Embodied carbon emissions of aluminum-containing commodities in international trade: China’s perspective

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Abstract
In recent years, global climate change has become an increasingly serious problem. Developing countries have assumed excessive responsibilities for carbon emissions under the principle of producer responsibility. A system that considers material flows to establish the responsibility for carbon emissions more accurately and fairly was proposed. In this study, the embodied carbon emissions (ECEs) of aluminum-containing commodities (ACC) in China’s international trade from 2008 to 2017 were analyzed via material flow analysis. The carbon emission coefficients of China’s imported and exported ACC were calculated and discussed. The main conclusions were as follows: (1) The annual imported and exported aluminum in ACC showed a fluctuating growth from 2008 to 2017. Overall, China imported a large amount of alumina and exports a large amount of aluminum-containing end products (ACEP) and semi-products (SP). (2) The imported and exported ECEs of ACC were mainly due to ACEP, which account for 57% and 68% of the imported and exported ECEs of ACC, respectively. (3) The ECEs of ACEP in international trade were mainly associated with vehicles, manufacturing equipment, and aircraft. (4) The share of exported and net exported ACC’s ECEs in domestic carbon emissions (calculated using the principle of producer responsibility) also increased from 1.3 and 0.9% to 2.8 and 1.7%. In addition, a more accurate share of international carbon emission responsibility was discussed, and policy recommendations to reduce carbon emissions and actively respond to global climate change were provided.

Keywords Material flow analysis · Embodied carbon emissions · International trade · Aluminum-containing commodities · China

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1 Introduction

Climate change has attracted considerable attention from the international community, as it significantly affects economic and social development (Lee and Yoo 2016). The 2018 Nobel Prize winner in economics, William (2014), stated that responding to climate change requires countries of different development levels to act together. With the development of international trade, embodied carbon emissions (ECEs) transferred between countries have become a research hotspot (Liu et al. 2008; Ding et al. 2009; Dong et al. 2011). Such researches are of great significance to distinguish carbon emission shares and reduction targets of trading partners, which can significantly impact global efforts to address climate change.

Since 2005, China surpassed the USA, and it became the world’s largest carbon emitter (Chen and Chen 2011). As one of the major contributors to global carbon dioxide emissions from fossil fuels, China has formulated clear strategic goals and practical steps to address climate change. China has led several efforts to mitigate climate change Ministry of Ecology and Environment of China (2015, 2016, 2017, 2018, 2019). After the Paris Agreement, China suggested the goal of peaking carbon emissions by 2030 in an independent contribution document submitted to the United Nations China National Development and Reform Commission (2015). However, a large amount of embodied carbon emissions (ECEs) is included in China’s exported aluminum-containing commodities (ACC). The current international climate negotiation framework system recommends the principle of producer responsibility to determine the carbon emission shares and emission reduction responsibilities (Li et al. 2018). The producer responsibility principle ignores the ECEs of imported commodities, which causes China and other developing countries to assume excessive carbon emission responsibility (Yu and Zhan 2016). Therefore, an accurate calculation of ECEs in international trade and the definition of China’s carbon emissions responsibility are of great practical significance to establish China’s contribution to climate change mitigation and its initiative in future climate negotiations.

The input-output method is commonly used to calculate ECEs in international trade (Xie and Jiang 2014). Previous studies show that there are three main input-output models to calculate ECEs in international trade. The first is the single-region input-output (SRIO) model, which does not consider technical heterogeneity (Gale IV 1995; Lin and Sun 2010; Yan and Yang 2010). The SRIO model assumes that the carbon emission factor of imported products is equal to that of domestic products. It ignores the differences between the carbon emission coefficients of various countries, which in turn cause a large deviation in the estimation results.

The second model is based on technical heterogeneity input-output (BTIO). The BITO model uses the carbon emission coefficient of an export country’s commodity to measure the ECEs in exported commodities; this model is primarily used in the study of ECEs in bilateral trade (Liu et al. 2010; Zhao et al. 2016). However, such studies do not analyze the trade in intermediate and final products separately. Consequently, they cannot clearly indicate the carbon emissions caused by the flow of intermediate products between countries. Upon the development of an input-output method, the use of multi-regional input-output (MIRIO) models became widespread (Chris et al. 2015; Chen et al. 2017). This third model is based on trade data of intermediate and final products of different countries by industry. It accurately measures the carbon emissions generated by the trade of intermediate and final products in various countries, by constructing an input-output matrix between countries (Wilting and Vringer 2009; Lin and Sun 2010; Wiedmann and Barrett 2013; Wu and Yang 2016; Yao et al. 2018; Liu et al. 2019). However, the calculation in an input-output method is based on the input-output table.
published by the country (Wen and Zhang 2020). Therefore, the update time of the input-output table of each country is not consistent, which leads to a data lag in the input-output table and, consequently, untimely updates.

The ECEs of certain types of product (such as ACC) cannot be calculated using input-output models. Regardless of the model (SRIO or MRIO) used to estimate the ECEs of all imported and exported commodities of one country or department, it is impossible to estimate the ECEs of all ACC in international trade, because both models use an input-output table to calculate the implied carbon emissions of imports and exports, and it is not possible to separate all ACC for a separate study (Li et al. 2018). In this context, material flow analysis (MFA) can be used to achieve this research goal.

The MFA method is based on the theory of conservation of matter and is used to identify the flow paths and laws of matter in a research system (Binder 2007a, 2007b). MFA can be used to accurately calculate the material flows of a class of commodities in international trade (Li et al. 2018). In addition, according to carbon emission calculation method 3 (product multiplied by product’s emission coefficient) of the 2006 National Greenhouse Gas Emissions Inventory by the Intergovernmental Panel on Climate Change (IPCC) (Lubetsky et al. 2006), the ECEs of iron-containing commodities (ICC) in international trade can be calculated by multiplying the aluminum and the carbon emission coefficients of each ICC. Therefore, the MFA method is more suitable than the input-output model to calculate the ECEs of ICC. In other words, MFA can be used in addition to the input-output model to calculate hidden carbon emissions (Li 2019).

In the present study, the ECEs of ACC in China’s international trades from 2008 to 2017 were analyzed using MFA based on the material flows of international trade between China and other countries. The purpose of this paper is to provide a basis for an accurate distribution of carbon emission responsibilities and then propose policy recommendations for carbon emission reduction.

2 Materials and methods

2.1 System boundaries

The material flows and carbon emissions of all internationally traded ACC in China from 2008 to 2017 were studied in this research. The investigated ACC included bauxite, alumina, unwrought aluminum (UA), aluminum old scraps (AOS), semi-products (SP), and aluminum-containing end products (ACEP).

2.2 Calculation method and data sources

The IPCC National Greenhouse Gas Inventories 2006 provided three methods to calculate the carbon emission of products (Lubetsky et al. 2006). Method 1 multiplies the amount of used fuel by the carbon emission coefficients of each fuel. Method 2 uses the carbon balance method, which tracks carbon emissions throughout the production process. Method 3 multiplies the product by the product emission coefficient.

In this study, the carbon emissions from ACC were calculated by combining Methods 1 and 3. First, the carbon emission coefficients of ACC were calculated using Method 1. The ACC energy intensity was determined, and the corresponding energy emission coefficient was
adopted to calculate the ACC carbon emission. Second, the ECEs of ACC in international trade were calculated by multiplying the quality of aluminum by the carbon emission coefficients of each ACC.

The calculation formula for the ECEs of ACC in international trade is

\[ C = W_\delta \times E_\delta \times H_\delta,\#(\) \]

where \( \delta \) is the different categories of ACC in imports or exports, \( W \) is the mass of ACC, and \( E \) is the carbon emission coefficients of ACC. Based on Eq. 1, the following relationship can be defined:

\[ C = (W_\delta \times H_\delta) \times \frac{E_\delta}{H_\delta},\#(\) \]

where \( H \) is the aluminum content coefficient of ACC, and \( W_\delta \times H_\delta \) is the aluminum material flows of ACC (pure aluminum).

The calculations in this paper are mainly divided into two parts: (1) aluminum material flows of all ACC categories in China’s international trade \( (W_\delta \times H_\delta) \); and (2) carbon emission coefficients of all ACC categories.

### 2.2.1 Aluminum material flows of ACC in international trade

The aluminum of imported or exported ACC can be calculated by Eq. 3.

\[ W_\delta \times H_\delta = \sum_{\delta=1}^{n} W_\delta \times H_\delta,\#(\) \]

where \( W \) is the weight of ACC, \( H \) is the aluminum content coefficient of ACC, and \( \delta \) is the category of ACC for imports or exports.

ACC data of imports and exports were obtained from the United Nations (2020). There are more than 1.28 million pieces of Chinese ACC trade data from 2008 to 2017, and each of them includes the name, country, quantity, and weight of imported and exported ACC.

All ACC trade data were collated and classified, and divided into six categories, namely bauxite, alumina, UA, AOS, SP, and ACEP. ACEP were subdivided into 55 subcategories. The aluminum content coefficients of different types of imported and exported ACC were organized as shown in Schedule 1 in Supplementary materials. In addition, the trade codes of all ACC (a total of 840) are listed in Schedule 2 in Supplementary materials.

### 2.2.2 ECEs of ACC in international trade

The carbon emission coefficients of ACC were determined based on the comprehensive energy intensity during their production, which include the consumption of primary energy (PE: Natural energy resources that exist in nature without any change or conversion, that is, energy directly obtained from nature without changing its form and grade, e.g., raw coal, crude oil, natural gas, water, wind, solar, geothermal, and ocean energy), secondary energy (SE: Artificial energy produced by direct or indirect processing and conversion of primary energy to meet the specific needs of production and residential processes, and rational use of energy. Examples are coke, gas, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, refinery...
dry gas, and electricity), energy-consumed medium (ECM: Working substances that are consumed in the production process. They are not used as raw materials and do not enter the product, while requiring energy intensity during preparation. Examples include fresh water, circulating water, compressed air, oxygen, and residual heat resources (RHR: Available residual heat determined by technical and economic analysis).

The carbon emission coefficients of ACC are represented by the amount of carbon emitted by the energy consumed in all processes (from ore mining to final product) to produce one ton of product. It includes the amount of carbon emitted by the energy consumed in the production of raw materials, but it does not include the carbon emissions of energy consumed during transportation. The energy intensity, technical and economic indicators, and data sources of various ACC are shown in Schedule 3 in Supplementary materials. Table 1 shows the brief calculation process of the carbon emission coefficients of all kinds of ACC. For the detailed calculation process, please refer to the section: Calculation method and data sources in the attachment.

The carbon emission coefficients of all kinds of ACC were calculated (Table 2). However, the aluminum material flow of China’s international trades was calculated based on pure aluminum. The carbon emission coefficient of pure aluminum materials was determined by the aluminum content of ACC, as shown in Table 2.

According to Eq. 2, the ACC’s ECEs of China’s international trades were obtained by multiplying the quality of aluminum of ACC by the carbon emission coefficients of pure aluminum.

2.3 Limitations

This study presented a few limitations. First, when the aluminum-containing coefficients of ACC were set, their changes in the time series were not listed. Therefore, an uncertainty analysis on the aluminum content coefficient of ACC in this article was carried out (the uncertainty of data is analyzed in Sect. 2.4). Second, the workload to calculate the comprehensive energy intensity of all ACEP was exceedingly large, and not all data were collected. Therefore, it was assumed that the carbon emission coefficient of pure aluminum in ACEP is equal to the carbon emission coefficient of pure aluminum in SP. This caused the ECEs of ACC to be a conservative value, and the actual value is likely higher. Third, not only the ACEP, but also alumina, UA, and SP have upstream processes. These upstream processes can happen in different countries other than the location where the final process happened, which may lead to underestimating or overestimating research results, but tracing upstream processes of ACCs is hardly to be done. Therefore, assuming all upstream processes take place in the country where the final process is located. Fourth, according to the availability, the data in this study were only updated up to 2017.

2.4 Uncertainty analysis

The data used in this research inevitably contains a certain degree of uncertainty. Therefore, the influence of these uncertainties on the results of China’s aluminum material flows and ECEs was calculated. Monte Carlo simulations that used suitable software package (Crystal Ball software) were performed to quantify uncertainties by repeat random sampling (Zgola 2011).

A specific distribution for each indicator was determined. The data of ACC in international trade was obtained from the UN Comtrade, which is a reasonably reliable and unique data
Table 1 The brief calculation processes of all kinds of ACC’s carbon emission coefficients

| Kinds of ACC | Calculation formula | Explanation and description of calculation formula |
|--------------|---------------------|--------------------------------------------------|
| Bauxite      | $E_1 = (E_{1A} * \theta_1 + E_{1B} * \theta_2) * E_{ce}$ | $E_1$ is the carbon emission coefficient of bauxite; $E_{1A}$ and $E_{1B}$ are the energy intensity of bauxite mined by opencast mining and underground mining, respectively; $E_{ce}$ is the carbon emission coefficient of standard coal; $\theta_1$ and $\theta_2$ are the proportion of bauxite mined in opencast mining and underground mining, respectively. |
| Aluminum concentrate | $E_2 = E_{2A} * E_{ce} + \frac{\omega_1 + \omega_2}{\gamma_1 + \gamma_2} * E_1$ | $E_2$ is the carbon emission coefficient of aluminum concentrate; $E_{2A}$ is the energy intensity of aluminum concentrate; $E_{ce}$ is the carbon emission coefficient of standard coal; $\gamma_1$ is the percentage of Al$_2$O$_3$ content in bauxite; $\gamma_2$ refers to the percentage of Al$_2$O$_3$ content in aluminum concentrate; $\rho_i$ is the recovery ratio of metal in beneficiation process. China’s imported bauxite does not need to be beneficiated. |
| Alumina      | $E_3 = E_{3A} * E_{ce} + \frac{\omega_1 + \omega_2}{\gamma_1 + \gamma_2} * E_2$ | $E_3$ is the carbon emission coefficient of alumina; $E_{3A}$ is the energy intensity of alumina; $E_{ce}$ is the carbon emission coefficient of standard coal; $\gamma_1$ is the percentage of Al$_2$O$_3$ content in aluminum concentrate; $\gamma_2$ is the percentage of Al$_2$O$_3$ content in alumina; $\rho_2$ is the recovery ratio of metal in alumina production process. |
| UA           | $E_4 = E_{4A} * E_{ce} * E_{ce} + \omega_1 * E_3 + \omega_2 * E_4 + \omega_3 * E_4 + \omega_4 * E_5 * \frac{\lambda}{\gamma_1}$ | $E_4$ is the carbon emission coefficient of UA; $E_{4A}$ is the electricity consumption intensity of UA; $E_{ce}$ is the carbon emission coefficient of electricity; $E_3$ is the carbon emission coefficient of standard coal; $\omega_1$, $\omega_2$, $\omega_3$, and $\omega_4$ are the material consumption of alumina, aluminum fluoride, cryolite, and carbon anode for the production of 1 ton of UA, respectively; $E_3$ is the carbon emission coefficient of alumina; $E_4$, $E_5$, and $E_6$ are the carbon emission coefficients of aluminum fluoride, cryolite, and carbon anode. |
| AOS          | $E_5 = E_{5A} * E_{ce}$ | $E_5$ is the carbon emission coefficient of AOS; $E_{5A}$ is the comprehensive energy intensity of AOS; $E_{ce}$ is the carbon emission coefficient of standard coal. |
| Aluminum ingots | $E_6 = E_{6A} * E_{ce} + \frac{E_4 * \lambda + E_5 * (1 - \lambda)}{(1 - \eta_1)}$ | $E_6$ is the carbon emission coefficient of aluminum ingots; $E_{6A}$ is the comprehensive energy intensity of aluminum ingots. $E_{ce}$ is the carbon emission coefficient of standard coal; $E_4$ and $E_5$ are the carbon emission coefficients of UA and AOS; $\eta_1$ is the loss rate of aluminum during the processing of aluminum ingots; $\lambda$ is the proportion of UA output in total aluminum output (UA + AOS). |
| SP           | $E_7 = E_{7A} * E_{ce} + \frac{E_6}{(1 - \eta_2)}$ | $E_7$ is the carbon emission coefficient of SP; $E_{7A}$ is the energy intensity of various types of SP. $E_{ce}$ is the carbon emission coefficient of standard coal; $E_6$ is the carbon emission coefficient of aluminum ingots; $\eta_2$ is the loss rate of aluminum during the processing of SP. |
| ACEP         | — | There are various types of ACEP, including vehicles, machinery, ships, etc. Thousands of ACEP made of SP must have different comprehensive. The workload of calculating the comprehensive of all ACEP is too large, and it is impossible to collect all data. Therefore, it is assumed that the carbon emission coefficient of pure aluminum in ACEP is equal to the carbon emission coefficient of pure aluminum in SP. |
source (http://comtrade.un.org). Accordingly, these data were considered completely reliable. The data of ACC’s aluminum-containing coefficient was obtained from various production standards and previous literature, for which the normal distribution was also recommended (standard deviation was set according to actual conditions and ranged from 5 to 15%). The data to calculate the ECC of ACC was also obtained from various production standards. Therefore, the normal distribution was also recommended (standard deviation was set according to actual conditions and ranged from 5 to 10%). Then, the Monte Carlo simulations were run to produce 10,000 random numbers for each element, based on the input data and distribution.

Finally, China’s aluminum material flows, as well as the maximum, minimum, and standard deviation of these flows, were calculated. The results of the uncertainty analysis are discussed in Sect. 3.5.

3 Results and discussion

The analyzed data and respective calculations were complex. Therefore, to facilitate the presentation of results, all calculation results in this section were calculated according to the mean value of the aluminum-containing coefficient and ECE coefficient ranges for various ACC.

3.1 Aluminum material flows in China international trades

Details of China’s imports and exports of aluminum in ACC from 2008 to 2017 are shown in Figs. 1 and 2. China imports a large amount of alumina and exports a large amount of ACEP and SP every year. The growth of annual imported and exported aluminum material of ACC in China’s international trade from 2008 to 2017 fluctuated. The annual import and export of aluminum material increased from 14.92 and 10.62 Tg in 2008 to 36.18 and 31.48 Tg in 2017, with mean annual growths of approximately 10 and 13%, respectively.

In 2008 to 2017, China’s imported ACC were mainly bauxite (~65%), ACEP (~15%), alumina (~10%), and smaller volumes of UA, AOS, and SP (Fig. 1). At the same time, China’s exported ACC were mainly ACEP (~72%) and SP (~20%), as shown in Fig. 2. The main reason for those exports is the highly developed manufacturing industry of China. The country imported large amounts of raw materials (bauxite) and processes them into SP and ACEP for export.
As shown in Figs. 1 and 2, China’s total aluminum material imports and traded commodity structures of ACC in 2012 were significantly different from the adjacent years. In 2012, the total amount of aluminum in China’s imported ACC was 17.59 Tg, which was considerably
lower than that in 2011 (20.50 Tg) and 2013 (29.31 Tg). The total amount of aluminum in China’s exported ACC was 4.24 Tg, which was also significantly lower than that in 2011.
12.69 Tg) and 2013 (10.76 Tg). Moreover, the proportion of ACEP in the structure of imported ACC decreased sharply from 15.53% in 2011 to 0.27% in 2012. The proportion of ACEP in the structure of exported ACC structure also decreased sharply from 68.32% in 2011 to 15.49% in 2012.

To further explore the reasons for these changes, the trade structure and quantity of imported ACC in 2012 were carefully analyzed. The results show that the quantity of bauxite and four categories of ACEP (automotive tools, stereos/radios, fax machines, manufacturing equipment, and tools) imported by China in 2012 decreased considerably. The main reasons are discussed as follows. First, the implementation of restriction policies on crude ores export in Indonesia in 2012 led to a reduction in China’s bauxite imports from Indonesia, which was an important supplier for the country. Second, in 2012, China’s import and export tariffs were partially adjusted, and import tax rates were introduced for some products, including the provisional tax rate for stereos/radios and fax machines. This is likely the reason for the decrease in the imports of these two types of ACEP. Finally, the manufacturing costs of automotive tools, and manufacturing equipment and tools in developed countries are relatively high. Multinational companies in developed countries are shifting the production of these products to low-cost countries and regions. As China has competitive advantages such as low labor costs, many of those manufacturers established joint ventures or wholly owned factories in China. These manufacturers sell their products directly to mainland China without exporting. Accordingly, since 2012, China’s imports of automotive tools, and manufacturing equipment and tools have gradually decreased. Regarding exports, due to the decrease in bauxite and ACEP imports in 2012, the export of ACEP decreased sharply to satisfy the domestic demand.

The proportion of ACC that China imports from different continents varied over time. In 2008, most ACC imported by China was from Asia (~67%). However, in the following years, the share of imports from other continents increased. In 2017, China imported ACC from Oceania (~26%), Africa (~25%), and Asia (~22%). At the same time, the proportion of ACC exports to different continents remained mostly unchanged. China exports ACC mainly to Asia (~54%), North America (~18%), and Europe (~17%).

### 3.2 ECEs of ACC in international trade

Details of the ECEs of ACC in China’s international trade from 2008 to 2017 are shown in Figs. 3 and 4. The results show that the annual growth of imported and exported ECEs of ACC fluctuated. The annual imported and exported aluminum material increased from 35.11 and 103.36 Tg in 2008 to 126.81 and 312.93 Tg in 2017, with mean annual growth rates of approximately 15 and 13%, respectively.

China’s imported ECEs of ACC are mainly concentrated on ACEP (~57%), alumina (~14%), UA (~12%), and SP (~12%). China’s exported ECEs of ACC are mainly concentrated on ACEP (~68%), SP (~24%), and UA (~6%). The main reasons for these results are the high carbon emission coefficient of pure aluminum in ACEP and high quality of imported and exported ACEP.

As seen in Figs. 3 and 4, China’s total ECEs of imported and exported ACC in 2012 were significantly different from those of adjacent years. In 2012, China’s imported ECEs of ACC mainly included alumina (~33%), UA (~31%), and SP (~24%). Moreover, China’s exported ECEs of ACC were mainly due to SP (~62%), ACEP (~17%), and UA (~16%). The main reasons for such results have been described in detail in Sect. 3.1. In addition, the proportion of
exported ACEP’s ECEs to the total ACC’s ECEs in 2017 increased to 96%, which indicates a significant amount of ACEP’s ECEs exported in 2017.
The proportion of ACC’s ECEs that China imports from different continents varied over time. The majority of ACC’s ECEs imported by China in 2008 was from Asia (~74%). Over
time, China’s imports of ACC’s ECEs from Asia decreased (~36% in 2017), and imports of ACC’s ECEs from other continents increased. From 2008 to 2017, China imported ECEs of ACC from Asia (~63%), Oceania (~17%), and Europe (~12%). At the same time, the proportion of ACC’s ECEs that China exports to all continents remained mostly unchanged. China’s exports of ACC’s ECEs were mainly to Asia (~54%), North America (~18%), and Europe (~17%).

3.3 ECEs of ACEP in international trade

The ECEs of ACEP in China’s international trade in 2017 are shown in Schedules 7 and 8 in Supplementary materials. The ECEs of imported ACEP mainly derive from countries and regions such as the USA, Japan, Germany, and the UK. The ACEP are mainly related to light motor vehicles, medium and large motor truck/trailers, aircraft, manufacturing equipment, and other commodities. At the same time, the ECEs of exported ACEP are mainly concentrated in countries such as the USA, China-Hong Kong SAR, Myanmar, and Japan. These ACEP are mainly associated with medium and large motor truck/trailers, forklift equipment, aircraft, marine vessels, buses and coaches, manufacturing equipment, and other commodities. In general, the ECEs of ACEP in international trade are mainly due to vehicles, manufacturing equipment, aircraft, and other commodities. This focus can be attributed to the fact that high-end ACEP (e.g., vehicles, manufacturing equipment, aircraft) produced in China are not as high in technology as those in developed countries. Therefore, to achieve leapfrog development, narrow the gap with developed countries, and increase overall national strength, high-priced advanced technology commodities should be imported, and internationally mature technologies should be understood and applied to the greatest extent. Then, the mass production of these products for export would depend on China’s manufacturing capacity.

3.4 ECEs of imported and exported ACC share in domestic carbon emissions

The ECEs of China’s imported and exported ACC increased from 35.11 and 103.36 Tg in 2008 to 126.81 and 312.92 Tg in 2017. The ECEs of China’s net exported ACC increased from 68.25 to 186.11 Tg from 2008 to 2017. The share of exported and net exported ACC’s ECEs in domestic carbon emissions (calculated using the principle of producer responsibility) also increased from 1.3 and 0.9% to 2.8 and 1.7% (Table 3).

The above analysis results show that although the ECEs of China’s imported ACC deduct part of the ECEs of China’s exported ACC (about 40.5% in 2017), China’s net exports of ACC contain a large amount of ECEs (about 1.7% in 2017), and they account for an increasing proportion of China’s total carbon emissions (calculated by the producer responsibility principle). Our previous research on the ECEs of ICC also reached a similar conclusion, and the share of net exported ICC’s ECEs in domestic carbon emissions was 3.9% in 2015 (Li et al. 2018). The methods used in this series of studies are the same. The ECEs of the iron element (aluminum element) in the ICC (or ACC) are calculated, and they are distinguished from each other, with no repeated statistical calculations. Therefore, the method used in this study can be used to calculate the ECEs of several common metal resources (iron, aluminum, and copper) commodities, and the conservative (or minimum) value of ECEs can be calculated for all exported metal commodities. This research provides a guide to adjust the foreign trade structure of metal commodities from the perspective of carbon reduction. Moreover, the results are of great significance to determine the carbon emission shares and emission reduction
responsibilities between trading partners, thereby affecting the efforts of countries to address climate change.

### 3.5 Uncertainty analysis results

A box-plot chart of the uncertainty analysis for China’s aluminum material flows in 2017 is shown in Fig. 5, which displays the median, mean, and quartiles (box) values. These data provide a good presentation of the uncertainty for each material flow. The uncertainty range (i.e., height of the box) of aluminum consumption was higher than that of the others, which demonstrates that there was a higher uncertainty in regard to the actual aluminum consumption. In contrast, other materials with lower uncertainties showed relatively flat boxes, which

| Year | Import ACC ECE | Export ACC ECE | Net export ACC ECE | Domestic carbon emissions* | Proportion of export | Proportion of net export |
|------|----------------|----------------|--------------------|---------------------------|---------------------|-------------------------|
| 2008 | 35.1           | 103.4          | 68.2               | 7807.3                    | 1.3%                | 0.9%                    |
| 2009 | 47.2           | 78.5           | 31.3               | 8366.1                    | 0.9%                | 0.4%                    |
| 2010 | 39.7           | 112.4          | 72.6               | 9126.9                    | 1.2%                | 0.8%                    |
| 2011 | 39.0           | 123.9          | 85.0               | 10,026.7                  | 1.2%                | 0.8%                    |
| 2012 | 18.4           | 39.1           | 20.7               | 10,259.1                  | 0.4%                | 0.2%                    |
| 2013 | 40.3           | 104.2          | 64.0               | 10,718.6                  | 1.0%                | 0.6%                    |
| 2014 | 40.9           | 146.9          | 105.9              | 10,836.5                  | 1.4%                | 1.0%                    |
| 2015 | 36.6           | 155.1          | 118.5              | 10,820.8                  | 1.4%                | 1.1%                    |
| 2016 | 29.3           | 154.5          | 125.2              | 10,966.7                  | 1.4%                | 1.1%                    |
| 2017 | 126.8          | 312.9          | 186.1              | 11,087.0                  | 2.8%                | 1.7%                    |

*Data obtained from KNOEMA (ca. 2019)

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Fig. 5 Uncertainty of China’s aluminum material flows in 2017. Upper, lower, and middle lines of the boxes are the third quartile, first quartile, and median of the data, respectively. Ma: maximum value; SD: standard deviation; Mi: minimum value
indicates that their simulation values were concentrated. Overall, the assessment results were considered highly reliable.

In fact, the data source determines the uncertainty of the data and final results. Schedule 10 in Supplementary materials shows the data quality indicators and uncertainty (Huang et al. 2012). Try to use raw data (with sufficient samples, with highly technical, time and geographical representativeness) obtained from field survey or measurement, which can greatly reduce the uncertainty of data and final results.

4 Conclusions and suggestions

4.1 Conclusions

The ECEs of ACC in China’s international trade from 2008 to 2017 was analyzed using MFA based on the international trade between China and other countries. The carbon emission coefficients of China’s imported and exported ACC were also calculated. The conclusions are as follows:

(1) China imported a large amount of alumina and exports a large amount of ACEP and SP. The annual imported and exported aluminum of ACC in China’s international trade from 2008 to 2017 showed a fluctuating growth. The annual imported and exported aluminum increased from 14.92 and 10.62 Tg in 2008 to 36.18 and 31.48 Tg in 2017, respectively. Their mean annual growth rates were approximately 10% and 13%, respectively.

(2) China’s imported and exported ACC’s ECEs are mainly due to ACEP. China’s imported and exported ACEP’s ECEs account for 57% and 68% of ACC’s ECEs, respectively. The growth of annual imported and exported ECEs of ACC in China’s international trade from 2008 to 2017 fluctuated. The annual imported and exported aluminum increased from 35.11 Tg and 126.81 Tg in 2008 to 103.36 Tg and 312.92 Tg in 2017, with mean annual growth rates of approximately 15% and 13%, respectively.

(3) The ECEs of China ACEP imports mainly derive from countries and regions such as the USA, Japan, Germany, and the UK. The ECEs of China’s ACEP exports are mainly concentrated in countries such as the USA, China-Hong Kong SAR, Myanmar, and Japan. The ECEs of ACEP in international trade were mainly due to vehicles, manufacturing equipment, aircraft, and other commodities.

(4) The ECEs of China’s imported and exported ACC increased from 35.11 Tg and 103.36 Tg in 2008 to 126.81 Tg and 312.92 Tg in 2017. The share of exported and net exported ACC’s ECEs in domestic carbon emissions (calculated using the principle of producer responsibility) also increased from 1.3 and 0.9% to 2.8 and 1.7%.

4.2 Policy suggestions

The following policy recommendations are suggested to accurately define all countries’ (especially developing countries such as China) carbon emission responsibilities and actively respond to global climate change:

(1) The principles for dividing cross-border carbon emissions need to change. The producer responsibility principle stipulates that producers are responsible for the carbon emissions generated by products and services produced in their territory (Zhang 2012). This causes a high transfer of carbon emissions from developed to developing countries, which unfairly bear
these carbon emission responsibilities. For instance, China’s exports of ACC contain a large amount of ECEs, and they account for an increasing proportion of China’s total carbon emissions (calculated by the principle of producer responsibility). However, the principle of consumer responsibility can also be unfair to developed countries (Andrew and Forgie 2008), as they would bear all carbon emission responsibilities of imported commodities while spending money on these commodities. Therefore, the Shared Responsibility Principle can be a reasonable carbon emission responsibility allocation method. Some scholars have conducted research on this topic. They applied the global value chain (GVC) decomposition model to measure traded ECEs and trace the carbon emissions throughout a product’s life cycle (Meng et al. 2014). From the GVC perspective, the share of carbon emission responsibility was examined based on value-added trade (Pan 2018).

(2) The development of renewable energy should be accelerated. From the perspective of China’s power structure in 2018 China Electric Power Association (2019), China’s power is mainly composed of thermal power (60.22%), hydropower (18.55%), wind power (9.70%), photovoltaic (9.18%), and nuclear power (2.35%). The carbon emission intensity of thermal power is much greater than that of other renewable energy sources (as shown in Schedule 11 in Supplementary materials). Therefore, the replacement of thermal power by renewable energy will greatly reduce the carbon emission intensity of China’s electricity. The current production of electrolytic aluminum and other processes require a large amount of electricity. If renewable electricity is available, the carbon emission intensity of primary aluminum can also be reduced. Therefore, governments of all countries should encourage and support renewable energy grid-connected power generation to reduce industrial emissions, for example, increasing the installed capacity of wind power and photovoltaic power generation, solving the current difficulties of China’s wind power on-grid and technical problems such as west-to-east power transmission.

(3) The trade structure of commodities should be adjusted. This study observed that China’s ECEs of ACEP in international trade are mainly concentrated on high-end products such as vehicles, manufacturing equipment, and aircraft. Due to China’s strong manufacturing capacity (Chen and Yang 2016), the country exports a large number of high-end products to obtain economic benefits, but these exports cause great environmental pressure. Therefore, the export of such high-ECE commodities should be restricted. Or consider converting the ECEs of ACC into the trade value of ACC based on the price of carbon trading, and use this part of the proceeds to conduct carbon emission reduction research and measures.

(4) Environmental costs should be added to commodity prices and should be used to manage and mitigate greenhouse gas emissions in commodity-exporting countries. At present, many countries already have carbon emissions trading schemes (Anke et al. 2020). However, international uniform carbon emission trading prices should be established, and the ECEs of traded commodities should be converted into environmental costs according to the carbon emissions trading price. Accordingly, those costs can be proportionally added to the price of commodities. Furthermore, commodity exporting countries could use the additional price to better manage their environment to reduce global emissions.

**Abbreviations**  
MFA, Material flow analysis; ECEs, Embodied carbon emissions; ACC, Aluminum-containing commodities; ACEP, Aluminum-containing end products; UA, Unwrought aluminum; SP, Semi-products; AOS, Aluminum old scraps
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Data availability  The data that support the findings of this study are available in the Supplementary materials.

Declarations

Competing interests  The authors declare no competing interests.

References

Andrew R, Forgie V (2008) A three-perspective view of greenhouse gas emission responsibilities in New Zealand. Ecol Econ 68(1–2):194–204
Anke CP, Hobbie H, Schreiber S, Dominik M (2020) Coal phase-outs and carbon prices: interactions between EU-emission trading and national carbon mitigation policies. Energy Policy 144:111647
Binder CR (2007a) From material flow analysis to material flow management Part I: social sciences modeling approaches coupled to MFA. J Clean Prod 15(17):1596–1604
Binder CR (2007b) From material flow analysis to material flow management Part II: the role of structural agent analysis. J Clean Prod 15(17):1605–1617
Chen JW, Chen XS (2011) A preliminary study on China’s long and medium-term strategic goals for reducing carbon emissions (I)—proposal on the reduction targets for 3 phases of implication in China. Sino-global Energy 16(05):1–9
Chen LJ, Yang K (2016) The Sino-Indian Capacity Cooperation under the background of the Belt and Road Initiative. Academic Exploration 10:36–43
Chen G, Hadjikakou M, Wiedmann T (2017) Urban carbon transformations: unravelling spatial and inter-sectoral linkages for key city industries based on multi-region input-output analysis. J Clean Prod 163:224–240
China Electric Power Association (2019) China power industry annual development report
China National Development and Reform Commission (2015) Enhanced actions on climate change: China’s intended nationally determined contributions
Chris B, Matthew JR, Chris K (2015) Developing a multi-scale multi-region input-output model. Econ Syst Res 27(2):172–193
Ding ZL, Duan XN, Ge QS, Zhang ZQ (2009) Control of atmospheric CO2, concentrations by 2050: a calculation on the emission rights of different countries. Sci China Earth Sci 52:1447–1649
Dong YL, Ishikawa M, Liu XB, Wang C (2011) An analysis of the driving forces of CO2 emissions embodied in Japan-China trade. Energy Policy 38(11):6784–6792
Gale LR IV (1995) Trade liberalization and pollution: an input-output study of carbon dioxide emissions in Mexico. Econ Syst Res 7:309–320
Huang N, Wang HT, Fan CD, Zhou SC, Hou P, Yang J (2012) LCA data quality assessment and control based on uncertainty and sensitivity analysis. Acta Sci Circumst 32(6):1529–1536
KNOEMA ca (2019) World Data Atlas. https://cn.knoema.com/atlas%e4%b8%ad%e5%9b%bd%e4%ba%8c%e6%b0%a7%e5%8c%96%e7%a2%b3%e6%8e%92%e6%94%be%e9%87%8f%e5%8d%83%e5%90%88. Accessed 26 June 2020
Lee SJ, Yoo SH (2016) Energy consumption, CO2 emission, and economic growth: evidence from Mexico. Energ Sourc Part B Econo Plann Pol 11:711–717
Li QF (2019) Comprehensive study on material flow, value flow and embodied carbon emissions of iron-containing commodities in China’s international trade. China University of Geosciences, PhD dissertation
Li QF, Wen BJ, Wang GS, Cheng JH, Zhong WQ, Dai T, Liang L, Han ZK (2018) Study on calculation of carbon emission factors and embodied carbon emissions of iron-containing commodities in international trade of China. J Clean Prod 191:119–126
Lin BQ, Sun CW (2010) Evaluating carbon dioxide emissions in international trade of China. Energy Policy 38(1):613–621
Liu YH, Ge QS, He FN, Cheng BB (2008) Countermeasures against international pressure of reducing CO₂ emissions on China’s potential of CO₂ emission reduction. Acta Geograph Sin 7:675–682
Liu XB, Ishikawa M, Wang C, DongYL, Liu WL (2010) Analyses of CO₂ emissions embodied in Japan-China trade. Energy Policy 38(3):1510–1518
Liu QY, Fang K, Cong JH (2019) The spatial-industrial transfer of carbon emissions embodied in inter-provincial trade and the influencing factors for Shanxi province: a MRIO-SDA study. J Environment Econ 4(2):44–57
Lubetsky J, Steiner BA, Lanza R (2006) IPCC guidelines for national greenhouse gas inventories. https://www.ipcc-nggip.iges.or.jp/public/2006gl/. Accessed 26 June 2020
Meng B, Peters GP, Wang Z, Meng L (2014) Tracing CO₂ emissions in global value chains. Energy Econ 73:24–43
Ministry of Ecology and Environment of China (2015). Annual report on China’s policies and actions to address climate change
Ministry of Ecology and Environment of China (2016) Annual report on China’s policies and actions to address climate change
Ministry of Ecology and Environment of China (2017) Annual report on China’s policies and actions to address climate change
Ministry of Ecology and Environment of China (2018) Annual report on China’s policies and actions to address climate change
Ministry of Ecology and Environment of China (2019) Annual report on China’s policies and actions to address climate change
Pan A (2018) Embodied carbon in China-US trade from perspective of global value chain. Statistical Research 35(1):53–64
United Nations (2020) UN Comtrade: International Trade Statistics. http://comtrade.un.org. Accessed 19 June
Wiedmann T, Barrett J (2013) Policy-relevant applications of environmentally extended MRIO databases experiences from the UK. Econ Syst Res 25(3):143–156
William D (2014) Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches. J Assoc Environ Resour Econ 1(1):273–312
Wilting HC, Vringer K (2009) Carbon and land use accounting from a producer’s and a consumer’s perspective—an empirical examination covering the world. Econ Syst Res 21(3):291–310
Wu KY, Yang TG (2016) Global picture and time evolution of international trade carbon transfer. Statistical Research 33(2):43–50
Xie JG, Jiang PS (2014) The measurement and decomposition of embodied energy consumption in China’s import and export trade: based on the input-output model. Economics Quarterly 13(4):1365–1392
Yan YF, Yang LK (2010) China’s foreign trade and climate change: a case study of CO₂ emissions. Energy Policy 38(1):350–356
Yao QH, Han MY, Liu WD (2018) Tracking embodied carbon flows in the Belt and Road regions. Acta Geograph Sin 73(11):2210–2222
Yu XH, Zhan XY (2016) Review of global carbon emission responsibility division principle. Sci Tech Ind 16(5):137–143
Zgola ML (2011) A triage approach to streamline environmental foot printing: a case study for liquid crystal displays. Massachusetts Institute of Technology, Cambridge, MA USA, pp 64–69
Zhang JL (2012) A study on carbon dioxide emission in China’s from consumption perspective. Huazhong University of Science and Technology, Wuhan, China, PhD Dissertation
Zhao YH, Wang S, Yang JQ, Zhang ZH, Liu Y (2016) Input-output analysis of carbon emissions embodied in China-Japan trade. Appl Econ 48(16):1515–1529

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