Embodied Carbon and Influencing Factors of China's Paper Industry's Export Trade to the United States

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The paper industry is a high-carbon emission and energy-intensive industry. From the perspective of low-carbon trade and carbon neutrality, its energy conservation and emission reduction are worthy of attention. This study used the input-output model to calculate the embodied carbon emissions of China’s paper industry’s export trade to the United States from 2006 to 2020 and used the logarithmic mean division index (LMDI) method to analyze influencing factors of the change of embodied carbon emissions. The study found that the embodied carbon emissions of China’s paper industry’s export trade to the United States generally shows a stable downward trend after reaching the peak with the increase of export trade scale; scale effect is the main factor that causes the embodied carbon emissions, while technological progress, policy support, and environmental regulations are important driving forces to promote carbon emission reduction. The research results of this paper not only can test and guide China’s paper industry trade policies and industrial policies, but they can also provide decision-making reference for China and the United States to promote the carbon emission reduction of the paper industry.

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INTRODUCTION

Low-carbon trade refers to a trade growth model based on low energy consumption, low pollution, and low emission. Trade embodied carbon emissions is an important issue related to global climate governance. The carbon embodied in international trade from a broad perspective should include carbon emissions in any link of international trade such as production and transportation. In a narrow sense, the embodied carbon in international trade refers to the transfer of carbon emissions embodied in traded products between countries. This definition does not include the carbon emissions in the process of international trade transportation and consumption by trading partners (Zhang *et al.* 2019). With the deepening of economic globalization, production links scattered all over the world are integrated into the global production network, and the separation of production and consumption has led to a large-scale transfer of global pollution emissions (Kanemoto *et al.* 2014). In the global division of labor system, developed countries control the production links with low energy consumption, low emission, and high value-added parameters, and they outsource the production links with high energy consumption, high emission, and low value-added parameters to developing countries, which allows the developed countries to not only obtain huge economic benefits but also to avoid the producer taking responsibility for pollution emission to a certain extent (Han and Wang 2019). Developing countries have received limited benefits, but they are facing great pressure on carbon emission reduction, and even become the “pollution refuge” of developed countries, which exacerbates the unfair distribution of global carbon emission reduction rights and responsibilities (Peng *et al.* 2015; Dang and Sheng 2018; Ma and Chen 2020). In this context, research studies on trade embodied carbon emissions are of great significance to distinguish the carbon emission share and emission reduction responsibility among trading partners and have a positive impact on promoting the joint efforts of countries to tackle global climate change.

The current carbon emission measurement principles of international trade are controversial, and it is difficult to define the carbon responsibilities and obligations among countries (Li 2018). Trade embodied carbon emissions in a broad sense should include carbon emissions from any link of international trade, such as production and transportation (Peters and Hertwich 2006; Ackerman *et al.* 2007; Weber *et al.* 2008; Chen and Chen 2011; Chen *et al.* 2013; Sato 2014). Therefore, scholars have conducted intensive research studies from energy consumption, climate change, carbon responsibility division, and other aspects, and the research focuses mainly include three aspects, the first of which is the calculation model of embodied carbon emissions, which builds a multinational and multi-regional input-output model to more reasonably and accurately measure the embodied carbon emissions in a country’s international trade (Peters and Hertwich 2008; Hertwich and Peters 2009; Peters 2010). Some scholars have also studied the impact of global value chain division on the trade embodied carbon emissions (Xu *et al.* 2020). The second aspect is carbon emission accounting and responsibility definition, which studies how to build a more reasonable and fair carbon emissions accounting scheme under the background of production decentralization and trade liberalization (Peng *et al.* 2016; Zhang and Sheng 2017; Li *et al.* 2020). The third aspect is the decomposition of driving factors of trade embodied carbon, and the logarithmic mean division index (LMDI) method is mainly used to decompose the driving factors of embodied carbon flows from the national, industrial, and product levels (Du and Sun 2012; Liu *et al.* 2014; Wang and Lu 2016; Han *et al.* 2018; Zhao and Liu 2020).

On the basis of the above research studies, scholars have made an empirical study on the embodied carbon emissions in China’s export trade from the aspects of trade countries and industrial categories (Zhang and Li 2018; Fei *et al.* 2020). According to the research on the embodied carbon emissions of Sino-US trade, China and the United States are the countries with the largest embodied carbon emissions of global export trade and import trade, respectively (Jing *et al.* 2015; Pan 2018), and the general research results show that papermaking, paper products, printing, and publishing industries belong to industries with high carbon emission intensity in the structure of China’s export commodities (Song 2012; Lv and Lv 2019). The relevant literature on the research of China’s paper industry mainly focuses on the following aspects: taking the production process of the paper industry as a practical case and focusing on the carbon footprint (Ma *et al.* 2012); verification of the relationship between carbon tariff and China’s paper printing export (Huang 2013); and using the world input-output database (WIOD) to calculate the trade embodied carbon emissions of China’s paper industry (Chen 2016).

China is the most important growth market of the global paper industry. In recent years, the production and consumption of paper and paperboard in China account for about one quarter of the global total. China’s paper industry and trade are in a stage of rapid development. The total output value of China’s paper industry was 785.15 billion yuan in 2020, and the total import and export trade of paper and paperboard reached 17.41 million tons (China Paper Association 2020). As an important basic raw material industry, the water pollution, waste gas, solid waste, and noise pollution of the paper industry are severe. In recent years, China’s paper industry and relevant government departments have continuously strengthened environmental governance, but the paper industry is still a typical industry with “high energy consumption and high pollution”. The trade of paper products between China and the United States has developed rapidly in recent years, and China has been in trade surplus for a long time. This paper uses the input-output model to quantitatively calculate the embodied carbon emissions in the Sino-US paper industry trade, investigate the influencing factors of the embodied carbon change, and explore reasonable measures and policies to promote the role of paper industry in the process of energy conservation and emission reduction, and deal with the low-carbon competition in the current international low-carbon economy era.

Based on previous studies, this study contributes to the existing research as follows: Firstly, as an industry with high carbon emission and high energy consumption accounting for a relatively high proportion of global carbon emissions, the paper industry can be taken as a study example, which can provide reference for other similar industries. At present, other similar research studies mainly have focused on the carbon emissions of a country’s domestic paper industry. Secondly, a large proportion of China’s paper industry trade belongs to processing trade. The research on the embodied carbon of China’s paper industry’s export trade to the United States can lay a foundation for the measurement of the embodied carbon of the import and re-export trade between the processing trade partners and help to reasonably measure the trade income of a country and its corresponding carbon emission responsibilities. Thirdly, on the basis of other studies, this paper makes some improvements and optimizations on the research methods and means: simplifying and improving the input-output table, considering the impact of imported intermediate products on the embodied carbon of export trade, and this can make the data more concise and the data of embodied carbon of trade more accurate.

Development of China’s Paper Industry and Sino-US Paper Industry Trade

Development of China’s paper industry

China is a traditional papermaking country. The sustained economic development has continuously stimulated the demand for paper and provided a broad space for the development of China’s paper industry. China’s paper production and consumption have ranked first in the world since 2009. Through the combination of imported technology and equipment and domestic independent innovation, China’s paper industry has basically completed the transition from early decentralized production capacity and extensive process production to intensive development mode. While absorbing and introducing foreign advanced technologies, China's paper industry pays attention to independent research and development, actively develops and adopts advanced and applicable technologies and equipment for clean production, energy conservation and consumption reduction, and promotes energy conservation and emission reduction. The overall energy consumption of China's paper industry decreased from 44.75 million tons of standard coal in 2010 to 41.02 million tons of standard coal in 2018, and the energy consumption per ton of paper decreased by 18.57% (China Paper Association 2020). Some excellent enterprises have completed the transformation from traditional paper industry to modern paper industry and entered the ranks of world advanced paper enterprises. Taking Chenming Paper as an example, the company took the lead in realizing a modern forest-pulp-paper integrated production model, using advanced low-energy-consumption cooking technology and low-water-consumption pulping technology, and all wastes generated from pulping are used as fuel for power generation. After the advanced treatment of sewage, the discharge index of the generated wastewater is far better than the national discharge standard, the dust removal efficiency of flue gas reaches 99.98%, and the desulfurization rate reaches 95%. With the intensive introduction of environmental protection policies, China puts environmental protection in a higher priority, which can greatly improve China's industrial structure, improve economic quality, significantly improve environmental quality, and fundamentally change the mode of economic growth (Research Group of Development Research Center of the State Council 2018).

As the world's largest importer of waste paper and pulp, China's paper industry has been extremely dependent on upstream raw material supply, and the production of raw materials for paper products is heavily dependent on imports from other countries. In 2020, China's import of pulp and waste paper reached 38.24 million tons, as shown in Table 1. At the same time, China's export of paper products is increasing every year. Among the major paper producing countries, China's space and ability to obtain trade interests in the international division of labor are limited. It is not optimistic to improve trade interests through the growth of export volume (Jiang *et al.* 2020). With the change of the global paper industry pattern, recycling and low-carbon environmental protection have become new development themes. Affected by trade friction, continuous tightening of environmental protection, limited raw material supply, and other factors, Chinese paper enterprises are accelerating the elimination of backward production capacity, starting to lay out overseas production capacity, and developing towards industrial chain integration by extending upstream and downstream, so as to control raw materials from the source, reduce costs, and improve international competitiveness. China's paper industry is undergoing industry consolidation and eliminating outdated production capacity. By the end of 2020, the number of paper production enterprises with annual operating income of more than 20 million yuan had dropped to 2,500, which is 400 less than in 2014 (China Paper Association 2020).

Table 1. Pulp Consumption in China (2019 to 2020) (Unit: Million Tons)

	2019	Proportion (%)	2020	Proportion (%)	Year by Year
Wood Pulp	35.81	37	40.46	40	12.99
Import	23.17	24	25.56	25	10.32
Domestic	12.64	13	14.90	15	17.88
Waste Paper Pulp	55.23	57	56.32	55	1.97
Import	0.92	1	2.49	2	170.65
Domestic	54.31	56	53.83	53	-0.88
Non Wood Pulp	58.5	6	5.22	5	-10.77
Total	96.89	100	102.00	100	5.27

Data source: Annual Report of China's Paper Industry 2019-2020 (CPA 2020)

Development of America paper industry and Sino-US paper industry trade

Globally, countries with large-scale paper products industry are mainly concentrated in Asia, North America, and Europe. However, the paper market in Europe and North America has been saturated, and the development potential is limited by the market capacity. Meanwhile, the Asia Pacific region is becoming the engine of the development of the global paper industry. China's paper and paperboard output accounted for the highest proportion in the world in 2019, accounting for 26.63%; followed by the United States, accounting for 16.86%. China and the United States are both major import and export countries (Fig. 1). Compared with other countries, the United States has unique natural conditions, extremely rich forest resources and relatively mature waste pulp extraction technology. The paper industry in the United States has expanded regionally with rich forest resources, and has realized the integrated layout of pulping, papermaking, and packaging in the industrial chain, which is in an advantageous position in the global industrial chain. The U.S. paper industry has an abundant supply of raw materials. The U.S. is a major pulp producer and exporter in the world. In 2017, waste paper exports accounted for 32.09% of global waste paper exports, and the recycling rate of waste paper was 68.1% (American Forest and Paper Association 2018). Under the influence of sufficient raw materials in the upstream and stable demand in the downstream, the overall development trend of the industry will tend to grow steadily in the future (Koopman *et al.* 2012). Domestic paper enterprises in the United States usually have the advantages of large production scale, high production technology level, and sufficient funds, which has created the dominant position of American paper enterprises in the global export of paper products.

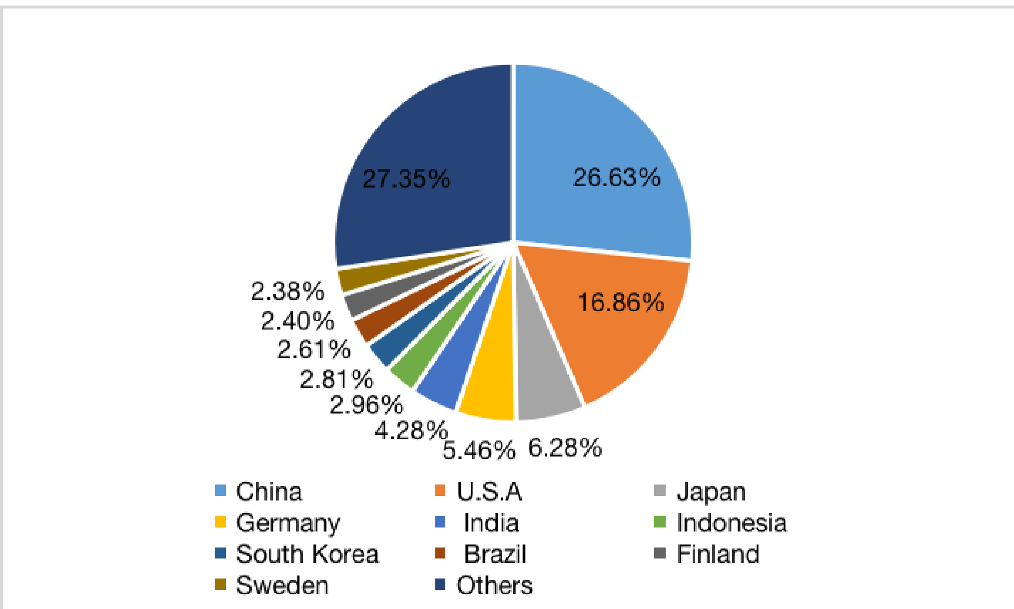

Fig. 1. Distribution of global paper production in 2019

In fact, the trade structure of China US paper industry reflects the complementarity of the paper industries of the two countries. China mainly imports pulp from the United States and exports paper and paper products to the United States. From the perspective of global pulp production and supply pattern, the United States is one of the major pulp exporters and China is the largest pulp importer in the world. China's export of paper products to the United States showed an increasing trend from 2006 to 2015, and the export volume reached $3.535 billion in 2018, nearly tripled from $1258 million in 2007. Due to the impact of the economic crisis and COVID-19, the US import demand for the paper products industry is slowly expanding. The United States imports more paper products from China, but the export quantity is small, and the trade deficit is gradually expanding. Under this background, it is more representative to investigate the embodied carbon emissions of Sino-US paper industry trade.

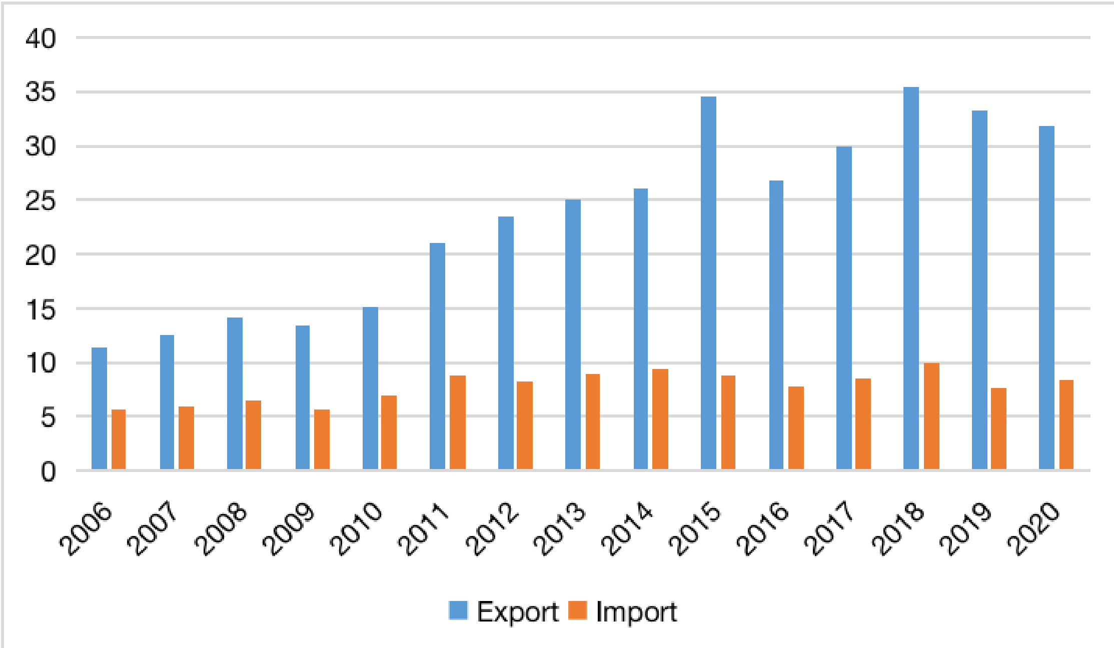

Fig. 2. Sino-US paper products import and export trade volume from 2006 to 2020 (Unit: 10^8 USD)

Measurement of Embodied Carbon Emissions in China's Paper Industry's Export Trade to the United States

Data source and related description

In China's Industry classification of national economy (GB 4754-2017 2017), the industry code of papermaking and paper products is category C, and it is in category 22 and sub categories 221, 222, and 223, which mainly covers pulp, papermaking, and paper products manufacturing. The investigation period of this research was 2006 to 2020. Combined with the classification of the paper industry in China's industry classification of national economy (GB 4754-2017 2017), this paper selected category 48 under HS code, mainly including paper and paperboard, pulp, paper, or paperboard products. The trade volume of the China US paper industry came from the UN Comtrade database, and the input-output table, input-output complete consumption coefficient, and industrial energy consumption data came from China's National Bureau of statistics; the carbon emission coefficient was taken from the IPCC (Intergovernmental Panel on Climate Change) carbon emission coefficient table.

Due to the different classification of some industries and sectors in China's input-output table in different years, to unify the data processing and the consistency of subsequent calculation, according to the customary practice of previous scholars on the calculation of trade embodied carbon emissions (Liu 2016; Du *et al.* 2021), and based on the input-output table according to China's industry classification of national economy (GB 4754-2017 2017), this paper integrated 42 sectors in China's input-output table into 17, as shown in Table 2.

Table 2. Industrial Classification

Number	Sector Classification	Number	Sector Classification
1	Agriculture, forestry, animal husbandry, and fishery	10	Manufacture of metal products
2	Mining	11	Manufacture of machinery and equipment
3	Food and tobacco processing	12	Construction
4	Textile industry, manufacture of leather, fur, feather, and related products	13	Transport, storage, postal services, information transfer, software, and information technology services
5	Other manufacturing	14	Wholesale and retail trades, accommodation, and catering
6	Production and distribution of electric power, heat power, and water	15	Real estate, leasing, and commercial services
7	Coking, gas, and petroleum processing	16	Finance
8	Manufacture of chemical products	17	Other services
9	Manufacture of non-metallic mineral products		

In view of the limitations of data source years, during the research period of this research, China only released the input-output table in 2007, 2010, 2012, 2015, 2017, and 2018, so the input-output data and its corresponding complete consumption coefficient of adjacent years were expanded from the above years. For example, the input-output data of 2018 and its corresponding complete consumption coefficient were extended to 2018 to 2020. At the same time, because the paper industry is not listed separately in the industry sector classification, this paper first calculated the trade embodied carbon emissions of other manufacturing sectors (sector No. 5), and then calculated the trade embodied carbon emissions of paper industry according to the proportion of input-output data of paper industry in other manufacturing industries in each year in the input-output table. In addition, due to data limitations, this paper only calculated the embodied carbon emissions of China's paper industry's export trade to the United States.

Model construction and calculation method

There are two methods widely used to measure trade embodied carbon emissions in the existing research studies: life cycle assessment (LCA) and input-output model. Life cycle assessment is a technology and method used to evaluate the environmental impact of products in their whole life cycle, that is, from the acquisition of raw materials, the production of products to the disposal of products after use (Suh *et al.* 2004). Life cycle assessment needs high data integrity, involving the materials required in the whole production process and the subsequent processing methods and disposal of products, so it is difficult to collect data. Due to the lack of detailed and complete input-output data, carbon emission accounting is difficult to calculate accurately, so its practicability is poor (Zhu *et al.* 2009; Chen *et al.* 2014). Input-output analysis method is a quantitative analysis method to study the interdependence between input and output among sectors in the economic system. The basis of input-output analysis is the input-output table. In contrast, the input-output model has low data requirements, and it is widely used to study the trade embodied carbon emissions. Therefore, this paper uses the input-output model to analyze the trade embodied carbon emissions.

Table 3. Simplified Input-output Table

Input \ Output		Intermediate Use							Total Final Use	IM	Gross Output
		Sector 1	Sector 2	…	Sector j	…	Sector n	Total			
Intermediate Input	Sector 1	x_{11}	x_{12}	…	x_{1j}	…	x_{1n}		y_1	IM_1	X_1
	Sector 2	x_{21}	x_{22}	…	x_{2j}	…	x_{2n}		y_2	IM_2	X_2
	⋮	⋮	⋮	⋱	⋮	⋱	⋮		⋮	⋮	⋮
	Sector i	x_{i1}	x_{i2}	…	x_{ij}	…	x_{in}		yi	IM_i	X_i
	⋮	⋮	⋮	⋱	⋮	⋱	⋮		⋮	⋮	⋮
	Sector n	x_{n1}	x_{n2}	…	x_{nj}	…	x_{nn}		y_n	IM_n	X_n
	Total										
Value Added		z_1	z_2	…	z_j	…	z_n				
Total Input		X_1	X_2	…	X_j	…	X_n	……			

Source: This table is simplified based on the input-output table of China in recent years.

Based on China's non-competitive input-output table in 2018, the main content is composed of three parts: the first part is intermediate use and intermediate input, which is the theme of the input-output table. It reflects the quantitative relationship between input and output among sectors and the technical connection of product production. The x_{ij} (i, j = 1, 2, 3, ..., n) represents the product quantity (value) produced by sector i allocated to sector j, or the product quantity consumed by sector i in the reproduction process of sector j. The second part includes final use, import, and total output, which is the horizontal extension of the first part. Final use mainly includes consumption expenditure by households, consumption expenditure by government, gross fixed capital formation, changes in inventories, and export, which reflects the final product and its flow direction. The third part is the vertical extension of the first part, which includes added value and total input. The added value can be subdivided into labor compensation, net taxes on production, depreciation of fixed assets and operating surplus, which reflects the initial distribution of GDP.

From the perspective of Table 3, the sum of intermediate use and final use of each sector i minus imports is equal to the total output, that is,

$$\sum\nolimits_{j=1}^{n} x_{ij} + y_i - IM_i = X_i \quad (i, j = 1, 2, \ldots, n) \tag{1}$$

Let $y_i - IM_i = Y_i$, then:

$$\sum\nolimits_{j=1}^{n} x_{ij} + Y_i = X_i \quad (i, j = 1, 2, \ldots, n) \tag{2}$$

Direct-consumption coefficient (recorded as a_{ij}) refers to the quantity of products or services directly consumed by sector i per unit of total output in the production and operation process of sector j, according to Eq. 3:

$$a_{ij} = x_{ij} / X_j \tag{3}$$

Bring Eq. 3 into Eq. 2:

$$\sum_{j=1}^{n} a_{ij}X_j + Y_i = X_i \ (i, j = 1, 2, \ldots, n) \quad (4)$$

Note the direct-consumption coefficient matrix is A:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix}$$

Then, Eq. 4 can be rewritten as,

$$AX + Y = X \quad (5)$$

where, $X = (X_1, X_2, X_3, \ldots, X_n)^T$ and $Y = (Y_1, Y_2, Y_3, \ldots, Y_n)^T$.

The complete-consumption coefficient refers to the quantity of products or services directly and indirectly consumed by each sector i for each unit of final products provided by a sector j, according to Eq. 6:

$$c_{ij} = a_{ij} + \sum_{k=1}^{n} c_{ik}a_{kj} \ (i, j = 1, 2, \ldots, n) \quad (6)$$

The complete-consumption coefficient of each product department is expressed in the form of a table, that is, the complete-consumption coefficient table or the complete-consumption coefficient matrix, which is usually represented by the letter B:

$$B = (I - A)^{-1} - I$$

In the above formula, matrix I is the identity matrix, so Eq. 5 can be rewritten as:

$$(E - A)^{-1} Y = X \quad (7)$$

The embodied carbon emissions of export trade of paper industry is C, the complete-consumption coefficient matrix is B, the export trade data matrix of China's paper industry to the United States is EX, the energy consumption matrix is R, and the carbon dioxide emission coefficient is Q, so that Eq. 8 is as follows:

$$C = B \cdot EX \cdot R.Q \quad (8)$$

Calculation results and analysis

According to the above calculation methods and relevant data, the authors put the relevant data from 2006 to 2020 into Eq. 8 for calculation, and the embodied carbon emissions of China's paper industry's export trade to the United States from 2006 to 2020 was obtained (as shown in Fig. 2).

In terms of total amount, the embodied carbon emissions of China's paper industry trade to the United States from 2011 to 2014 were nearly stable at about 1.5 million tons. In 2015, due to the surge in export volume, trade embodied carbon emissions were relatively high. Since 2016, it has generally shown a slow upward stage. In 2020, with the impact of Sino-US trade friction and COVID-19, the volume of exports declined, and the embodied carbon emissions of trade also declined.

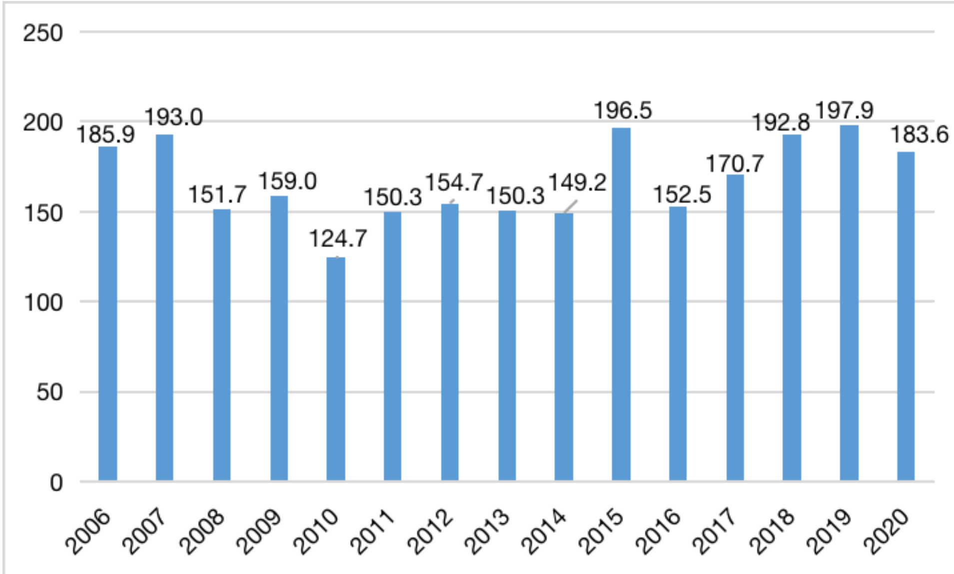

Fig. 3. Embodied carbon emissions in China's paper industry's export trade to the United States from 2006 to 2020 (Unit: 10^4 t)

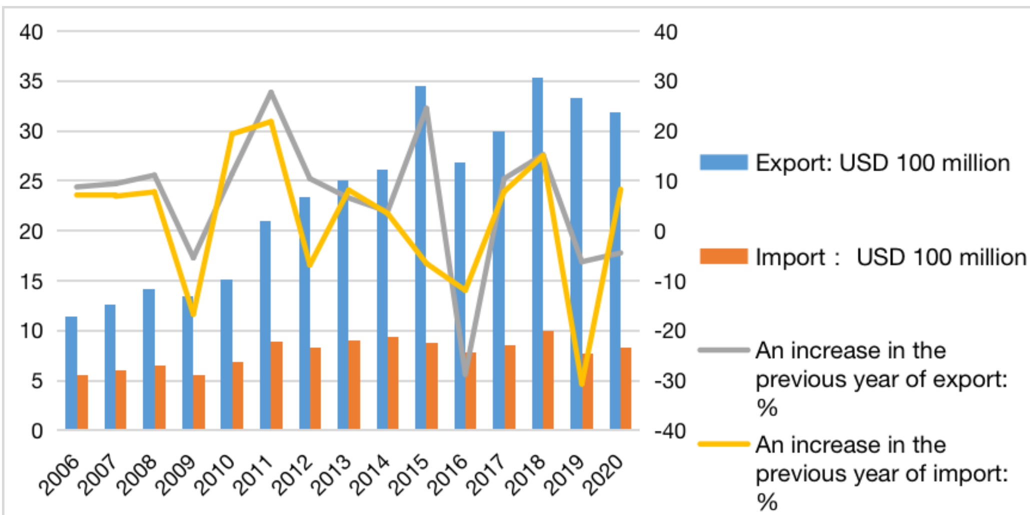

Fig. 4. Sino-US paper products import and export trade volume

Comparing the development trend of Sino-US paper industry trade and embodied carbon emissions, the authors found that Sino-US paper industry trade has basically shown an upward trend year by year since 2006, but the embodied carbon emissions of China's paper industry export trade to the United States showed a downward trend after 2006 and decreased slightly and gradually stabilized after reaching the peak in 2015. This trend is consistent with the transformation and upgrading process of China's paper industry. That is, although the export volume basically shows an upward trend, the carbon emission shows a downward trend due to the improvement of China's paper industry technology and environmental protection requirements. The growth trend after 2015 is mainly due to the growth of export scale, which will be verified and explained in the next part of this paper. This judgment of this paper is consistent with the judgment of scholars on the research of China's total carbon emission. According to the research and calculation of China's carbon emissions by Ping (2020), the decline of carbon emission intensity accounted for two-thirds of the total decline from 2006 to 2017, and the trend of reduction of carbon emission intensity became increasingly obvious after 2006, which means that the effect of China's emission reduction is improving. In terms of industry, the carbon emission intensity of the paper industry decreased from 1.63 in 1997 to 0.15 in 2017.

In the Sino-US paper industry trade, most trade embodied carbon is generated in China. Considering that China imports a large amount of waste paper as an intermediate input product of paper products, China has undertaken too much trade embodied carbon emissions, which is unfavorable to the implementation of China's sustainable development strategy of a low-carbon economy. It is also noteworthy that to achieve the goals of carbon peak and carbon neutralization, the challenges faced by China's paper industry, which is still rising in demand and output and accounts for more than 80% of fossil energy in the energy supply system, are extremely severe. However, in this context, the export trade of China's paper industry to the United States still has such a large embodied carbon emission, and the influencing factors behind it are worthy of intensive study, which will be reviewed in the next part of this paper.

Influencing Factors of Embodied Carbon Emissions in China's Paper Industry's Export Trade to the United States

Introduction to LMDI method

In recent years, scholars mostly have used the regression model or the index decomposition method to analyze the influencing factors of carbon emissions. Compared with the regression analysis method, index decomposition analysis (IDA) can quantify the driving factors behind the change of total carbon emissions, such as the structural change of economic activities and the intensity change of energy consumption. It can intuitively show the key factors affecting carbon emissions. Therefore, IDA has unique advantages in the research of energy consumption and carbon emissions. The proposal of Kaya identity establishes the corresponding relationship between carbon dioxide emission and factors such as population, economic development level, and energy utilization efficiency (Kaya 1989). On this basis, decomposition technology has developed rapidly. Ang *et al.* (1997) believes that the function of decomposition analysis is to decompose a total index into several research indexes set in advance, that is, first to define a function related to the decomposed index and use this function to obtain the influence of each decomposed index on the change of the decomposed index. Therefore, the improved logarithmic mean divisia index (LMDI) proposed by Ang (2001) realized complete decomposition.

Compared with other methods, the LMDI decomposition method satisfies the reversibility of factors, it can eliminate the residual term, it overcomes the shortcomings of other methods, such as residual term after decomposition, and it solves the problem of zero value affecting the calculation, which makes this method more convincing (Zhu *et al.* 2009). The LMD method has been widely used in national, regional, sectoral, and industrial studies due to its excellent characteristics, and has become the most popular factor decomposition method in the field of energy economics and carbon emissions (Ang *et al.* 1998). In the analysis of LMDI method, the reasons for the change of energy consumption intensity are divided into "structure effect" and "efficiency effect", and the factor decomposition method is used to measure and analyze the size of structure effect and efficiency effect. Based on these research foundations, this paper uses LMDI method to analyze the influencing factors of the change of embodied carbon emissions in China's paper industry's export trade to the United States.

Calculation method and process

The LMDI analysis method can quantitatively evaluate the relative impact of each decomposition factor on the target variable through exponential decomposition operation, and this method has the advantages of no residual after decomposition and can deal with the zero value problem (Ang *et al.* 1998), so it is applicable to the analysis of influencing factors of trade embodied carbon emissions. The calculation process is as follows: Firstly, the LMDI method is used to decompose the carbon emissions of China's paper industry's export trade to the United States at different stages into three factors: trade scale, trade structure change, and carbon intensity. Secondly, the specific impact and contribution rate of various factors on the change of carbon emissions are calculated. Finally, the calculation results are compared and analyzed to compare the main factors affecting carbon emissions in different stages and the different roles of various factors in different stages.

According to the complete decomposition method of LMDI, the embodied carbon change ($\triangle V_{tot}$) of China's paper industry's export trade to the United States can be decomposed into scale effect ($\triangle V_{tra}$), structure effect ($\triangle V_{str}$), and carbon intensity effect ($\triangle V_{int}$) from the base period "1" to "2". The formula is as follows,

$$\triangle V_{tot} = \triangle V_{tra} + \triangle V_{str} + \triangle V_{int} \tag{9}$$

where $\triangle V_{tot}$ represents the change of embodied carbon emissions of China's paper industry's export trade to the United States, and $\triangle V_{tra}$ refers to the impact of changes in the scale of China's paper industry's export trade to the United States on the embodied carbon emissions of export trade, which is called scale effect. It is generally believed that there is a positive correlation between the total amount of trade and the embodied carbon emissions of trade; $\triangle V_{str}$ refers to the impact of the change of China's paper industry's export trade structure to the United States on the embodied carbon emissions of export trade, which is called structural effect. Affected by the reallocation and specialization of resources, it is generally believed that the change of input structure leads to the change of embodied carbon emissions; $\triangle V_{int}$ represents the impact of carbon emission intensity on the embodied carbon emissions of China's paper industry's export trade to the United States, also called technology effect, which is reflected in the improvement of productivity, the continuous increase of research and development (R&D) funds, and the diffusion and transfer of technology, and it is generally considered to have a positive effect. Subscripts 1 and 2 in the following formula represent the base period and report period respectively. To reflect the technical effect of time change and limited by the availability of data on GDP by industry, the authors measured the carbon emission intensity of the paper industry by the ratio of carbon dioxide emission to the operating income of enterprises in the industry and the relevant data were from the China Statistical Yearbook (2006-2020).

The calculation formulae of the three kinds of effects are as follows,

$$\triangle V_{tra} = F(v^{t1}{}_j, v^{t2}{}_j)[\ln(y^{t2}) - \ln(y^{t1})] \tag{10}$$

$$\triangle V_{str} = F(v^{t1}{}_j, v^{t2}{}_j)[\ln(s^{t2}) - \ln(s^{t1})] \tag{11}$$

$$\triangle V_{int} = F(v^{t1}{}_j, v^{t2}{}_j)[\ln(i^{t2}) - \ln(i^{t1})] \tag{12}$$

$$F\left(v_j^{t_1}, v_j^{t_2}\right) = \frac{v_j^{t_2} - v_j^{t_1}}{\ln(v_j^{t_2}) - \ln(v_j^{t_1})} \tag{13}$$

where v_j^{t1} and v_j^{t2} represent the embodied carbon emissions of export trade of sector product j in time period t; y^{t1} and y^{t2} represent the export trade volume of products of sector j in time period t; s^{t1} and s^{t2} represent the proportion of export trade volume of products of sector j in the total export trade volume in time period t; and i^{t1} and i^{t2} represent the carbon emission intensity of export commodities of products in sector j in time period t.

According to the above calculation formula, the calculation formula of the contribution rate of each factor can be obtained according to Eqs. 14 through 16:

$$Y_{tra} = \triangle V_{tra} / \triangle V_{tot} \times 100\% \quad (14)$$

$$Y_{str} = \triangle V_{str} / \triangle V_{tot} \times 100\% \quad (15)$$

$$Y_{int} = \triangle V_{int} / \triangle V_{tot} \times 100\% \quad (16)$$

Calculation results and analysis

According to the development trend of China's paper industry's export trade to the United States, taking 2020 and 2015 as the dividing point, this paper makes a structural decomposition of the embodied carbon change of China's paper industry's export to the United States in the three periods of 2006 to 2010, 2010 to 2015, and 2015 to 2020. Through substituting relevant data into the above series of formulas, the effect decomposition of embodied carbon emissions of China's paper industry's export trade to the United States was obtained (as shown in Table 4). The trade structure of China's paper industry with the United States is relatively special, and China has a long-term trade surplus, so the authors only calculated the embodied carbon of China's paper industry's export trade to the United States due to data accessibility.

Table 4. Effect Decomposition of Embodied Carbon Emissions from China's Paper Industry's Export Trade to the United States

Period	Scale Effect		Structure Effect		Carbon Emission Intensity Effect		Embodied Carbon Change (10^4 t)
	Contribution value (10^4 t)	Contribution rate (%)	Contribution value (10^4 t)	Contribution rate (%)	Contribution value (10^4 t)	Contribution rate (%)	
2006 to 2010	-18.96	-149.87	-1.54	-12.13	33.15	262	12.65
2010 to 2015	54.04	2806.46	9.81	509.43	-61.92	-3215.89	1.93
2015 to 2020	1.04	22.20	0.08	1.78	3.56	76.01	4.68

From 2006 to 2010, the export embodied carbon of China's paper industry to the United States increased 126,500 tons, among which the contribution value of carbon emission intensity to the change of export embodied carbon was 331,500 tons, a contribution rate of 262%. At this stage, the export scale of China's paper industry to the United States was small, which indicates that China's paper industry at this stage had high energy consumption and high carbon emission intensity, which was the main reason for the high embodied carbon emissions in export. The carbon emissions of China's paper industry peaked around 2010 and continued to decline after 2012, and the carbon emission intensity of the paper industry continued to decline (as shown in Fig. 4).

From 2010 to 2015, the energy intensity effect was the main driving force for carbon emission reduction, with a contribution value of -619200 tons. Although the scale of the paper industry and export trade continued to expand at this stage, the carbon emissions of the paper industry tended to decline after 2015 due to the comprehensive effects of technological progress, the promotion of relevant national policies, and the elimination of backward production capacity by enterprises. The effect of carbon emission intensity was negative. The improvement of production technology and the reduction of energy consumption intensity play an important role in offsetting the embodied carbon growth of export trade, and it partially offset the increase of carbon content caused by scale effect, which shows that China achieved remarkable results in low-carbon production and carbon emission reduction during this period. In fact, at this stage due to the pressure of eliminating backward production capacity, industrial structure adjustment, and energy conservation and emission reduction, a large number of small paper factories were shut down, and a total of 29 million tons of paper production capacity was eliminated. From 2011 to 2014, a total of 287 backward and overcapacity enterprises were eliminated in China's paper industry.

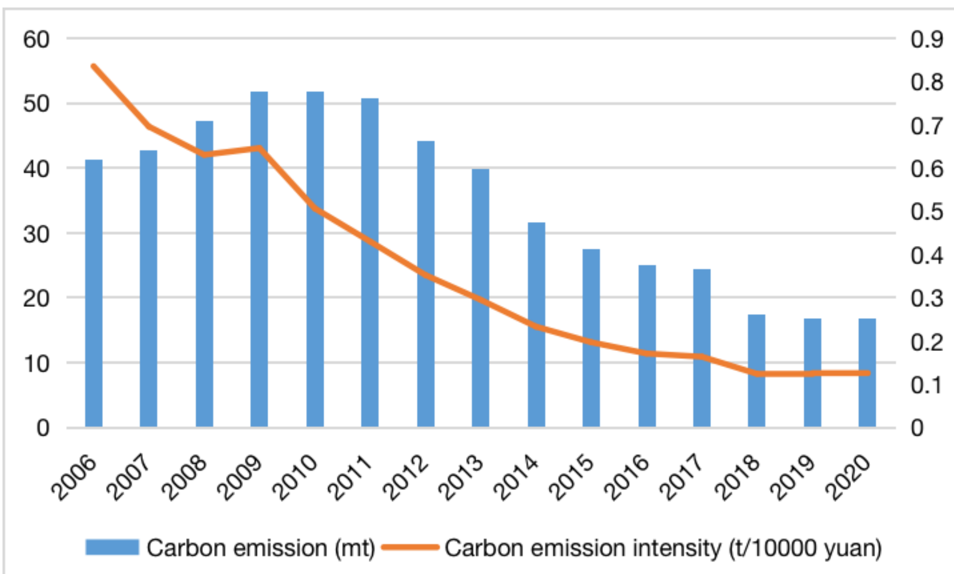

Fig. 5. Change trend of carbon emission and carbon emission intensity of China's paper industry

From 2015 to 2020, due to the impact of Sino-US trade friction, the trade volume of Sino-US paper industry fluctuated, but the carbon emission intensity effect was positive during this period, which may be due to the change of export product structure caused by the adjustment of China's paper industry structure affected by trade friction; both scale effect and structure effect were positive, but the total amount of export embodied carbon emission had little change. From the perspective of policy, at this stage, China's State Council, the Ministry of ecological environment and other departments successively issued policies to support and standardize the development of the paper industry, including development planning, pollution control, and green production of the paper industry. From the perspective of carbon emission intensity of China's paper industry, it maintained a slow decline at this stage, indicating that the improvement of energy-saving and emission reduction technologies and the promotion of government policies are conducive to the continuous reduction of carbon emissions.

DISCUSSION

Among the influencing factors of trade-embodied carbon emissions, the contribution of trade scale to carbon emission is particularly prominent. Among many research studies on the embodied carbon emissions of China's export trade, it is considered that the increasing trade scale plays a role in promoting the embodied carbon of trade, and among many influencing factors, the scale effect brought by the rapid development of trade has the largest historical contribution rate to carbon emissions (Chen 2009). Gao *et al.* (2011) used the environmental input-output model to calculate the embodied carbon emissions of 17 import and export sectors in China and found that the embodied carbon emissions of China's export trade showed an increasing trend with the increase of trade surplus. In short, research on China's trade embodied carbon mainly focuses on export trade, and the main conclusion is that trade scale effect and structural adjustment promoted the increase of China's export embodied carbon emissions, while technology improvements and energy efficiency tended to reduce China's export embodied carbon emissions (Tian and Zhang 2011; Lu *et al.* 2014; Li and Tang 2021). Although the current study only takes the paper industry trade as an example, the analysis results of the empirical part further confirm the above research conclusions.

The carbon emission intensity of China's paper industry is showing a downward trend. Existing studies have shown that there are three main factors for the decline of carbon emission intensity: the improvement of energy utilization efficiency caused by technological progress, the increase of the proportion of renewable energy used to reduce fossil energy consumption, and the transformation and upgrading of industrial structure (Du *et al.* 2015; Guo *et al.* 2021). Shi *et al.* (2019) constructed a comprehensive decomposition framework and believed that technological progress is the key to achieve sustainable growth of energy productivity and long-term reduction of carbon emission intensity. Ping *et al.* (2020) estimated China's carbon emission intensity by industry and believed that the emission intensity of China's paper industry showed a downward trend. The improvement of energy utilization efficiency caused by technological progress is an important reason for the decline of carbon emission intensity of China's paper industry. The current study further supports this conclusion. It should also be pointed out that the rapid development of China's paper industry is inseparable from the promotion of industrial policy, while trade policy helps to promote the upgrading of industrial structure and cultivate industrial competitiveness. China's supporting policies for the paper industry have experienced changes from "structural adjustment" to "sustainable development" and then to "green manufacturing". The technological progress and innovation of China's paper industry is an important support for the transformation and upgrading of the paper industry and carbon emission reduction. From the empirical results of this paper, the technological progress of the paper industry is inseparable from the support and promotion of industrial policies.

From a global perspective, trade-embodied carbon emissions are not simply the single responsibility of producer countries. With the increasingly global trade relations and rising trade volume, the problem of "trade embodied carbon" continues to intensify (Peters *et al.* 2011), and China's current economic type is export-oriented, and the energy and emissions consumed by the production of export commodities account for a large proportion of China's energy consumption and carbon emissions (Huang and Liu 2011; Wang *et al.* 2019). Some studies use the World Input-Output Database (WIOD) to study the international correlation effect of China's trade embodied carbon. On this basis it is believed that China is a net exporter of trade embodied carbon, and there are country and sector differences (Deng and Zhang 2016). The research objects of the current paper are the United States and China, and the selected paper industry is a high carbon emission industry, and the results of this paper also confirm the above conclusions. In the existing international division of labor system, developed countries or regions have long been in a favorable position for the transfer of embodied carbon responsibility, while developing countries or regions are in a disadvantageous position (Peng *et al.* 2016). If the production responsibility law is used to calculate and confirm China's carbon emissions responsibility, it will not only greatly increase China's burden of emission reduction, but also violate the principle of fairness (Shi 2012). Therefore, the control of trade embodied carbon emissions requires coordination and cooperation from all countries in the world (Yu and Zhan 2018).

The research on the embodied carbon emissions of paper industry trade from the perspective of processing trade is a direction that can be further studied in the future. Because it is difficult to distinguish the source and destination of embodied carbon in processing trade, only a few scholars have been involved in this topic for a long time. Processing trade occupies a large proportion of China's foreign trade, as does the paper industry trade. Subdividing the embodied carbon sources of re-export after import and re-import after export between trading partners in the processing export trade will become a hot research topic in the future. Such research will help to reasonably measure a country's trade income and its corresponding carbon emission responsibilities. In addition, in future research, scholars can consider comparing the carbon emission and carbon emission intensity of China's paper industry with that of other countries in the context of carbon trading to more widely and thoroughly study the international carbon flow of the paper industry and provide policy reference for the optimization of the industrial structure and trade structure of the paper industry and energy conservation and emission reduction.

CONCLUSIONS

1. The embodied carbon emissions in China's paper industry's export trade to the United States generally showed a stable downward trend after reaching the peak with the increase of export trade scale. A large number of exports of the paper industry has promoted the increase of trade interests to a certain extent, reflecting the export trade advantages of China's paper industry. Simultaneously, it has exacerbated the shortage of raw materials and environmental pollution in the paper industry. The scale effect is the main factor causing the embodied carbon emissions in China's paper industry's export trade to the United States. The continuous expansion of export scale not only leads to the continuous consumption of domestic resources, but also brings carbon emissions and environmental pollution, which have become the primary factor aggravating the embodied carbon in China's paper industry's export trade.
2. Technological progress, policy support from the national and industrial levels, environmental regulation, and other factors are important driving forces to promote carbon emission reduction in China's paper industry and export trade. Judging from the direct and indirect consumption coefficients of China's paper industry, the overall trend has shown a sharp decline, indicating that the improvement of production technology has played a certain role in reducing energy consumption. At the same time, China's development and support policies for the paper industry have experienced changes

from "structural adjustment" to "sustainable development" and then to "green manufacturing", which is the policy factor for the continuous decline in the carbon emission intensity of the paper industry.

Policy Implications

In view of the problems related to the embodied carbon emissions in China's paper industry's export trade to the United States, the authors put forward the following policy initiatives:

1. Promote the rationalization of the paper industry structure and trade structure and promote the high-quality development of paper industry trade. China's paper industry is in a stage of rapid growth. It is necessary to eliminate outdated production capacity based on the premise of sustainable development, promote the rational layout of the industrial structure and product structure, promote the development of the paper industry in a high-quality and diversified direction, and extend the domestic value chain (Yao and Hou 2016). As far as paper industry trade is concerned, China should shift from export quantity-oriented to quality- and efficiency-oriented and realize the green and low-carbon development of paper industry and trade under the constraints of resources and energy (Liu 2018).
2. Optimize the energy structure and continue to promote energy-saving parameters and improve the utilization efficiency of resources and emission reduction technologies. Fossil fuel emission is the main emission type of China's paper industry, in which the use of coal accounts for the vast majority of fossil fuel emission. With low energy efficiency and large carbon emission, the energy structure of the paper industry needs to be improved. One of the main ways to reduce carbon emissions for the pulp and paper industry in developed countries is to increase the proportion of biomass energy (Panoutsou *et al.* 2017). For example, the proportion of biomass energy in the EU has reached 60% of all fuels in 2019, accounting for 53% of all primary energy, while China's biomass energy accounts for less than 20% of all energy (Shi *et al.* 2019). While optimizing the energy structure, adopting more advanced production technology or production equipment is an effective way to improve energy efficiency and reduce carbon emissions, which can effectively curb the growth trend of carbon emissions embodied in export trade (Sun and Ren 2021).
3. Continue to encourage the paper industry to actively participate in carbon trading and promote the emission reduction and emission control of paper enterprises. The paper industry is one of the first eight industries to be included in carbon trading in China. For paper enterprises that have not yet been included in the scope of emission control, they can form carbon assets by participating in Chinese Certified Emission Reduction project and realize them through the carbon trading system, so as to occupy a place in the carbon trading market. Participating in carbon emission trading can curb carbon emissions at the source, complement the elimination of outdated papermaking technology, and finally promote the papermaking industry to embark on the road of energy conservation and emission reduction.
4. Pay attention to the emission reduction effect of intermediate inputs, increase carbon sinks, and reduce carbon sources. The change of intermediate input structure is also an important reason for the increase of embodied carbon emissions in China's paper industry's export trade (Sheng and He 2016). Among them, high carbon emission

industries, such as chemical industry, agriculture, forestry, animal husbandry, fishery, and water conservancy, electric power, natural gas, and water supply industry, have made outstanding contributions to the paper industry. Therefore, it is necessary to encourage enterprises to shift to the non-wood fiber and waste paper raw materials, to increase the carbon sink and reduce carbon emissions. China is also gradually promoting the forestry-pulp-paper integration. In addition to providing wood pulp raw materials for downstream papermaking, the upstream raw material forest can also absorb carbon dioxide, greatly increase carbon sink, provide biofuel, and reduce carbon source (Geng *et al.* 2020).

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