. In recent years, the
51 relationship has been studied using different methods and technologies in the past
52 published papers, but the results of different literatures have shown great differences.
53 No consensus has been reached on the direction of the causal relationship between
54 carbon emissions and economic growth. Therefore, it is necessary to conduct in-depth
55 research, reveal the variables that lead to the relationship and explore the future research
56 directions of carbon emissions and economic growth. Therefore, this paper uses a
57 bibliometric method to systematically review and analyze the literature on carbon
58 emissions and economic growth of the core database of web of science.

59 Therefore, this study uses bibliometric methods to analyze the basic characteristics
60 of the annual publication volume, subject categories, and research areas. The
61 knowledge map software CiteSpace is used for visual analysis to build a country
62 cooperation network, institution cooperation network, and keyword co-occurrence
63 network to comprehensively analyze the research hotspots and trends of carbon
64 emissions and economic growth research. Scientific literature can reflect the
65 development level and development trend of a certain subject area. With the rapid

development of computers, networks, and information technology, bibliometrics has developed rapidly, and its theory, methods, and methods have become increasingly perfect. As a tool for quantitative analysis of documents(Montoya et al. 2014), bibliometrics can reveal the development history and research hotspots of a certain field through quantitative and qualitative analysis of external characteristics of the document, such as title, author, keywords, citations, etc. CiteSpace is a visual analysis tool based on the Java platform(Fang et al. 2018). It integrates information visualization methods and data mining algorithms. It also has certain advantages in capturing scientific frontiers, hotspots and trends(Cui et al. 2018). CiteSpace has been widely used in many fields of information science, computer science, and information science(Hu et al. 2019).

The main content of this article includes 5 chapters. The Literature Review reviews the literature on carbon emissions and economic growth over the past five years. Methods and data sources describe the methodology framework and data sources for this study. Bibliometric analysis presents the main findings of bibliometrics. The last part is Conclusions.

2. Literature Review

In recent years, human activities have led to a rapid increase in greenhouse gas emissions such as carbon dioxide, which has led to global warming. A series of disasters, such as the melting of the iceberg, triggered alarm bells for human survival and the sustainable development of society. Therefore, it is imperative for mankind to find an

effective method to ensure stable economic growth and reduce carbon emissions. We review the literature over the past five years. In addition, in this section, we list the empirical literature on the causal relationship between carbon emissions and economic growth by author, time range, country, method, and empirical results, as shown in Table 1.

Zhang and Da proved economic growth has proved to be the main driving force for the increase in carbon emissions in the past few decades in China(Zhang and Da 2015). Begum et al. studied the impact of GDP growth, energy consumption and population growth on carbon dioxide emissions in Malaysia, and the results proved that economic growth will increase Malaysia's carbon dioxide emissions (Begum et al. 2015). Tang and Tan prove that economic growth was a key determinant of CO₂ emissions in Vietnam between 1976 and 2009(Tang and Tan 2015). Ahmad and Du proved that there is a positive correlation between carbon dioxide emissions and economic growth in Iran (Ahmad and Du 2017). Hdom studied the interrelationships between carbon dioxide emissions, electricity, and economic growth in South America, and the results proved that economic growth promotes carbon dioxide emissions(Hdom 2019). Bekun et al. have proved that there is an inverse relationship between economic growth and carbon dioxide emissions(Bekun et al. 2019).Wang et al. proves that there is a single causal relationship between economic growth and carbon emissions(Wang et al. 2016). Wang et al. proved that there is a causal relationship between economic growth and carbon dioxide in the long run(Wang et al. 2018). Mikayilov et al. proved that economic growth has a positive effect on carbon dioxide emissions in the long run

110 in Azerbaijan (Mikayilov et al. 2018). Chen et al. explored the relationship between per
111 capita carbon dioxide emissions, GDP, and the results showed that the increase of GDP
112 will increase carbon dioxide emissions (Chen et al. 2019a). Zaidi et al. Studied the
113 dynamic links between economic development, and carbon emissions in APEC
114 countries, and the results show that economic growth has promoted carbon dioxide
115 emissions (Zaidi et al. 2019). Du et al. have proved that there is a positive correlation
116 between economic growth and carbon emissions in China's construction industry (Du et
117 al. 2019). Wang et al. prove that the US achieved moderate economic growth while
118 reducing carbon emissions during 2007-2016 (Wang et al. 2019). Kizito Uyi
119 Ehigiamusoe and Lean research proved that economic growth reduces the carbon
120 emissions of high-income groups, but it has the opposite impact on low-income and
121 middle-income groups (Kizito Uyi Ehigiamusoe and Lean 2019).

122 Alshehry and Belloumi proved a bidirectional causality between Saudi Arabia's
123 carbon dioxide emissions and economic growth (Alshehry and Belloumi 2015). Long et
124 al. have proved that there is a two-way causal relationship between China's economic
125 growth and carbon dioxide emissions from 1952 to 2012 (Long et al. 2015). Ahmad et
126 al. proves that there is a two-way causal relationship between India's economic growth
127 and carbon emissions from 1971 to 2014 (Ahmad et al. 2016). Ezzo and Kehoe prove that
128 there is a two-way causal relationship between economic growth and CO₂ emissions in
129 12 selected countries in sub-Saharan Africa (Ezzo and Kehoe 2016). Zhang and Gao
130 proved that there is a two-way causal relationship between China's economic growth
131 and CO₂ emissions (Zhang and Gao 2016). Chaabouni and Saidi proved that there is a

bidirectional causality between carbon dioxide emissions and GDP per capita(Chaabouni and Saidi 2017). Liu and Hao proved that there is a long-term two-way causal relationship between carbon dioxide emissions and economic growth in countries along the “Belt and Road”(Liu and Hao 2018).Zhang et al. proved that there is a two-way causal relationship between carbon emissions and economic growth in China's major grain-producing regions(Zhang et al. 2019a).Chen et al. proved that there is a bidirectional causality between economic growth and carbon dioxide emissions in China(Chen et al. 2019b).

Saidi and Hammami proved that carbon dioxide emissions have a negative impact on economic growth(Saidi and Hammami 2015).Mehdi Ben Jebli and Youssef studied and proved that there is a one-way causal relationship from carbon dioxide emissions to GDP in the short term(Mehdi Ben Jebli and Youssef 2019).

Ahmad et al. proved that there is an inverted U-shaped EKC relationship between carbon dioxide emissions and economic growth (Ahmad et al. 2017).Yang et al. proved that there is an inverted U-shaped EKC relationship between carbon dioxide emissions and economic growth in Russia(Yang et al. 2017).Wang and Li studied China's carbon emissions and GDP per capita from 1990 to 2014, and the results proved that the relationship between carbon dioxide emissions and economic growth was an inverted U-shape(Wang and Li 2019).Nie et al. proved that the carbon dioxide emissions in eastern China are positively correlated with GDP, while the central and western regions have an inverted U-shaped relationship.(Nie et al. 2019). Hanif et al. proved that there is an environmental Kuznets curve in 15 Asian developing countries(Hanif et al. 2019).

Balsalobre-Lorente et al. proved that there is an N-type EKC relationship between economic growth and carbon emissions(Balsalobre-Lorente et al. 2018). Bouznit and Pablo-Romero proved that the relationship between Algeria's carbon dioxide emissions and economic growth is consistent with the EKC curve (Bouznit and Pablo-Romero 2016).Zaman and Moemen studied the relationship between energy consumption, carbon dioxide emissions, and economic development, and the results showed compliance with the EKC curve (Zaman and Moemen 2017).Murat et al. proved that the EKC curve is effective for Turkey (Murat et al. 2018).Zhang et al. studied the relationship between economic growth and carbon emissions in developing countries, and the results showed that some countries conformed to the EKC curve(Zhang et al. 2019b).

Gorus and Aydin s proved that there is no causal relationship between economic growth and carbon emissions in the Middle East and North Africa countries (Gorus and Aydin 2019).Salahuddin et al. proved that there is no causal relationship between economic growth and carbon dioxide in OECD from 1991 to 2012 (Salahuddin et al. 2016).

The overall results studied in this article show that the literature has reached conflicting results. There is no consensus on the causal relationship between carbon emissions and economic growth. The main points are as follows. ① There is a single causal relationship runs from economic growth to carbon emission.② There is a bidirectional causality between carbon emission and economic growth. ③ There is a single causal relationship runs from carbon emissions to economic growth. ④ The

economic growth and carbon emissions conform to the EKC curve. ⑤ There is no obvious relationship between economic growth and carbon emissions. Understanding the link between carbon emissions and economic growth will help economies make energy policies and develop energy in a sustainable manner. However, the results of studies in different literatures have shown great differences. Therefore, it is necessary to conduct in-depth research to reveal the important variables of the relationship between carbon emissions and economic growth. Therefore, this article systematically reviews and analyzes the literature on carbon emissions and economic growth of the core database of web of science.

Table 1 A Summary of empirical studies on carbon emissions–economic growth nexus.

Authors	Period	Country	Methodology	Causality relationship
Zhang and Da. (Zhang and Da 2015)	1996-2010	China	LMDI	GDP→CE (Positive correlation)
Begum et al.(Begum et al. 2015)	1970-2009	Malaysia	Dynamic ordinary least squared and the Sasabuchi–Lind–Mehlum U tests.	GDP→CE (Positive correlation in the long run)
Tang and Tan. (Tang and Tan 2015)	1976-2009	Vietnam	Cointegration and Granger causality.	GDP→CE (Positive correlation)
Ahmad and Du .(Ahmad and Du 2017)	1971-2011	Iran	The autoregressive distributed lag (ARDL) bounds testing approach	GDP→CE (Positive correlation)
Hdom. (Hdom 2019)	1980-2010	South American	ARDL approach	GDP→CE (Positive correlation)
Bekun et al.(Bekun et al. 2019)	1960-2016	South Africa	Co-integration approach, bounds test, critical values and approximate p-values.	GDP→CE (Negative correlation)
Wang et al.(Wang et al. 2016)	1995-2012	China	Panel data model.	GDP→CE(Positive correlation)
Wang et al.(Wang et al. 2018)	1980–2011	170 countries	Panel unit root test, panel cointegration test, panel granger causality test, and impulse response and variance decomposition methods.	GDP→CE(Positive correlation)
Mikayilov et al.(Mikayilov et al. 2018)	1992–2013	Azerbaijan	Five different cointegration methods	GDP→CE(Positive correlation)
Chen et al. (Chen et al. 2019a)	1980-2014	China	ARDL approach and vector error correction model (VECM) Granger causality approach	GDP→CE(Positive correlation)

Zaidi et al.(Zaidi et al. 2019)	1990-2016	Asia Pacific Economic Cooperation countries	Westerlund Cointegration approach, Continuously Updated Bias-Corrected (CUP-BC) and Continuously Updated Fully Modified (CUP-FM) methods	GDP→CE(Positive correlation)
Du et al.(Du et al. 2019)	2005-2015	China	The standard deviational ellipse method.	GDP→CE(Positive correlation)
Wang et al.(Wang et al. 2019)	2007-2016	The United States	Cobb–Douglas production function and extended Kaya equation	GDP→CE (Negative correlation)
Kizito Uyi Ehigiamusoe and Lean (Kizito Uyi Ehigiamusoe and Lean 2019)	1990-2014	122 countries involved high-income group, low-income and middle-income groups.	First-generation and second-generation cointegration and estimation procedures	GDP→CE (Negative correlation in high-income group) GDP→CE(Positive correlation in low-income and middle-income groups)
Alshehry and Belloumi. (Alshehry and Belloumi 2015)	1971-2010	Saudi Arabia	Johansen multivariate cointegration	GDP←→CE (in the long run)
Long et al.(Long et al. 2015)	1952-2012	China	Granger causality	GDP←→CE
Ahmad et al. (Ahmad et al. 2016)	1971-2014	Indian	ARDL approach; VECM model.	GDP←→CE
Esso and Keho. (Esso and Keho 2016)	1971-2010	African countries	Granger causality	GDP←→CE
Zhang and Gao. (Zhang and Gao 2016)	1995-2011	China	Panel causality tests	GDP←→CE
Chaabouni and Saidi. (Chaabouni and Saidi 2017)	1995-2013	51 countries	Dynamic simultaneous-equations models; generalized method of moments	GDP←→CE

Liu and Hao. (Liu and Hao 2018)	1970-2013	The countries along “the Belt and Road”.	VECM model, FMOLS and DOLS approaches	GDP $\longleftrightarrow$ CE
Zhang et al.(Zhang et al. 2019a)	1996-2015	China	ARDL approach, Granger causality and VECM model.	GDP $\longleftrightarrow$ CE
Chen et al.(Chen et al. 2019b)	1995-2012	China	Panel causality tests	GDP $\longleftrightarrow$ CE (in the long run)
Saidi and Hammami (Saidi and Hammami 2015)	1990-2012	58 countries	Production function approach	CE $\rightarrow$ GDP (Negative correlation)
Mehdi Ben Jebli and Youssef. (Mehdi Ben Jebli and Youssef 2019)	1980-2013	Brazil	ARDL approach	CE $\rightarrow$ GDP
Ahmad et al.(Ahmad et al. 2017)	1992-2011	Croatia	Autoregressive Distributed Lag (ARDL) and VECM method	GDP $\longleftrightarrow$ CE (in the short term). Meet Environmental Kuznets Curve in the long run.
Yang et al.(Yang et al. 2017)	1998-2013	Russia	Guidelines for National Greenhouse Gas Inventories suggested by the IPCC.	Meet Environmental Kuznets Curve.
Wang and Li (Wang and Li 2019)	1990-2014	China	PSO algorithm-based grey Verhulst model	Inverted U-shape
Nie et al.(Nie et al. 2019)	1995-2014	China	PSTR model	GDP $\rightarrow$ CE(Positive correlation in Eastern China). Inverted U-shape in Central and Western China.
Hanif et al.(Hanif et al. 2019)	1990-2013	Emerging Asian economies	ARDL model.	Meet Environmental Kuznets Curve.

Balsalobre-Lorente et al.(Balsalobre-Lorente et al. 2018)	1985-2016	Germany, France, Italy, Spain, and the United Kingdom	Carbon emission function.	The N-shaped Environmental Kuznets Curve relationship
Bouznit and Pablo-Romero (Bouznit and Pablo-Romero 2016)	1970–2010	Algeria	ARDLmodel.	Meet Environmental Kuznets Curve.
Zaman and Moemen .(Zaman and Moemen 2017)	1975-2015	90 countries	Panel unit root test	Meet Environmental Kuznets Curve.
Murat et al.(Murat et al. 2018)	1960-2013	Turkey	Unit root tests, Bounds testing approach, VECM granger causality test	Meet Environmental Kuznets Curve.
Zhang et al.(Zhang et al. 2019b)	1995–2017	50 representative developing countries	Cross-sectional dependence test, panel unit root test, panel cointegration tests.	Some countries meet Environmental Kuznets Curve.
Gorus and Aydin (Gorus and Aydin 2019)	1975-2014	MENA countries	Granger causality analysis	GDP-----CE
Salahuddin et al.(Salahuddin et al. 2016)	1991-2012	OECD countries	Pedroni panel cointegration test	GDP-----CE
Note: GDP→CE means that the causality runs from economic growth to carbon emission.				
CE→ GDP means that the causality runs from carbon emission to economic growth.				
GDP←→CE means that bi-directional causality exists between carbon emission and economic growth.				
GDP-----CE means that no causality exists between carbon emission and economic growth.				

3. Methods and data sources

The data used in this study was obtained from the Science Citation Index Expanded (SCI-E) of Web of Science core database, which is an internationally recognized authoritative database. The keywords “carbon emission*” and “economic* growth” were used to search the titles, abstracts and keywords within the time frame from 2001 to 2019. The search includes article and review. The data was obtained on the February 2, 2020, and a total of 3318 records were retrieved.

As a tool for quantitative analysis of documents, bibliometric methods are often used to quantitatively analyze academic literature and patents(Giovanni et al. 2011; Li and Zhao 2015; Mayr and Scharnhorst 2015). Quantitative and qualitative analysis of external characteristics of a document (such as title, author, keywords, and citations) can reveal the development history, research hotspots, and the interaction between disciplines in a certain field, thereby exploring the development trend of the scientific field.

The scientific knowledge atlas is a graph showing the development process and structural relationship of scientific knowledge [26]. CiteSpace is based on the Java platform. It has certain advantages in capturing scientific frontiers, hotspots and trends. It has been widely used in many fields such as information science, computer science, and information science(Hu et al. 2019). CiteSpace integrates information visualization methods, bibliometric methods and data mining algorithms, and has the dual properties and characteristics of "graph" and "spectrum"(Li et al. 2017). It is both a visual

knowledge graph and a serialized knowledge pedigree. CiteSpace takes snapshots of specific areas based on time series and links them together to derive changes and trends in this area(Chen 2006). CiteSpace supports the analysis of the structure and time of various networks derived from scientific publications (Peng et al. 2020). Reveal key disciplines and frontier areas of future research by tracking the hot topics and the latest cutting-edge issues of existing research(Cui et al. 2018).

The visualization process of Citespace mainly includes three main steps: similarity standardization processing, clustering, and visualization methods.

(1) Similarity standardization processing.

Data preprocessing is the first step of visual analysis and the basis of data visual analysis. In order to obtain ideal results and better display the relationship between the data, it is necessary to ensure the quality of the preprocessed data. The standardized algorithms of Citespace include Cosine, Dice and Jaccard.

The Cosine similarity algorithm evaluates the similarity of two vectors by calculating the cosine of the angle between them.

In two-dimensional space, the cosine of the angle between the two vectors is:

$$\cos \alpha = \frac{A * B}{|A| * |B|} \quad (1)$$

The cosine similarity of a multidimensional space vector is as follows:

$$\cos \alpha = \frac{\sum_{i=1}^n (A_i * B_i)}{\sqrt{\sum_{i=1}^n (A_i)^2} * \sqrt{\sum_{i=1}^n (B_i)^2}} \quad (2)$$

Jaccard similarity algorithm:

$$J = |A \cap B| \div |A \cup B| \quad (3)$$

The Jaccard coefficient is the intersection of the words common to two texts

divided by the set of all words in both texts. The closer the Jaccard coefficient value is to 1, the more similar the two texts are.

The Dice similarity coefficient can calculate the similarity of two strings:

$$Dice = \frac{2 * comm(S_1, S_2)}{leng(S_1) + leng(S_2)} \quad (4)$$

In formula (4), $comm(S_1, S_2)$ is the number of the same characters in S_1, S_2 , and $leng(S_1)$ and $leng(S_2)$ are the lengths of the strings S_1, S_2 .

(2) Clustering

Clustering is to group data objects into multiple classes or clusters. The principle of division is that the objects in the same cluster have good similarity, but the objects between different clusters are quite different. In the function menu of CiteSpace software, the clusters menu contains algorithms that can be selected during the clustering process, including Clustering algorithms, LLR algorithms, and MI algorithms.

The Clustering algorithm belongs to the inter-class distance algorithm in the hierarchical clustering algorithm.

$$D_{pq}^2 = \frac{1}{n_p n_q} \sum_{\substack{\vec{x}_j \in \omega_q, \\ \vec{x}_i \in \omega_p}} d_{ij}^2 \quad (5)$$

In the formula, p and q are two clusters. The distance between them is determined by the average distance between the units i, j .

Likelihood ratio (LLR) clustering algorithm:

$$LLR = \log \frac{p(C_j | V_{ij})}{p(\bar{C}_j | V_{ij})} \quad (6)$$

In the formula, it is assumed that for the category C_j , the frequency, concentration,

and dispersion of the word W_i constitute a vector V_{ij} . LLR is the log-likelihood ratio of the word W_i to the category C_j . $p(C_j|V_{ij})$ and $p(\bar{C}_j|V_{ij})$ are the density functions of W_i in category C_j and $\bar{C}_j$, respectively.

MI (mutual information) clustering algorithm:

$$MI(w, c) = \sum_{w, c} p(w, c) \log \frac{p(w, c)}{p(w)p(c)} \quad (7)$$

In the formula, $p(w, c)$ is the co-occurrence probability of w and c ; $p(w)$ and $p(c)$ are the probability of occurrence of w and c respectively.

(3) Visual methods

The clustering view in CiteSpace is a graph based rendering method, while the time-line view and time-zone view are time-based rendering methods. In the graph-based visualization method, the relationships between nodes are linked by wires, and the connections between nodes can clearly reflect the connection between two objects. But in large networks, there are many and complicated connections between nodes. There may be situations where the label element is covered between different nodes, and the visualization effect will be affected. Each document can be linked to a specific point in time according to its specific publication time, and large-scale networks can be separated by time slicing. The time-series visualization method is mainly to detect the change trend of the subject over time, and to detect the mutation words in the literature in combination with clustering algorithm. It is used to detect and visualize the trends and changes over a period of time, and to further predict the development trend of the subject matter.

This study uses bibliometric methods to analyze the basic characteristics of the

annual publication volume, subject categories, and research areas. The knowledge map software CiteSpace is used for visual analysis to build a country cooperation network, institution cooperation network, and keyword co-occurrence network to comprehensively analyze the research hotspots and trends of carbon emissions and economic growth research. The retrieval process of this article is shown in Figure 1.

Figure 1. The retrieval process

4. Bibliometric analysis

4.1 Annual trend

At present, the development of a green economy has become a hot issue in the global environment and economy. Since mankind entered the industrial society, economic development has been rapid. However, with economic growth, resources and environmental issues have become increasingly prominent. Carbon dioxide and other greenhouse gas emissions have increased sharply, which has led to global warming, and a series of disasters such as the melting of icebergs have caused alarm for human survival. Therefore, the development of a green economy to promote industrial adjustment is the only way to sustain economic growth and maintain ecological balance.

The change in the number of documents over time is an important indicator of the development and evolution of the research field, reflecting the development trend of the field. As of February 2, 2020, the web of science database retrieved included 3330 articles on carbon emissions and economic growth. Among them, Article and Review totaled 3315, accounting for 99.55% of the total literature, and are the main research objects of this article. As can be seen from Figure 2, during the period 2001-2019, the global research showed an overall upward trend. There has been a significant increase after 2016, which has a lot to do with the signing of the Paris Agreement. Especially in 2018 and 2019, the number of papers has exploded.

Figure 2. Annual trend of publications.

4.2 Countries

4.2.1 The characteristics of the countries

A total of 112 countries or regions around the world have participated in research. This article tracks the countries where they are based on the author information recorded in the publications. Table 2 lists the top 20 countries or regions with the highest total literature. Among the 112 publishing countries or regions, China ranked first (1503, 45%), followed by the United States (523, 16%). It can be seen that in recent years, scientific researchers and institutions in China, the United States, the United Kingdom and other countries have paid great attention to the study of carbon emissions and economic growth.

Table 2. The top 20 most productive countries/regions

No.	Country/region	TP	No.	Country/region	TP
1	China	1503	11	Japan	94
2	USA	523	12	Taiwan	89
3	England	226	13	Netherlands	84
4	Turkey	223	14	Spain	80

5	Australia	194	15	Italy	72
6	Pakistan	172	16	Sweden	65
7	Malaysia	150	17	Austria	64
8	Germany	122	18	Canada	64
9	India	105	19	Saudi Arabia	60
10	France	99	20	South Korea	57

Note: TP is the total number publications of one country/region

304 Table 3 shows the trend of the volume of papers issued by the top 5 countries
305 during 2001-2019. We can see from the figure that the whole of each country is on the
306 rise. In addition, the number of countries studying carbon emissions and economic
307 growth has increased over time. As can be seen from Table 2, the United States is the
308 first country to conduct research. And in 2001-2011, the United States published on
309 carbon emissions and economic growth publications consistently ranked first in the
310 world. According to the data in Tables 1 and 2, the carbon emissions and economic
311 growth published by Chinese scholars during the period of 2001-2019 exceeded the
312 total number of global papers by 45%. In addition, China's publications published in
313 2012-2019 are ranked first in the world. Therefore, in terms of the total number of
314 papers, carbon emissions and economic growth studies participated by Chinese scholars
315 have played an important role in world research. Figure 3 marks the top 20 countries
316 and regions with the highest total publications. Regional distribution characteristics
317 indicate that most studies are concentrated in developed countries. Most of these
318 countries are located in Eurasia and the Americas, with Europe the most.

Table 3. Annual trends of publications in top 5 countries/regions					
	China	USA	England	Turkey	Australia
2001	0	6	0	0	0
2002	0	7	4	0	1
2003	3	3	0	1	1
2004	1	3	0	2	0

2005	1	7	2	0	0
2006	0	6	2	0	1
2007	6	10	6	3	3
2008	2	8	7	3	2
2009	6	14	2	4	2
2010	12	18	12	5	7
2011	19	24	9	4	3
2012	27	25	13	2	9
2013	43	33	10	4	11
2014	73	49	11	9	8
2015	97	37	15	21	22
2016	158	46	19	36	20
2017	217	65	33	38	26
2018	320	68	38	27	28
2019	518	94	43	64	50

319 The development of scientific literature depends to some extent on the policy
320 support behind it. We will explore the policy support behind research. According to the
321 2018 Global Energy and Carbon Dioxide Status Report published by the IEA, global
322 carbon dioxide emissions reached 33.1 billion tons. It set a new historical high and will
323 continue to rise in the future. With the rapid development of China's economy, and total
324 carbon dioxide emissions have remained high. China has the highest total carbon
325 dioxide emissions in 2018, reaching 9.5 billion tons, accounting for 28.7% of global
326 carbon dioxide emissions. The continuous increase of total carbon emissions has put
327 China under tremendous pressure to reduce emissions and become one of the factors
328 restricting the rapid and healthy development of China's economy.

329 Since 2007, in order to actively fulfill the responsibilities of major powers, China
330 has set up a special group to coordinate and formulate policies and measures related to
331 climate change. In December 2011, the State Council of China comprehensively set
332 clear targets for the reduction of carbon dioxide emissions per unit of GDP in each
333 region. In 2015, the Chinese government announced targets to control greenhouse gas

emissions at the Paris Climate Conference. In November 2016, the State Council explicitly proposed that by 2020, carbon dioxide emissions per unit of GDP will be reduced by 18% compared with 2015. In December 2017, the National Development and Reform Commission announced the official launch of the national carbon market. This indicates that China has entered a new stage in controlling and reducing carbon emissions through market mechanisms and economic means.

Figure 3. The top 20 most productive countries/regions

4.2.2 Country collaboration

In this section, we analyze the country from the cooperation between countries. Based on the downloaded data, we used the CiteSpace visualization tool to perform national co-citation network analysis on the literature data in the field of carbon emissions and economic growth, and constructed a national cooperation network correlation diagram for carbon emissions and economic growth related research (Figure

4). Every node represents a country, the larger the node, the more the country publishes. The connection between the nodes indicates a cooperative relationship between the two countries. All countries in Figure 4 have more or less cooperated with other countries. It can be seen from the figure that several countries prefer to work together with some countries, thereby forming some research clusters. For example, China cooperates with Canada, India, and Scotland. The UK has cooperation with Germany, Finland, and the Netherlands. As a result, a network of national cooperation associations with the United Kingdom, the United States, China, the Netherlands, India and Germany as the core has been formed.

Figure 4. The academic collaborative relationships among the countries/regions.

Table 4 shows the countries with the most cooperation with the top 20 countries.

In the table, the country with the most cooperation with China is the United States, and the number of cooperation publications is 169. Of the top 20 countries, the United States, Britain, Australia, Pakistan, France, the Netherlands, Japan, Sweden, Taiwan and Canada have the most cooperation with China. It shows that in the field of carbon emissions and economic growth, China is the preferred cooperation country in other countries or regions.

Table 4. Country/region collaboration

No.	Country/region	CM	Count	No.	Country/region	CM	Count
1	China	USA	169	11	Japan	China	34
2	USA	China	169	12	Taiwan	China	19
3	England	China	66	13	Netherlands	China	25
4	Turkey	Malaysia	19	14	Spain	Chile	9
5	Australia	China	52	15	Italy	England	12
6	Pakistan	China	64	16	Sweden	China	14
7	Malaysia	Pakistan	37	17	Austria	USA	26
8	Germany	USA	32	18	Canada	China	15
9	India	USA	16	19	Saudi Arabia	Pakistan	22
10	France	China	21	20	South Korea	USA	12

Note: CM means the countries that cooperate most with it.

Count refers to the number of cooperation between two countries/regions.

4.2.3 Country total citation

Table 5 lists the total number of citations and average citations of national publications and ranks them from highest to lowest. The table shows that the total number of publications in China and the total number of citations for publications rank first in the world, but the average citations for their articles rank only 18th in the world. In addition, US publications rank second in total citations. This was followed by the United Kingdom, Turkey and Australia. The table shows that Austria publications are

ranked first in the world on average, but the total number of citations for publications is 9th in the world, indicating that its publications have a great influence worldwide. Table 4 shows that the total number of citations for publications in some countries is low, but the average citation value for publications is high. The countries involved include France (ranked 10 in the total number of publications and ranked 3 in the average citation of publications), Japan (11, 6), and Austria (17, 1). This evidence indicates that the number of publications published by these three countries is small, but each one has received a large number of citations worldwide. It also shows that these countries value the quality of carbon emissions and growth research publications rather than the quantity. In contrast, the number of publications in some countries is higher, but the average citation value of publications is lower. Examples are China (1, 18), the United Kingdom (3, 7), Turkey (4, 8), Australia (5, 11), and Pakistan (6, 17). Although these countries have published a large number of articles, the citation rate of the articles is not high, so these countries should pay more attention to the quality of the research in the subsequent research. In addition, some countries have higher total citations and higher average citations for publications. These countries include the United States (2, 2), Malaysia (7, 4), and Turkey (8, 5).

Table 5. Country/region citations

NO.	Country/region	TP	TC	Rank(TC)	CPP	Rank(CPP)
1	China	1503	29470	1	19.61	18
2	USA	523	26197	2	50.09	2
3	England	226	9505	3	42.06	7
4	Turkey	223	9020	4	40.45	8
5	Australia	194	7211	5	37.17	11
6	Pakistan	172	3789	12	22.03	17
7	Malaysia	150	6547	6	43.65	4
8	Germany	122	5214	7	42.74	5

9	India	105	4088	10	38.93	9
10	France	99	4713	8	47.61	3
11	Japan	94	3960	11	42.13	6
12	Taiwan	89	3329	13	37.40	10
13	Netherlands	84	2955	14	35.18	13
14	Spain	80	1882	16	23.53	16
15	Italy	72	2671	15	37.10	12
16	Sweden	65	1765	17	27.15	14
17	Austria	64	4148	9	64.81	1
18	Canada	64	1712	18	26.75	15
19	Saudi Arabia	60	1106	19	18.43	20
20	South Korea	57	1101	20	19.32	19

Note: TP is the total number publications of one country/region.

TC is the total number citations of one country /region.

CPP is the citations of per publication.

4.3 Institutions

4.3.1 The characteristics of the institutions

It was found that among the top 20 institutions (Table 6) in 2001-2019, Chinese institutions accounted for 15. They are Chinese Academy of Sciences (total of 219 publications from 2001 to 2019), Beijing Institute of Technology (151), Tsinghua University (95), North China Electric Power University (93), Xiamen University (83), Institute Of Geographic Sciences and Natural Resources Research (68), China University Of Mining and Technology (65), China University Of Petroleum (62), Beijing Normal University (57), Sun Yat Sen University(47), Collaborat Innovat Ctr Elect Vehicles Beijing (43), Tianjin University (42), Peking University (40), Sustainable Dev Res Inst Econ Soc Beijing (40), Jiangsu University (39). There are two U.S. agencies: University of California System (48) and United States Department of Energy (42). In addition, there is only one in Pakistan, Turkey and Austria: Comsats University Islamabad (61), Cag University Turkey (47) and International Institute for

Applied Systems Analysis (39). We also find that the institutions that study carbon emissions and growth are mostly universities. They have formed a close network of scientific cooperation to jointly push forward knowledge innovation and spread in this field.

In addition, Table 6 lists the total number of citations and average citations of the publications of the institution and ranks them from highest to lowest. The table shows that the Chinese Academy of Sciences (6278 total publication citations) ranked first, followed by Beijing Institute of Technology (4107), Cag University Turkey (3365), United States Department of Energy (3110) and International Institute for Applied Systems Analysis (3014). Through analysis, we find that the number of publications in some institutions is relatively small, but the average citations of publications are high. Including International Institute for Applied Systems Analysis (19,1), United States Department of Energy (16,2), Cag University Turkey (12,3), University Of California System (11,4), and Comsats University Islamabad (9,4). This shows that although these institutions have published a small number of publications, they have received a large number of citations worldwide in each publication. It also shows that these organizations place greater emphasis on the quality of research articles. In contrast, the number of publications in some institutions is higher, but the publications have lower average citations. For example, Chinese Academy of Sciences (1,8), Beijing Institute of Technology (2,10), Tsinghua University (3,7), North China Electric Power University (4,17), Xiamen University (5,11). This shows that these institutions pay more attention to the number of publications and ignore the quality of publications.

426 Therefore, these institutions should pay more attention to the quality of publications in
427 the subsequent research.

428

Table 6. The performances of the top20 most productive institutions.

No.	Institution	TP	TC	Rank(TC)	CPP	Rank(CPP)
1	Chinese Academy of Sciences	219	6278	1	28.67	8
2	Beijing Institute of Technology	151	4107	2	27.20	10
3	Tsinghua University	95	2946	6	31.01	7
4	North China Electric Power University	93	1341	12	14.42	17
5	Xiamen University	83	2185	8	26.33	11
6	Institute of Geographic Sciences and Natural Resources Research	68	2113	10	31.07	6
7	China University of Mining and Technology	65	1257	13	19.34	13
8	China University of Petroleum	62	1023	15	16.50	16
9	Comsats University Islamabad	61	2456	7	40.26	5
10	Beijing Normal University	57	1620	11	28.42	9
11	University of California System	48	2147	9	44.73	4
12	Cag University Turkey	47	3365	3	71.60	3
13	Sun Yat Sen University	47	1096	14	23.32	12
14	Collaborat Innovat Ctr Elect Vehicles Beijing	43	820	16	19.07	14
15	Tianjin University	42	696	17	16.57	15
16	United States Department of Energy	42	3110	4	74.05	2
17	Peking University	40	564	18	14.10	18
18	Sustainable Dev Res Inst Econ Soc Beijing	40	454	19	11.35	19
19	International Institute for Applied Systems Analysis	39	3014	5	77.28	1
20	Jiangsu University	39	407	20	10.44	20

Note: TP is the total publications of one institution; TC is the total number citations of one institution;
 CPP is the citations of per publication.

Figure 5. The academic collaborative relationships among the institutions.

Table 7. Institution collaboration

No.	Institution	TP	Most cooperative institution	Count
1	Chinese Academy of Sciences	219	Institute of Geographic Sciences and Natural Resources Research	68
2	Beijing Institute of Technology	151	Collaborat Innovat Ctr Elect Vehicles Beijing	43
3	Tsinghua University	95	Chinese Academy of Sciences	13
4	North China Electric Power University	93	Acad Baoding Low Carbon Dev	4
5	Xiamen University	83	Jiangxi University of Finance and Economics	16
6	Institute of Geographic Sciences and Natural Resources Research	68	Chinese Academy of Sciences	42
7	China University of Mining and Technology	65	Jiangsu Normal University	9
8	China University of Petroleum	62	Beijing Institute of Technology	13
9	Comsats University Islamabad	61	Montpellier Business School	12
10	Beijing Normal University	57	Chinese Academy of Sciences	16
11	University of California System	48	University of California Berkeley	21
12	Cag University Turkey	47	Multimedia University	13
13	Sun Yat Sen University	47	Chinese Academy of Sciences	20
14	Collaborat Innovat Ctr Elect Vehicles Beijing	43	Sustainable Dev Res Inst Econ Soc Beijing	30
15	Tianjin University	42	Leiden University	6
16	United States Department of Energy	42	Lawrence Berkeley National Laboratory	23
17	Peking University	40	Shanghai Jiao Tong University	6
18	Sustainable Dev Res Inst Econ Soc Beijing	40	Beijing Key Lab Energy Econ Environm Management	31
19	International Institute for Applied Systems Analysis	39	Potsdam Institut Fur Klimafolgenforschung	5
20	Jiangsu University	39	Nanjing Normal University	6

Note: TP is the total publications of one institution; Count refers to the number of cooperation between two institutions.

4.3.2 Institution collaboration

We use CiteSpace to build a global institution cooperation network correlation diagram (Figure 5) of carbon emissions and economic growth research. Each node in the graph represents an institution, the larger the node, the more the organization sends. The connection between the nodes indicates a cooperative relationship between the two institutions. As can be seen from the figure, the University of Chinese Academy of Sciences cooperates with Sun Yat-sen University, Tsinghua University, China University of Mining and Technology, Fudan University and China University of Petroleum. Shandong University and Xiamen University also cooperate.

Table 7 shows the organizations that have cooperated the most with the top 20 organizations. In the table, the institution that cooperates most with the University of Chinese Academy of Sciences is the Institute of Geographical Sciences and Natural Resources. The number of cooperative publications is 68, accounting for 31% of the total publications of the University of Chinese Academy of Sciences and other institutions. We also found an interesting phenomenon, with more than half of the institutions prefer to cooperate with domestic institutions rather than foreign institutions.

4.4 Authors

High-yielding authors usually master the research hotspots and cutting-edge trends in the field. Table 8 lists the top 10 authors worldwide, including their nationality, the total number of publications, and their main research directions. As can be seen from Table 7, Lin Boqiang published 60 publications, becoming the world's largest author of

454 carbon emissions and economic growth publications. Followed by Ozturk, Ilhan;
455 Shahbaz, Muhammad; Zaman, Khalid; Wang, Shaojian, etc. Scholars engaged in
456 carbon emissions and economic growth research come from China, Turkey, Pakistan
457 and Malaysia. Seven of the ten high-yielding authors are from China, meaning that
458 Chinese scholars are an integral part of global carbon emissions and economic growth
459 research.
460

Table 8. The performances of the top20 most active authors.

No.	Author	Country	TP	TC	CPP	R(CPP)	h-index	R(h-index)	Main subject areas
1	Lin, Boqiang	China	60	1736	28.93	6	26	3	Environmental Sciences Ecology
2	Ozturk, Ilhan	Turkey	47	3379	71.89	1	28	1	Environmental Sciences Ecology
3	Shahbaz, Muhammad	China	43	2630	61.16	3	28	2	Environmental Sciences Ecology
4	Zaman, Khalid	Pakistan	42	837	19.93	10	19	5	Environmental Sciences Ecology
5	Wang, Shaojian	China	37	1177	31.81	5	17	7	Environmental Sciences Ecology
6	Wei, Yi-Ming	China	32	2036	63.63	2	21	4	Environmental Sciences Ecology
7	Wang, Qiang	China	29	738	25.45	9	17	8	Science Technology Other Topics
8	Long, Ruyin	China	25	692	27.68	7	14	9	Science Technology Other Topics
9	Wang, Zhaohua	China	25	644	25.76	8	11	10	Environmental Sciences Ecology
10	Al-Mulali, Usama	Malaysia	24	1268	52.83	4	18	6	Energy Fuels

Note: TP is the total number publications of one author. TC is the total number citations of author. CPP is the citations of per publication.

Table 8 also lists information such as the total number of citations and average citations for author publications and the h-index of authors. The h-index was proposed by Hirsch J.E.(Hirsch 2005) in 2005 to measure scientific outputs. The h-index was defined as “a scientist has index h if h of his/her N papers have at least h citations each, and the other (N-h) papers have fewer than h citations each” (Braun et al. 2006). In our study, h-index is applied to estimate the impacts of authors (Mao et al. 2015). The table shows that the total publications and citation averages of Ozturk, Ilhan; Shahbaz, Muhammad and Wang, Shaojian are at the forefront. In addition, Bertonecini, Massimo publications ranked second in total citations and average citations. In addition, we found that the citation average ranking of the same author was similar to the h-index ranking. We have also followed the research directions of these authors, and we have found that Environmental Sciences Ecology, Energy Fuels and Science Technology Other Topics are hot research areas of carbon emissions and economic growth.

The dominance factor (DF) (Firdaus et al. 2019) is a ratio that measures the score of a multi-author article where the author is the first author (B. and Rajendran 2012; Wu et al. 2015). The DF ranking calculates the author's dominance in the article. The calculation formula of Dominance Factor is shown in (8).

$$DF = \frac{NMF}{NMT} \quad (8)$$

Table 9 lists the author's dominance factors. From the table, we can see that Wang, Qiang appeared as the first author in 26 of 29 multi-author articles. The dominant factor reached 0.9, ranking first. In addition, we found that although Lin and Boqiang published 60 articles, their advantage factor was only 0.42, ranking fifth. In addition,

we also found that Wei, Yi-Ming has a dominant factor of 0.

Table 9. Author's dominance

No.	Author	Multi authored	First authored	DF	R(DF)
1	Lin, Boqiang	60	25	0.42	5
2	Ozturk, Ilhan	41	4	0.10	8
3	Shahbaz, Muhammad	43	19	0.44	3
4	Zaman, Khalid	41	5	0.12	7
5	Wang, Shaojian	37	12	0.32	6
6	Wei, Yi-Ming	32	0	0.00	10
7	Wang, Qiang	29	26	0.90	1
8	Long, Ruyin	25	2	0.08	9
9	Wang, Zhaohua	25	11	0.44	4
10	Al-Mulali, Usama	23	16	0.70	2

4.5 Research areas

This study counts the subject areas involved in carbon emissions and economic growth research from 2001 to 2019. In the field of research, Environmental Sciences Ecology is a hotspot area for international research. Of the 3315 articles retrieved, 2007 were related to the field of Environmental Sciences Ecology, accounting for about 61% of the total publications (Table 10). Energy Fuels and Science Technology Other Topics are two other research areas with dense distribution of carbon emissions and economic growth.

Figure 6 depicts the annual changes in the five research areas in which carbon emissions and economic growth are most densely distributed. As can be seen from Figure 6, from 2001 to 2013, there were fewer studies and fewer research areas were involved. From 2014 to 2019, research has been increasing. Environmental Sciences Ecology has been at the top of the list and has grown rapidly from 2015 to 2019.

Environmental Sciences Ecology has always been a key area for scholars and experts to conduct research on carbon emissions and economic growth. The total amount of research has maintained a rapid growth, indicating that research in this area is still deepening.

The total amount of research on carbon emissions and economic growth is increasing, not only in the increase in the number of studies in a certain subject area, but also in the increasingly extensive field of research-related research.

Table 10.The top 20 research areas.

No.	Research Areas	TP	Fraction
1	Environmental Sciences Ecology	2007	0.61
2	Energy Fuels	1118	0.34
3	Science Technology Other Topics	1049	0.32
4	Engineering	742	0.22
5	Business Economics	372	0.11
6	Meteorology Atmospheric Sciences	173	0.05
7	Thermodynamics	167	0.05
8	Agriculture	100	0.03
9	Geology	66	0.02
10	Biodiversity Conservation	63	0.02
11	Water Resources	56	0.02
12	Forestry	52	0.02
13	Chemistry	47	0.01
14	Public Environmental Occupational Health	44	0.01
15	Mathematics	37	0.01
16	Biotechnology Applied Microbiology	36	0.01
17	Materials Science	36	0.01
18	Construction Building Technology	34	0.01
19	Geography	32	0.01
20	Physics	29	0.01

Note: TP is the total number publications of one research area.

Figure 6. Annual trends.

4.6 Articles

Table 11 lists the top 20 most cited articles, including titles, authors, journals, and citations, and areas of research. As of the time we download the data (2020.02.02), the most frequently cited article was “Powering the planet: Chemical challenges in solar energy utilization”, published in 2006 in Proceedings of the National Academy of Sciences of the United States of America by Lewis and Nocera, and cited 4764 times in Web of Science Database. It is completed by American scholars, and its research direction is Science & Technology-Other Topics. By analyzing the top 20 most cited articles, we find that there are 7 articles completed by American authors in cooperation. Followed by Turkey, there are 5 articles whose authors participated in cooperation. There are 3 articles completed by Chinese authors in cooperation. In addition, the top 20 most cited articles are related to Australia, France, Germany, Netherlands, Austria,

India, Norway, Japan, Italy, Malaysia and Iran. By analyzing the top 20 most cited journals, 4 articles were published in Ecological Economics (Journal Impact Factor in 2018 is 4.281) and 3 articles were published in Proceedings of The National Academy of Sciences of the United States of America (Journal Impact Factor in 2018 is 9.58) and two more articles published in Energy Policy (Journal Impact Factor in 2018 is 4.88). The main research directions in the first 20 articles are Environmental Sciences & Ecology, Business & Economic and Energy & Fuels. In addition, Meteorology & Atmospheric Sciences, Chemistry, and Engineering are also regarded as hot areas for carbon emissions and economic growth.

Table 11. The top 20 frequently cited articles

No.	Title	Country	Journals	Research Areas	Year	TC	JIF (2018)	Author(s)
1	Powering the planet: Chemical challenges in solar energy utilization	USA	Proceedings of The National Academy of Sciences of the United States of America	Science & Technology - Other Topics	2006	4764	9.58	Lewis and Nocera (Lewis and Nocera 2006)
2	Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks	Australia England USA France Austria	U Academy of Sciences of the United States of America	Science & Technology - Other Topics	2007	1145	9.58	Canadell et al. (Canadell et al. 2007)
3	Environmental Kuznets Curve hypothesis: A survey	India	Ecological Economics	Environmental Sciences & Ecology; Business & Economics	2004	1042	4.281	Dinda (Dinda 2004)
4	Global challenges and strategies for control, conversion and utilization of CO2 for sustainable development involving energy, catalysis, adsorption and chemical processing	USA	Catalysis Today	Chemistry; Engineering	2006	1024	4.888	Song (Song 2006)
5	A literature survey on energy-growth nexus	Turkey	Energy Policy	Business & Economics; Energy & Fuels; Environmental Sciences & Ecology	2010	616	4.88	Ozturk (Ozturk 2010)
6	Growth in emission transfers via international trade from 1990 to 2008	Norway Germany USA	Proceedings of The National Academy of Sciences of the United States of America	Science & Technology - Other Topics	2011	607	9.58	Peters et al.(Peters et al. 2011)

7	Energy consumption, carbon emissions, and economic growth in China	China	Ecological Economics	Environmental Sciences & Ecology; Business & Economics	2009	587	4.281	Zhang and Cheng (Zhang and Cheng 2009)
8	An econometric study of CO(2) emissions, energy consumption, income and foreign trade in Turkey	Turkey	Energy Policy	Business & Economics; Energy & Fuels; Environmental Sciences & Ecology	2008	587	4.88	Halicioglu (Halicioglu 2008)
9	Deforestation driven by urban population growth and agricultural trade in the twenty-first century	USA	Nature Geoscience	Geology	2010	552	14.48	DeFries et al. (DeFries et al. 2010)
10	Energy consumption, income, and carbon emissions in the United States	Turkey, USA	Ecological Economics	Environmental Sciences & Ecology; Business & Economics	2007	515	4.281	Soytas et al. (Soytas et al. 2007)
11	State-of-the-Art of CO2 Capture with Ionic Liquids	Netherlands	Industrial & Engineering Chemistry Research	Engineering	2012	494	3.375	Ramdin et al. (Ramdin et al. 2012)
12	Electrophoretic deposition of carbon nanotubes	England	Carbon	Chemistry; Materials Science	2006	472	7.466	Boccaccini et al. (Boccaccini et al. 2006)
13	A global boom in hydropower dam construction	Germany	Aquatic Sciences	Environmental Sciences & Ecology; Marine & Freshwater Biology	2015	470	2.303	Zarfl et al. (Zarfl et al. 2015)

14	Environment Kuznets curve for CO2 emissions: A cointegration analysis for China	China Turkey	Energy Policy	Business & Economics; Energy & Fuels; Environmental Sciences & Ecology	2009	459	4.88	Jalil and Mahmud (Jalil and Mahmud 2009)
15	Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996-2010	USA China	Atmospheric Chemistry and Physics	Environmental Sciences & Ecology; Meteorology & Atmospheric Sciences	2011	451	5.668	Lu et al.(Lu et al. 2011)
16	Impact of elevated CO2 on shellfish calcification	Netherlands France	Geophysical Research Letters	Geology	2007	431	4.578	Gazeau et al.(Gazeau et al. 2007)
17	Energy consumption, economic growth, and carbon emissions: Challenges faced by an EU candidate member	Turkey	Ecological Economics	Environmental Sciences & Ecology; Business & Economics	2009	393	4.281	Soytas and Sari (Soytas and Sari 2009)
18	Models-3 community multiscale air quality (CMAQ) model aerosol component - 1. Model description	USA	Journal of Geophysical Research-Atmospheres	Meteorology & Atmospheric Sciences	2003	391	3.633	Binkowski and Roselle (Binkowski and Roselle 2003)
19	Emissions of air pollutants and greenhouse gases over Asian regions during 2000-2008: RegionalEmission inventory in ASia (REAS) version 2	Japan Italy	Atmospheric Chemistry and Physics	Environmental Sciences & Ecology; Meteorology & Atmospheric Sciences	2013	387	5.688	Kurokawa et al.(Kurokawa et al. 2013)
20	A global review of energy consumption, CO2 emissions and policy in the residential sector (with an overview of the top ten CO2 emitting countries)	Malaysia Iran	Renewable & Sustainable Energy Reviews	Science & Technology - Other Topics; Energy & Fuels	2015	381	10.556	Nejat et al.(Nejat et al. 2015)

Note: TC is the number of total citations; JIF (2018) refers to the Journal Impact Factor in 2018.

4.7 Research hotspots

The key words of the paper are generally considered as the author's elaboration of the core ideas of the article. It is a literature search mark that reflects the main research content of the paper. It can simply, directly and comprehensively summarize the core research content of the thesis, which implies the research status, hotspots and future development trends of a certain research area(Yu et al. 2016).This article uses keyword frequency analysis and constructs a keyword co-occurrence network to identify research hotspots in carbon emissions and economic growth research in 2001-2019. We imported the downloaded data into CiteSpace. The time zone is set to 1 year, and the threshold is set to the top 50 keywords. We use path finder to trim the connections between nodes to build keyword clusters (Figure 7). Among them, each node represents a keyword. Connections represent a relationship between two keywords. In other words, the two keywords appears in the same article. This article lists the top 20 keywords, which are shown in Table 12. The words largely represent the hotspots of carbon emissions and economic growth research during 2001-2019.

Table 12. The top 20 keywords in carbon emission and economic growth research

No.	Keywords	TK	Centrality	No.	Keywords	TK	Centrality
1	economic growth	1388	0.08	11	cointegration	322	0.13
2	carbon emission	1323	0.23	12	urbanization	312	0
3	energy consumption	971	0.05	13	energy	301	0.09
4	carbon dioxide emission	656	0.07	14	renewable energy	275	0.07
5	China	648	0.04	15	financial development	275	0.1
6	environmental kuznets curve	514	0.05	16	income	238	0.14
7	impact	417	0.1	17	greenhouse gas emission	235	0.02
8	consumption	409	0.04	18	electricity consumption	233	0.13
9	growth	380	0.02	19	panel data	226	0.13

10	climate change	336	0.05	20	decomposition analysis	216	0.09
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Note: TK is the total number of keywords

547 Economic growth and carbon emission are keywords that appear more frequently,
548 which is consistent with the theme of research we have done. Excluding Economic
549 growth and carbon emission, the 10 most common keywords are: energy consumption,
550 carbon dioxide emission, China, environmental kuznets curve, impact, consumption,
551 growth, climate change, cointegration, urbanization. These represent the focus and
552 hotspots of blockchain and energy research from 2001 to 2019. We clustered all the
553 keywords and got 13 clusters: energy consumption (#0), carbon reduction(#1), nuclear
554 energy(#2), carbon tax (#3), regional affluence(#4), california beef production system
555 (#5), soil management(#6), nuclear energy consumption (#7), global atmospheric
556 methane(#8), annex parties(#9), environmental kuznets curve (#10), extensive grazing
557 system (#11), considering greenhouse gas consequence (#12). Among them, # 0
558 represents the largest group, and #12 represents the smallest group. Therefore, energy
559 consumption and carbon emission reduction are the top priorities of carbon emissions
560 and economic growth research from 2001 to 2019.

Figure 7. Keywords clustering map

In order to directly reflect the research hotspots in different time periods and make reasonable predictions for future development, we use Citespace to construct a time zone map. Among them, emergent words can unearth new research hotspots and reflect research frontiers and trends(Zhang et al. 2020). In view of this, this article reveals the development trend by analyzing the Citespace time zone chart according to the emergence and frequency of keywords and hot keywords. This article imports the downloaded data into CiteSpace. The time slice is 1 year, the node type is a keyword, and the threshold is set to (2,3,15), (3,3,20), (3,2,20). A path finder is used to trim the connections between nodes to construct a time map of keywords (Figure 8). In addition, we analyzed keywords over a 5-year time span (Table 13, Table 14).

Figure 8. The Timezone view of hot keywords.

By analyzing the table and time zone graph, we find that as time increases, the number of keywords and the number of each keyword increase during the time period. For example, the keyword economic growth only appeared 12 times between 2001 and 2005, but it appeared 1092 times between 2016 and 2019. We found that the words that are on the rise from 2001 to 2019 are energy consumption, China, carbon dioxide reduction, co-integration, renewable energy. Through keyword hotspot analysis and keyword trend analysis, we have identified future research directions and hotspots. (1) What is the relationship between carbon emissions, economic growth and energy consumption. (2) The efforts of China in carbon reduction and economic growth. (3) How to reduce carbon dioxide emissions while ensuring stable economic growth. (4) The research on carbon emissions and economic growth in the fields of urbanization, financial development, renewable energy, and climate change.

Table 13. The top 20 keywords in 2001-2010

No.	2001-2005	TK	2006-2010	TK
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1	economic growth	12	economic growth	49
2	carbon dioxide emission	10	carbon dioxide emission	34
3	kyoto protocol	5	environmental kuznets curve	31
4	policy	5	carbon emission	28
5	energy	4	emission	26
6	model	4	climate change	26
7	climate change	3	energy consumption	24
8	greenhouse gas emission	2	energy	23
9	modeling	2	model	22
10	pollution	2	income	22
11	co2 abatement	2	impact	19
12	energy consumption	2	China	17
13	environment	2	consumption	16
14	impact	2	cointegration	12
15	China	2	policy	11
16	bioma	2	intensity	11
17	induced technological change	2	carbon dioxide	10
18	methane	2	electricity consumption	10
19	intensity	2	carbon sequestration	9
20	substitution	2	country	9

Note: TK is the total number of keywords

588

Table 14. The top 20 keywords in 2010-2019

No.	2011-2015	TK	2016-2019	TK
1	co2 emission	236	economic growth	1092
2	economic growth	235	carbon dioxide emission	1047
3	energy consumption	174	energy consumption	772
4	carbon emission	134	carbon emission	548
5	china	133	china	510
6	carbon dioxide reduction	108	carbon dioxide reduction	497
7	growth	96	environmental kuznets curve	414
8	energy	96	impact	322
9	consumption	90	consumption	307
10	cointegration	83	urbanization	280
11	emission	79	financial development	250
12	income	76	growth	247
13	impact	76	renewable energy	238
14	climate change	76	climate change	233
15	environmental kuznets curve	71	cointegration	228
16	electricity consumption	56	panel data	191
17	model	54	greenhouse gas emission	181
18	time series	48	energy	179
19	greenhouse gas emission	47	electricity consumption	168

5. Conclusions

A comprehensive understanding of the relationship between carbon emissions and economic growth will help develop strategies to reduce carbon emissions without sacrificing economic development. In recent years, the relationship has been studied using different methods and technologies in the past published papers, but the results of different literatures have shown great differences. Therefore, it is necessary to conduct in-depth research, reveal the variables that lead to the relationship and explore the future research directions of carbon emissions and economic growth. In this study, bibliometric methods were used to analyze the basic characteristics of the annual publication volume and the distribution of journals. This research uses knowledge map software CiteSpace for visual analysis, and builds a national cooperation network, institutional cooperation network, and keyword co-occurrence network to comprehensively analyze the research hotspots and trends of carbon emissions and economic growth. Through the analysis of bibliometric methods, we come to the following conclusions.

(1) Through the analysis of the overall trend, we found that during the period of 2001-2019, the global research on carbon emissions and economic growth showed an overall upward trend. After 2016, the research has increased significantly, especially in 2018 and 2019, the number of publications has exploded. This has a lot to do with the signing of the Paris Agreement. The adoption of the Paris Agreement demonstrates the clear commitment of countries to the development of a low-carbon and green economy.

It sent a clear and strong signal to the world, pointed out the direction for further strengthening the goal of reducing emissions in the future, and laid the basic pattern for the extensive participation of countries in the world in reducing emissions.

(2) Regardless of the total number of papers, institutions, and highly cited papers, Carbon emissions and economic growth research in China has always been among the best, and it plays a significant role in global research. In this sense, China has led global carbon emissions and economic growth research. In recent years, China's fossil energy consumption and greenhouse gas emissions have risen rapidly. According to the "Global Energy and Carbon Dioxide Status Report 2018" published by the International Energy Agency, global carbon dioxide emissions reached 33.1 billion tons, a record high and will continue to rise in the future. Among them, China has the highest total carbon dioxide emissions, reaching 9.5 billion tons, accounting for 28.7% of global carbon dioxide emissions. The continuous increase of total carbon emissions has put China under tremendous pressure to reduce emissions. In June 2015, China submitted to the UN's National Contribution Report on Climate Change, clearly stated the goal of achieving 2030 peak carbon emissions, and strived to achieve the peak as soon as possible. China also announced greenhouse gas emission control targets at the 2015 Paris Climate Conference. By 2030, carbon dioxide emissions per unit of gross domestic product will decrease by 60% -65% compared to 2005.

(3) By analyzing the cooperative relationships between countries, institutions, and highly cited articles, we found three interesting phenomena. ① Of the top 20 countries, the United States, Britain, Australia, Pakistan, France, the Netherlands, Japan, Sweden,

Taiwan and Canada have the most cooperation with China. It shows that in the field of carbon emissions and economic growth, China is the preferred cooperation country in other countries or regions. ② Of the top 20 institutions, more than half of them are more inclined to cooperate with institutions in their home countries than those in foreign countries. ③ Of the 20 highly-cited articles, 7 were completed by American authors. These phenomena indicate that in the field of carbon emissions and economic growth, the United States is the preferred cooperative country in other countries or regions.

(4) The key words of the paper are generally considered as the author's elaboration of the core ideas of the article. It is a literature search mark that reflects the main research content of the paper. It can simply, directly and comprehensively summarize the core research content of the thesis, which implies the research status, hotspots and future development trends of a certain research area. ①What is the relationship between carbon emissions, economic growth and energy consumption. ②The efforts of China in carbon reduction and economic growth. ③How to reduce carbon dioxide emissions while ensuring stable economic growth. ④ The research on carbon emissions and economic growth in the fields of urbanization, financial development, renewable energy, and climate change.

Declarations

1. Ethics approval and consent to participate

Not applicable

2. Consent for publication

Not applicable

3. Availability of data and materials

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

4. Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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6. Authors' contributions

Rongrong Li: Methodology, Investigation, Writing- Original draft, Writing- Reviewing and Editing,

Qiang Wang: Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation, Supervision, Writing- Reviewing and Editing.

Lina Zhan: Methodology, Software, Investigation, Writing- Original draft, Writing-

Reviewing and Editing,

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Figures

Figure 1

The retrieval process

Figure 2

Annual trend of publications.

Figure 3

The top 20 most productive countries/regions. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

The academic collaborative relationships among the countries/regions.

Figure 5: Academic collaborative relationships among the institutions. The network diagram shows connections between various universities and research centers, with nodes representing institutions and edges representing collaborative relationships. The network is highly interconnected, with many nodes having multiple connections. The institutions are distributed across the map, with a high concentration in the central and upper-right areas.

Figure 5

The academic collaborative relationships among the institutions.

Figure 6

Annual trends.

Figure 7

Keywords clustering map

Figure 8

The Timezone view of hot keywords.