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Mapping China's copper cycle from 1950–2015: Role of international trade and secondary resources

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ABSTRACT

China's high copper demands and poor mineral endowments have led it to rely heavily on the international copper trade. However, the importance of the metal trade has not been adequately appreciated. This study explores the role of metal trade in copper security through a high-resolution material flow analysis of China's copper cycle from 1950 to 2015 that covers over 300 types of copper-containing products. We found that the annual inflow of copper has increased from 4.3 KT/yr to 14 MMT/yr from 1950 to 2015, which drove the increase of copper stocks accumulated in buildings, infrastructures, and products from 7 kg/cap to 56 kg/cap. The total copper in-use stocks in China were approximately 80 MMT in 2015. However, about 70% of all copper used in China in this period was imported from other nations. Thus, this study indicates that more attention should be paid to the importance of the copper waste trade in China.

1. Introduction

Metal trade is linked to national prosperity and sustainable development (Graedel et al., 2015a), with copper being one of the most pervasive materials owing to its high corrosion resistance, ductility, and good electrical conductivity (Elshkaki et al., 2016). Accordingly, copper plays a critical role in finished products in national defence, telecommunication, electric power, and electronic appliances. In particular, copper has played a critical role in low-carbon technologies and transportation electrification (Elshkaki et al., 2016; Hache et al., 2019). As the largest developing country, China has become the world's largest copper producer and consumer. However, supply security issues associated with copper consumption in China could significantly constrain the sustainable development of China's copper industry, affecting the implementation of a circular economy. Thus, understanding the copper cycle and tracing the increasing number of copper products from mining, in-use, and end-of-life has become critical in China and worldwide.

Mineral resources are not equally distributed in all nations, making mineral security one of the paramount national priorities (Gulley et al., 2018). Net import reliance (NIR) is widely used to measure the risk of a country's exposure to foreign mineral sources. NIR assesses "how much of a country's domestic consumption of a specific commodity is obtained from foreign sources." NIR is applied with limited focus on the mining stage (European Commission, 2014; Graedel et al., 2015b; Nassar et al., 2015); however, few studies have focused on the importance of resource dependence based on the whole life cycle. The whole life cycle indicates the relationship amongst material flow, resource utilisation, and environmental effects in each stage and provides a scientific basis for optimal management of resources and the environment. Difficulties in whole-life cycle assessment include the quantitative analysis of the material inflow and outflow at each stage, mass balance issues, and evaluation of resource security. Anthropogenic material cycle (Chen and Graedel, 2012a) analysis can contribute to filling such gaps for whole-life cycle assessment (Chen and Graedel, 2012b). The anthropogenic material cycle assesses solid material from its extraction to production, fabrication and manufacturing, use, and finally to disposal into waste

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management and recycling. Return flows occur at several stages and make losses to the environment in several different forms.

Material/substance flow analysis (MFA/SFA) is the state-of-the-art quantitative method to trace material flows and stocks within a specific temporal and spatial boundary. A model for regional metal stocks and flows (STAF) was developed by the Industrial Ecology working group at Yale University and applied, for example, to European copper flows (Spatari et al., 2002). Several case studies on copper cycles have been developed at the city (Kral et al., 2014; Zhang et al., 2014a, 2012), country (Chen et al., 2016; Daigo et al., 2009; Gulley et al., 2018; Serenho and Allwood, 2016; Zeltner et al., 1999), and regional levels (Glöser et al., 2013; Soulier et al., 2018a). These studies on the copper cycle can be static (for a point in time) or dynamic (over a time interval) (Chen and Graedel, 2012a). An example of static analysis is the study by Spatari et al. (2005), who analysed copper stocks and flows for 56 countries/ regions in 1994. Dynamic research is preferred because it can provide information on reservoir stocks and the evolution of stocks and flows over time (Chen and Graedel, 2012a). The assessment of historical copper flows from 1945 to 1999, the excellent analysis of copper recycling rates, and the trade of final products are given by (Ruhrberg, 2006).

Those studies provided solid results for analysing the copper cycle on different scales. Nevertheless, few studies have focused on the importance of resource dependence based on the whole life cycle. Trade is necessary for national metabolism, especially for scarce material resources. China has a high external dependence on copper resources, owing to a large copper consumption and poor domestic copper reserves. Reducing China's dependence on copper resources is vital for its sustainable development. However, as a global manufacturer, China also exports a lot of resources and copper-containing products to other countries. The role of trade in such a metabolism has not been explored in detail. Most previous research on national copper MFA focused on the stocks and flows (Soulier et al., 2018b; Spatari et al., 2005, 2002; Vexler et al., 2004; Wang et al., 2015; Wiedenhofer et al., 2015; Zhang et al., 2015, 2014b), and studies involving copper trade mainly considered primary products, semi-products, waste or scrap, without much consideration of high-resolution final products containing copper.

While the analysis of material flows at high product resolution is very valuable, it is rarely done because it requires collecting a large amount of data on copper contained in traded products. Therefore, a high-resolution investigation of the final products' trade flows may fill this gap and support the development of policies or strategies to improve the management of copper flows.

Restrictions for the trade of mineral resources have become intensive worldwide because of concerns for national mineral resources security (Chen and Graedel, 2012a). Because large amounts of solid waste have long been imported, some of which have caused significant environmental and health hazards, the import of copper waste and scrap with a low grade has been prohibited in China, starting in 2020. This indicates that the trade pattern of copper scrap will shift dramatically in the coming years (Ryter et al., 2021). Thus, this study aimed to analyse the development of China's copper cycle and uncover important trading factors in the national economic metabolism from 1950 to 2015. The main goals were to (1) explore how copper flows and stocks in the Chinese socioeconomic system have evolved since 1950, with a particular focus on a high-product resolution; (2) investigate the role of copper products trade in the national economic metabolism; (3) determine the amount of copper resources that have been indirectly exported; (4) use the empirical findings to explore possibilities to increase resource supply security

2. Materials and methods

2.1. System boundary and quantification process

2.1.1. System boundary

Fig. 1 presents the framework of this study, including the system boundary and key processes of China's copper cycle, which is divided into five process steps: material production, semi-products fabrication, products manufacturing, products final in-use, and waste management (details can be found in the *Supporting Information*). In this study, the geographic boundary for our analysis was limited to mainland China, and the copper flows and stocks (all in copper content) were quantified annually from 1950–2015. The trade flows of over 300 copper-containing products from all five stages were traced from 1978 to 2015. The amount of copper trade before the establishment of China's open-door policy in 1978 was considered to be negligible. This study follows the standard dynamic material flow analysis (Chen and Graedel, 2012a; Müller et al., 2014) to quantify copper flows and stocks within China's geographic boundary, and the key producers are described as follows:

2.1.2. Quantification process and data source

(1) Production flows. There are two production routes in the production of copper, including ore-based primary production and scrap-based secondary production route. First, under the mass balance principle, the inflow, outflow, losses, and trade from the material production Eqs. (1) and (2), semi-products fabrication, products manufacturing, and waste management stage were quantified, the details of which are described in the *Supporting Information.*

$$F_{\mathrm{rc}} = F_{\mathrm{rc1}} + F_{\mathrm{rc2}} \tag{1}$$

$$F_{\mathrm{rc1}} = P_{Ore} + \sum_{j=1}^{3}\left(F^{1,\mathrm{j}}_{import} - F^{1,\mathrm{j}}_{export} - L_{1,\mathrm{j}}\right) \tag{2}$$

Where F_{rc} is refined copper flowing into the fabrication stage; $\mathrm{F_{rc1}}$ and $\mathrm{F_{rc2}}$ are primary and secondary refined copper, respectively; and P_{ore} is domestic copper ore production. $F^{1,\mathrm{j}}_{import}$ and $F^{1,\mathrm{j}}_{export}$ refer to the weight/ quantity of copper contained in product j; j= 1–3 represents copper concentrate, blister copper, and refined copper through import and export, respectively. $L_{1,\mathrm{j}}$ refers to the losses of copper in mining, smelting, and refining. *Frc2 can be obtained directly from the statistical yearbook or calculated (SI Table S6).*

In Eq. 3, F_s refers to the semi-products flowing into the manufacturing stage:

$$F_{\mathrm{s}} = F_{rc} + \sum_{j=1}^{3}\left(F^{2,\mathrm{j}}_{import} - F^{2,\mathrm{j}}_{export} - L_{2,\mathrm{j}}\right) - RS + NS \tag{3}$$

$F^{2,\mathrm{j}}_{import}$ and $F^{2,\mathrm{j}}_{export}$ refer to the weight/quantity of copper contained in fabrication in product j; j= 1–11 represents semi-products of copper from rolling, extrusions, and others through import and export, respectively. $L_{2,\mathrm{j}}$ refers to the losses of copper in rolling, extrusions, and others. NS refers to the new scrap produced by the manufacturing process and returned to the fabrication process. RS refers to the recycled slag returned to the smelting stage.

After the end-of-life scrap flows (F_{scrap}) into the waste management stage, a part of old scrap flow returns to secondary production W_p and the manufacturing stage W_m. W_s is the sum of W_p and W_m. Additionally, copper may be lost to the environment (dissipation) or abandoned in place and non-collectable for practical purposes (e.g., many subterranean cables). Although both (dissipation and abandonment) are potentially reversible copper losses, they are currently considered dead ends.

Data source: production of copper-containing products and loss rate of each stage was obtained from the USGS (USGS, 2015) and China Non-ferrous Metals Industry yearbook of 2015(China Non-ferrous

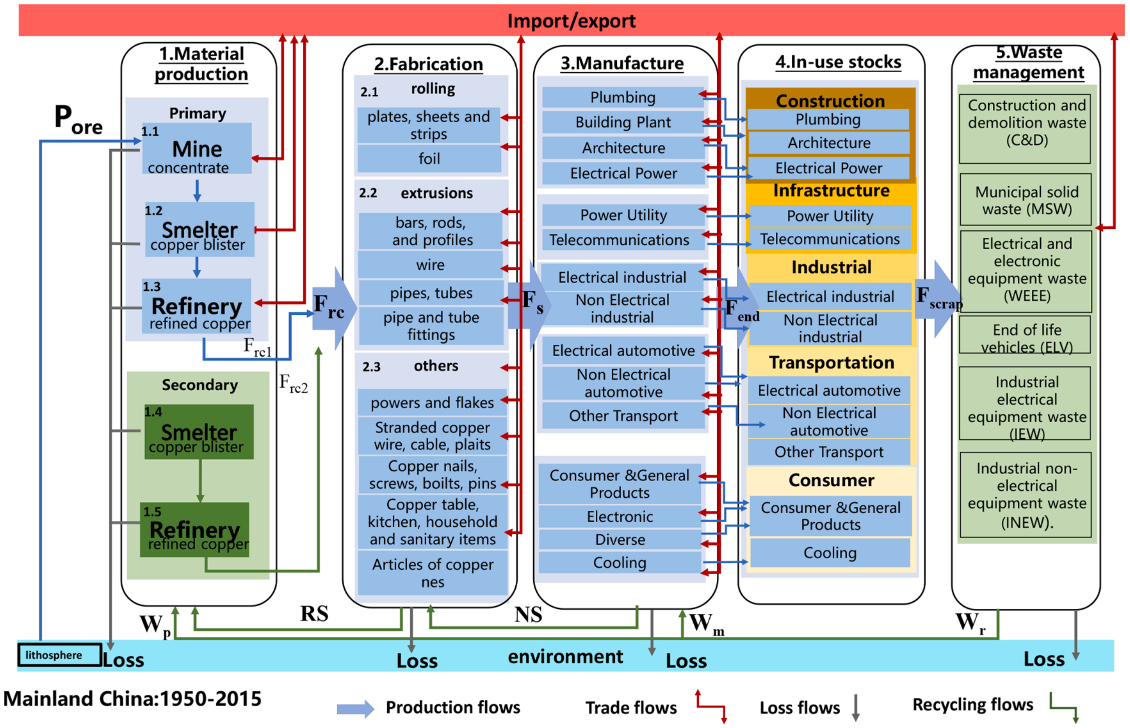

Fig. 1. Framework of copper stocks and flows quantification in China. Processes are indicated with black rounded rectangle boxes; the light blue arrows show the flows of each process; red arrows represent the trade flows; copper secondary production and recycled copper flows are shown in green; all the losses are shown as the light grey arrows.

Metals Industry Association, 2015). Before 1990, the historical data was compiled from the China Non-ferrous Metals Industry (The Committee of China Non-ferrous Metals Industry Yearbook, 1993). Trade data stems from two sources: data before 1992 is from the historical data compilation of the China Non-ferrous Metals Industry, while data for 1992–2015 is from the UN Comtrade Database (UN Comtrade, 2014). Copper content and the HS 92 commodity codes are given in detail in the S.I.

(2) In-use stocks. We applied the bottom-up approach for quantifying copper in-use stocks in China from 1950 to 2015. Approximately 75 copper-containing products were collected and classified into 12 sectors: plumbing, architecture, electrical power, power utility, telecommunications, electrical use, non-electrical use, electrical automotive, non-electrical automotive, other transportation, consumer products, and cooling. The linkage among products and sectors can be found in the S.I. The copper in-use stock for each product i from 1 to 75 can be estimated using the following equation (Zhang, 2015):

$$S(t) = \sum_{i} N_i(t) \times m_i(t) \tag{4}$$

Where S(t) is the cumulative in-use stocks for copper-containing products in year t; $N_i(t)$ is the volume of in-use products obtained from the National Bureau of Statistics of China; and $m_i(t)$ is the copper intensity of each product summarised in Table S1 of S.I and was measured by experts and from the literature (Zhang, 2015). the 12 categories of final products can be further classified into five end-use sectors, shown in Fig. 1: Building & Construction, Infrastructure, Industrial, Transportation, and Consumer. The categories used in the calculation of the copper in-use stocks in China are identified based on previous research(Rauch, 2007; van Beers, 2007).

Data source: copper containing products in-use stocks were directly measured from the National Bureau of Statistics of China, 1949–2016.

(3) Waste flows. Similar to most dynamic MFA studies Chen & Graedel, 2012; Müller et al., 2014), the outflows from societal use ($outF_i(t)$), in this case copper scrap (F_{scrap}), were quantified through the stock driven model and lifetime distribution approach: Quantification of the inflows to Societal use F_{end} and the outflows $F_{scrap}$by Stock driven model (Eqs. 5 and (6), relevant process reference (3) waste flows.

$$inF_i(t) = S_i(t) - S_i(t-1) + outF_i(t) \tag{5}$$

$$F_{scrap}(i,t) = \sum_{k=1}^{b} F_{end}(i,t-k) \times L(t-k, \mu_i, \sigma_i) \tag{6}$$

Where $S_i(t)$ and $S_i(t-1)$ represents the cumulative in-use stocks for the copper-containing product i in year t and $t-1$, respectively; $inF_i(t)$ refers to the inflows to societal use. F_{end} is the inflow of product i (in copper content) to the in-use stage, which is also the final copper demand of China. $L(t-k, \mu_i, \sigma_i)$ is the product lifetime equation, for which Normal and Weibull distributions were widely applied (Pauliuk et al., 2013;; Spatari et al., 2005). Normal distribution was chosen for this study because it is straightforward and easy to conduct (Melo, 1999;; Spatari et al., 2005). The mean lifetime μ for each product category can be found in Table S5. The waste flows were categorised into five groups: construction and demolition waste (C&D), municipal solid waste (MSW), electrical and electronic equipment waste (WEEE), end of life vehicles (ELV), industrial electrical equipment waste (IEW), and industrial non-electrical equipment waste (INEW).

(4) Trade flows. The quantification of international trade for more than 400 copper-containing products, including copper concentrate, copper waste, three types of copper blister, four types of refined copper products, 21 types of semi-products, and 357 types of final products, was primarily based on the United Nations Commodity Trade Database (U.N. Comtrade) (UN Comtrade, 2014). For detailed customs code and copper content, refer to the *Supporting Information*. The trade data of copper-containing products in U.N. Comtrade is reported by individual countries with physical and monetary values. In addition, the trade value of imports and exports is often inconsistent in these two countries reports. As a matter of convenience and unification, we used the maximum value of different reports as the trade value between countries.

2.2. National trade dependence measurement

By quantifying how much of a country's domestic consumption of whole-life stage copper-containing products is obtained from foreign sources, NIR indicators provide insights into that country's exposure to a potential supply disruption from foreign sources. This study calculated NIR for each stage of copper's whole life cycle to identify the status of foreign reliance on China's copper resources. Detailed data can be found in *Supporting Information Tables S1–S3, and S5*.

Here, we calculated the NIR of the total and six processes of copper's life cycle. The six processes included mining, smelting, refining, fabrication, manufacturing, and waste management, which correspond to copper concentrate, copper blister, refined copper, semi-products, and final products. The calculation of copper-containing product NIR consists of the net import of copper product divided by the apparent copper consumption. We calculated the NIR of each process i in year t, which is represented by the following equation:

$$NIR_{i,t} = \frac{I_{i,t} - E_{i,t}}{P_{i,t} + I_{i,t} - E_{i,t}} \tag{7}$$

Where $I_{i,t}$ represents imports from other countries of the process i in year t; $E_{i,t}$ represents China's exports to other countries of the process i in year t; $P_{i,t}$ represents China's domestic production of process i in year t.

Note that each copper-containing product's H.S. Codes (Harmonized System) are relevant for the import and export data analysis using the U.N. Comtrade database. Except for final and waste copper products, the other production of copper-containing products is available from China's nonferrous metals statistical yearbook from 1949 to 2015. The amount of final and waste copper product production was calculated using the stock-driven model described in Section 2.1.

3. Results

3.1. China's domestic copper production and consumption

To support the expansion of China's urbanisation and industrialisation, approximately 168 MMT (million tons, as shown in Fig. 2) of copper have been consumed in China, of which 130 MMT were imported from other countries. In comparison, only 38 MMT have been derived from domestic sources. The cumulative amount of international trade of copper-containing products (primary, intermediate, final, and waste products) between China and other countries reached over 180 MMT from 1950 to 2015, of which the imports occupied 130 MMT, while exports occupied 50 MMT. Moreover, there has been a continuously rising trend of copper consumption in China, with an annual growth rate of 120,000 tons/year. This resulted in a strong growth of in-use stocks of copper, which increased from 5 MMT in 1950 to 80 MMT in 2015. In 2015, the most significant part of in-use copper stocks was in infrastructures (59.6%), followed by buildings (25.8%). The cumulative stocks and flows from 1950 to 2015 are shown in Fig. 2, and several critical features related to China's copper whole life cycle can be summarised as follows:

(1) High copper demand with limited domestic copper resources in China. The scale of domestic raw copper mining production grew from 5 kt to 1710 kt from 1950 to 2015, with an overall growth of more than 340 times. However, the cumulative copper ore extracted in China was only about 30 MMT, which could not meet domestic copper demand. The amount of refined copper production increased from 0.29 MMT in 1950 to 7.99 MMT in 2015, with an average annual growth rate of 13%, and the cumulative consumption of semi-products (rolled, extruded, and other products) reached 114 MMT. Excluding the domestic supply, the imported refined copper products still account for 31% of the total refined copper production.

The per capita demand for copper in-use stocks rose from 7 kg in 1950 to 56 kg in 2015 (growth rate: 3% per year) (Fig. 3a). If Chinese

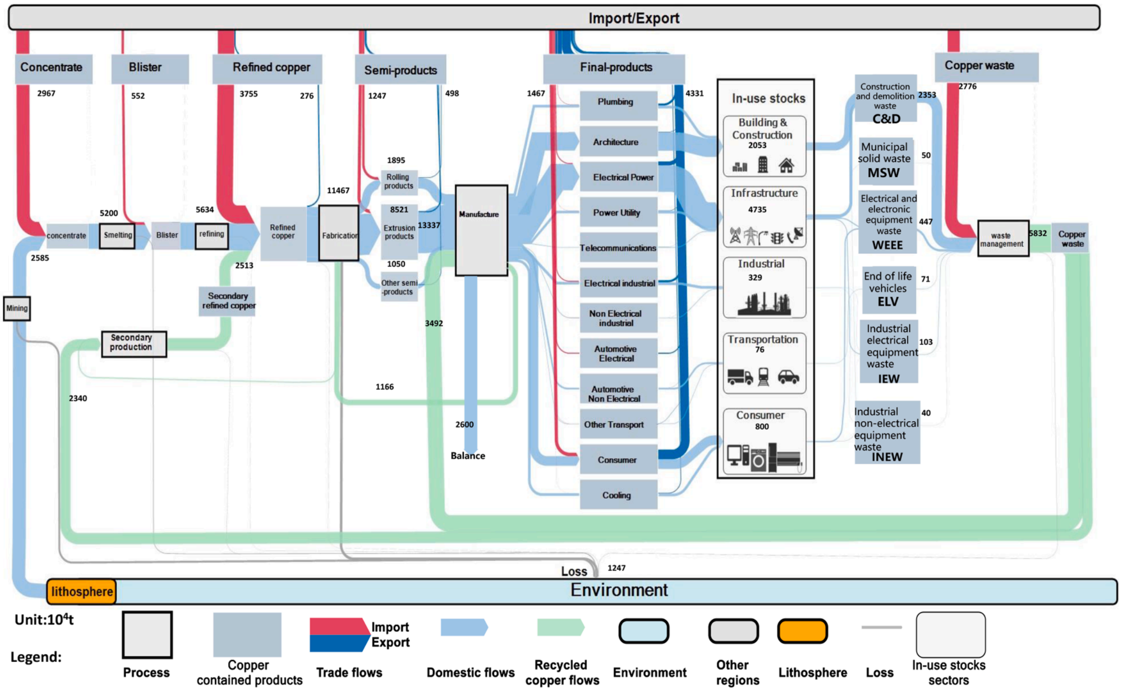

Fig. 2. Historical cumulative copper stocks and flows from 1950 to 2015. The orange line represents the domestic production input of each stage; the red line represents the import flow; the dark blue line represents the export flows; the light grey line represents the losses of each process; the green line represents the post-consumer copper scrap. Additionally, the value of flows into the in-use stocks was calculated using the bottom-up method. NOTE: the balance-item of 26 MMT shown in Fig. 2 results from two methods to calculate the value flowing into the manufacturing stage: top-down is 168 million tons, while bottom-up is 142 million tons, with an error of 26 million tons. In this study, we used the bottom-up results for discussion and analysis.

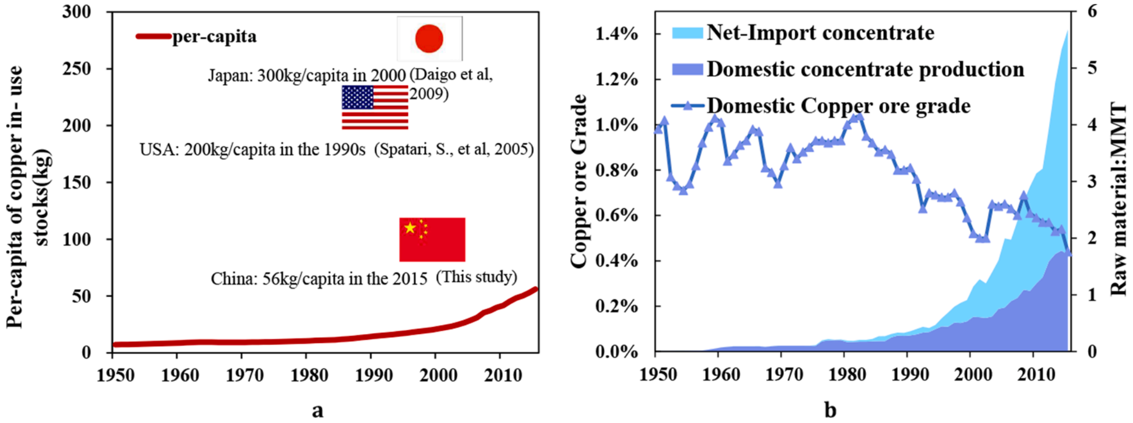

Fig 3. Copper life cycle in China from demand and supply perspectives. *a) Copper in-use stocks per capita in China from* 1950 to 2015, and comparison with developed countries; b) Copper raw materials production and copper ore grade from 1950 to 2015 in China.

copper stocks continue growing as in the past decade (see Fig. 3a), this is likely to drive copper extraction in China and worldwide. Notably, Chinese geological copper reserves are estimated to be 27 MMT (18% of the total future stock needs). This highlights the intensifying dependence of China on overseas copper resources and the urgency for efficient material use and recycling systems.

(2) Efficient use of materials in China's domestic copper production. The volume of recycled copper inputs showed a continuously growing trend and reached 2.2 MMT in 2015, accounting for 35% and 21% of the total production of refined copper and semi-products, respectively (Fig. 2). From 1950 to 2015, only 12 MMT of copper or 7% of the total copper inflow were lost during the entire lifecycle. Most of the loss flows were generated as tailings, slags, powder, or dross in the production stage, mainly in mining (34%), smelting (12%), refining

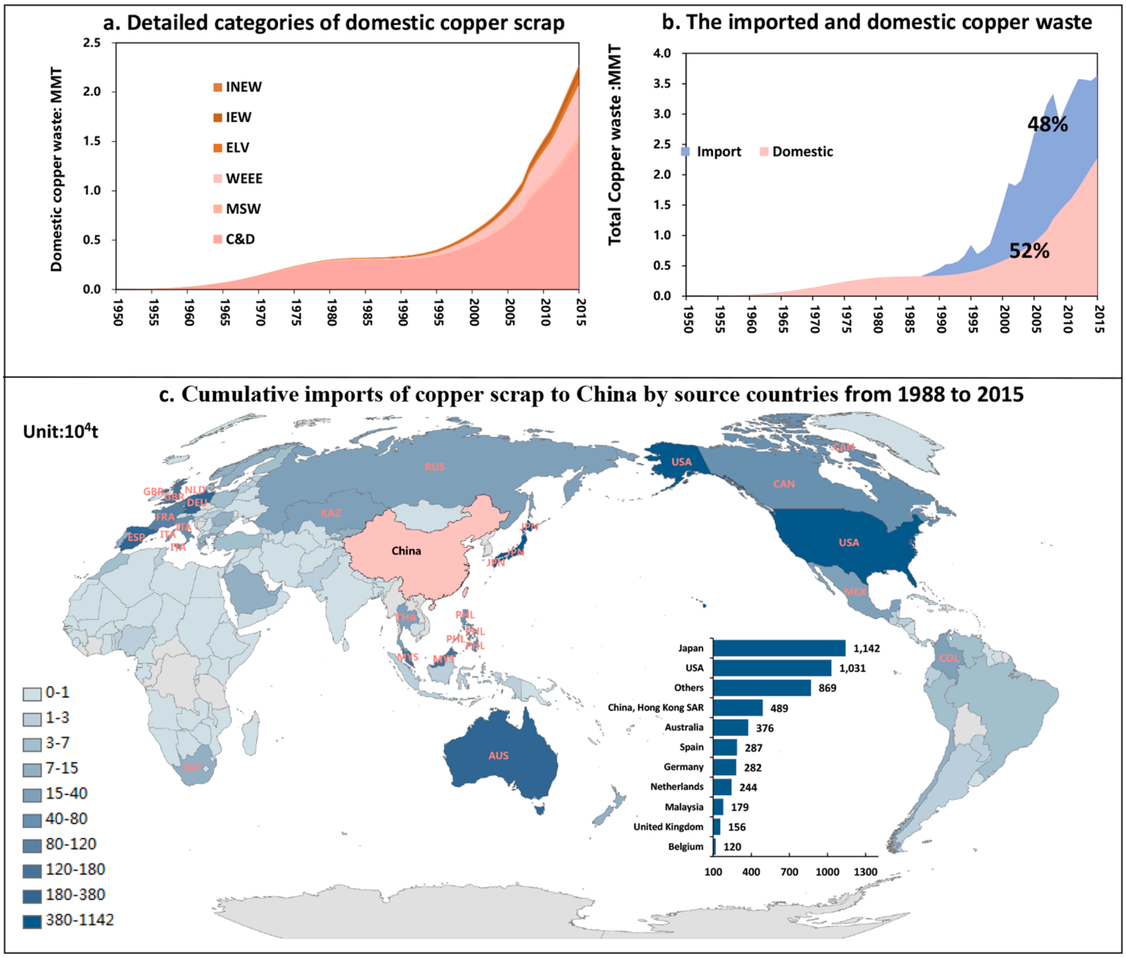

Fig. 4. The evolution of China's copper waste generation and old copper scrap. *a) Detailed categories of domestic copper* scrap. Abbreviation note: Construction and demolition waste (C&D), Municipal solid waste (MSW), Electrical and electronic equipment waste (WEEE), End of life vehicles (ELV), Industrial electrical equipment waste (IEW), Industrial non-electrical equipment waste (INEW). b) Imported and domestic copper scrap. The percentage shown in the figure is the accumulation from 1988 to 2015(UN Comtrade Database 2015). c) Cumulative imports of copper scrap to China by source countries from 1988 to 2015.

(3%), extruding (7%), rolling (32%), and others (4%). Notably, the copper loss in the end-of-life stage was mainly landfilled and decapitated to the environment, and the accumulated loss reached 830,000 tons. Nevertheless, the resource losses in the end-of-life stage only accounted for 7%, mainly because of the high recycling rate (90%) of copper in China. Most of those old scraps (65%) return to re-manufacturing, with the rest turning to re-smelting as secondary production. The low losses and the high recycling rate indicate that copper is used rather efficiently in China. Because of the high-value and easy-recycling properties of copper scrap, the production of China's refined copper increased from 0.29 MMT in 1950 to 7.99 MMT in 2015, with an average annual growth rate of 13%, amongst which the output of refined recycled copper accounted for approximately 35% of the total refined production. The total production of refined copper from recycled metal increased from 7600 tons in 1950 to 2.3 MMT in 2015, with an annual growth rate of 9% in China.

(3) Growing waste generation and old copper scrap. As a global manufacturer, approximately 150 MMT of the final copper products were produced in China from 1992 to 2015. As shown in Fig. 2, the infrastructure sector has always been the essential end-use sector for copper, accounting for more than 60% of copper consumption, followed by the Building & Construction (21 MMT) and Consumer sectors (8 MMT). With the increasing domestic copper consumption, copper scrap generation has increased synchronously. The total old scrap increased from 2800 tons in 1950 to 2.3 MMT in 2015, with an annual growth rate of 11% in China (Fig. 4a). In total, around 31 MMT of old scrap has been generated from the in-use stocks in the past 65 years. This study allocated the old scrap into six specific waste streams (Soulier et al., 2018a): C&D (23 MMT, 77%), MSW (0.5 MMT, 2%),WEEE (4.5 MMT, 15%), ELV (0.71 MMT, 2%), IEW (1 MMT, 3%), and INEW (0.4 MMT, 1%). C&D accounts for the largest proportion of old scrap, amongst which the subsystem with the most scrap is architecture (residential and non-residential buildings) (16 MMT, 53%) (Fig. 4a). This is mainly due to China's rapid growth in population and economy. Owing to the growing construction of infrastructure and buildings since the 1990s in China, the proportion of copper scrap in the construction sector is larger than in other sectors, accounting for 34% of the total copper scrap of construction and demolition waste (C&D). In addition to domestically generated old scrap, imported scrap is another major source of secondary copper production, with cumulative copper scrap from 1950 to 2015 accounting for 48% of the total scrap supply (Fig. 4b). Notably, the ratio of imported to total scrap use increased from 10% to peaks of 58% in 2001 and 2005 and since declined to 30% in 2015. The peak value was mainly due to China's exemption of value-added tax on copper scrap enterprises in the same period and the reduction of import tariff on copper scrap from 1.5% to 0. In contrast, the main reason for the decline in the import of copper scrap is that China issued the policy of abolishing the value-added tax exemption on waste materials in January 2009.

3.2. *High import dependence on the global copper market*

Generally, the total cumulative imports of copper-containing products are more than 80% of China's total copper consumption in the same period. This indicates that the high import dependence on foreign copper resources underpins China's copper metabolism. Insight into the international trade flows of copper-containing products and detailed characteristics of the evolution, composition, and partners of China's copper trade pattern from 1950 to 2015 are discussed in this section.

(1) Evolution of net import reliance. The net import reliance (NIR) of China's copper showed a continuous growth trend from 1990 to 2015 (Fig. 5) and peaked in 2013 (83%). In addition, the NIR of each stage of the copper life cycle shows substantial heterogeneity as follows: 1) Synchronised with the NIR of copper's whole life cycle, the NIR of concentrate and refined copper have increased significantly from 1990 to 2015, driven by the boosting copper industry capacity and domestic consumption. The NIR of concentrate rose from 1990 to 2015 and reached 80% in 2015. Meanwhile, the NIR of refined copper showed a fluctuating growth trend from 1992 and reached approximately 60% in 2008, then fluctuated around 40%. 2) The NIR of waste copper rose to a peak of 60% in 2005, then fell to 30% in 2015, of which blister was

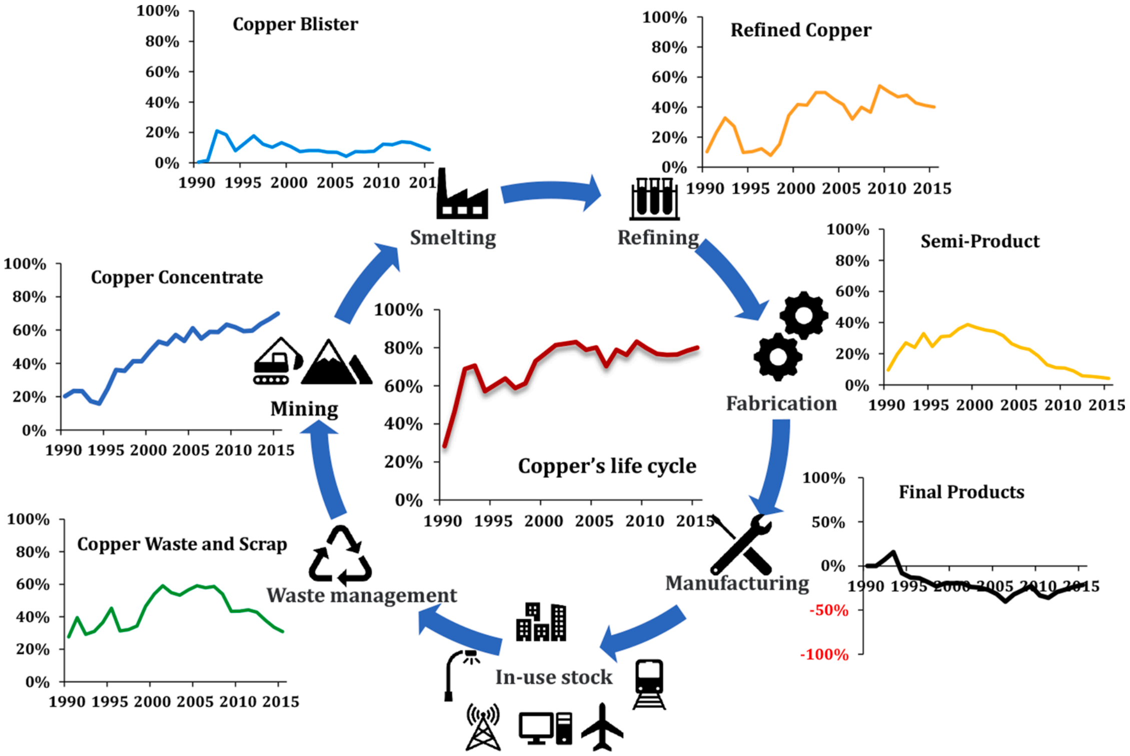

Fig 5. External dependence of copper-containing products along with copper's whole life cycle. *(Note:% values refer to the NIR, positive values refer to net imports, and negative values to net exports).*

always less than 20%. 3) The NIR of semi-product and final products have declined annually. Moreover, China shifted from a net importer to a net exporter of final products because nearly half of the final products are exported to other countries. Generally, China is a net importer of copper resources, and with the continuous growth of the economy, the net import of copper has continued to grow, reaching 7 MMT in 2015. However, copper resources are imported as primary products and semi-products. amongst them, copper concentrate, refined copper, and copper scrap are the main copper products imported by China.

(2) Composition of China's copper trade. On the import side, copper resources are imported as primary products and semi-products. amongst them, copper concentrate (26%), refined copper (32%), and copper scrap (31%) are the major copper products imported by China. From 1990 to 2015, China imported over 74 million tons of copper waste and scrap, representing more than half of the world's total exports (Fig. 6). On the export side, final products account for 85% of the total export of copper resources. More than one-fifth of China's copper resources (approximately 40 MMT from 1990 to 2015) have been exported, with approximately 50% as consumer products. China's top ten copper-containing products are cables, pipe parts, refined copper foil, vehicles, metal locks, other electrical conductors, metal hooks, strip staples, and various padlocks. Still, most of the final product flows were domestically "consumed" (accumulated as the in-use product stocks).

(3) Trade partners of China's copper-containing products. China's trade partners for copper-containing products encompassed 183 countries from 1990 to 2015 (HS92 code) (Fig. 7). The source countries of Chinese imports for copper-containing products are Chile, Japan, the United States, Australia, and Peru, with total import amounts of 30 MMT, 9.5 MMT, 8.8 MMT, 7 MMT, and 5.9 MMT, respectively. Chile is China's largest exporter, providing China with 99% of the import of primary copper products (copper concentrate, blister, refined copper), and China's imports of primary copper products from Chile account for more than 35% of total global imports. Japan is in second place and exports roughly 5 MMT, followed by the United States. As the largest importer of copper scrap, China's imported copper scrap mainly comes from developed countries like the United States, Japan, the UK, and Australia (Fig. 4C).

The top five destinations of Chinese exports for copper-containing products are the United States, Hong Kong SAR, Rep. of Korea, Japan, and Taiwan region, with total import amounts of 10 MMT, 7 MMT, 4 MMT, 3 MMT, and 2 MMT, respectively. The United States is the largest importer of China's copper-containing products, with 95% being final products. The second-largest importer is Hong Kong SAR, which serves as a trading hub and indirectly exports China's copper-containing products from mainland China to other regions. The remaining export destinations of copper-containing products are mainly Asian countries, such as Rep. of Korea and Japan.

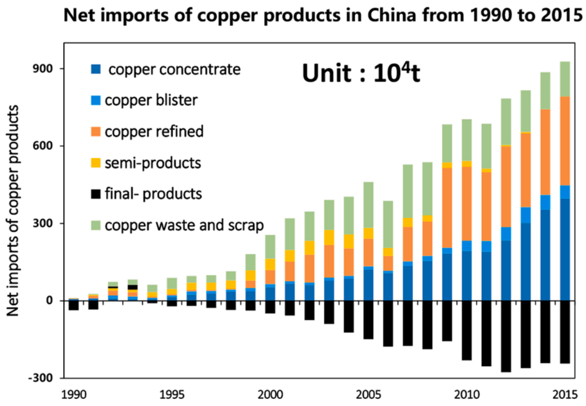

Fig. 6. Composition of China's copper trade.

4. Discussion

From the supply perspective, our study indicates that imported copper scraps have significantly contributed to China's copper industry. Compared to domestic copper scrap, imported copper scrap is collected and recycled easily, as it has been classified, screened, and dismantled in depth. International copper scrap accounts for more than half of China's copper scrap consumption, which deserves to be considered an important supplementary source of copper raw materials. Copper ore and copper waste are both raw materials for copper smelting. China's copper ore reserves are small, and the grade is declining yearly. Compared with copper waste, the grade of copper ore is much lower, which makes domestic mining more complex, and the resulting environmental pollution is difficult to repair. Thus, the import ban of copper scrap that the Chinese government announced in 2018 has raised concerns about the security of copper raw materials in the short term.

Despite the strong growth of in-use copper stocks, the per capita level of stocks in China is with 56 kg in 2015 still low compared to developed countries (e.g., 200 kg/capita in the USA in the 1990s or 300 kg/capita in Japan in 2000, as shown in Fig. 4a). This gap and the historical trend of stock growth in China indicate that copper stocks in China will likely continue to grow. In order to reach a level of per capita stocks of 200 kg by 2060, China would require 200 million tons of copper resources to reach a similar level by 2060, which represents 25% of the world's copper reserves. The amount of copper scrap generated in China will increase rapidly as in-use stocks reach retirement age. Therefore, a significant contribution can be made to China's copper resource supply if the copper scrap is effectively collected and recycled. However, as China's demand for copper resources is rising continuously, a significant proportion of copper resources is still dependent on imports. This highlights that enhancing copper's recovery rate should be emphasised to secure resources.

From the consumption perspective, the high-resolution investigation of China's copper flows revealed that China dominates the global copper market. The copper resource trade accounts for 50% of the world's copper consumption and has become a significant factor affecting global copper demand. Before the 1990s, most raw materials were obtained from domestic mining activities. Later, China began importing raw materials for refined copper production, including copper concentrate, blister, and waste or scrap, which account for 70% of the refined copper consumption, to fill the increasing copper demand gap. China's leading role began in 2001 when it joined the WTO, and its copper import has ranked first in the world since then. In 2017, China consumed 40% of the world's copper resources. Imports of copper-containing products enable China's copper consumption, and such high dependence on international trade is becoming a pressing challenge to its resource security.

Thus, this study makes the following recommendations: 1) Regarding the imported copper scrap, the Chinese government should resolutely ban the import of low-quality waste but appropriately import higher-quality copper scrap. It should also support research institutes and enterprises to improve the research on environmental and health impact assessment to quantitatively evaluate the overall cost, benefits, and risks of scrap trade on resource efficiency, environment, and economy. In addition, detailed customs data on solid waste trade should be publicised, helping to support more effective and well-founded industrial policies for scrap trade. 2) Regarding domestic copper scrap, enhancing copper's sustainable use is significant. Thus, there is an urgent need for policymakers to focus on the waste system construction, such as clarifying the type and quantity of copper scrap and its main distribution, identifying the recycling rate of each waste product as well as the processing technology, and improving the utilisation rate of copper scrap flow into the manufacturing process (direct use of copper scrap).

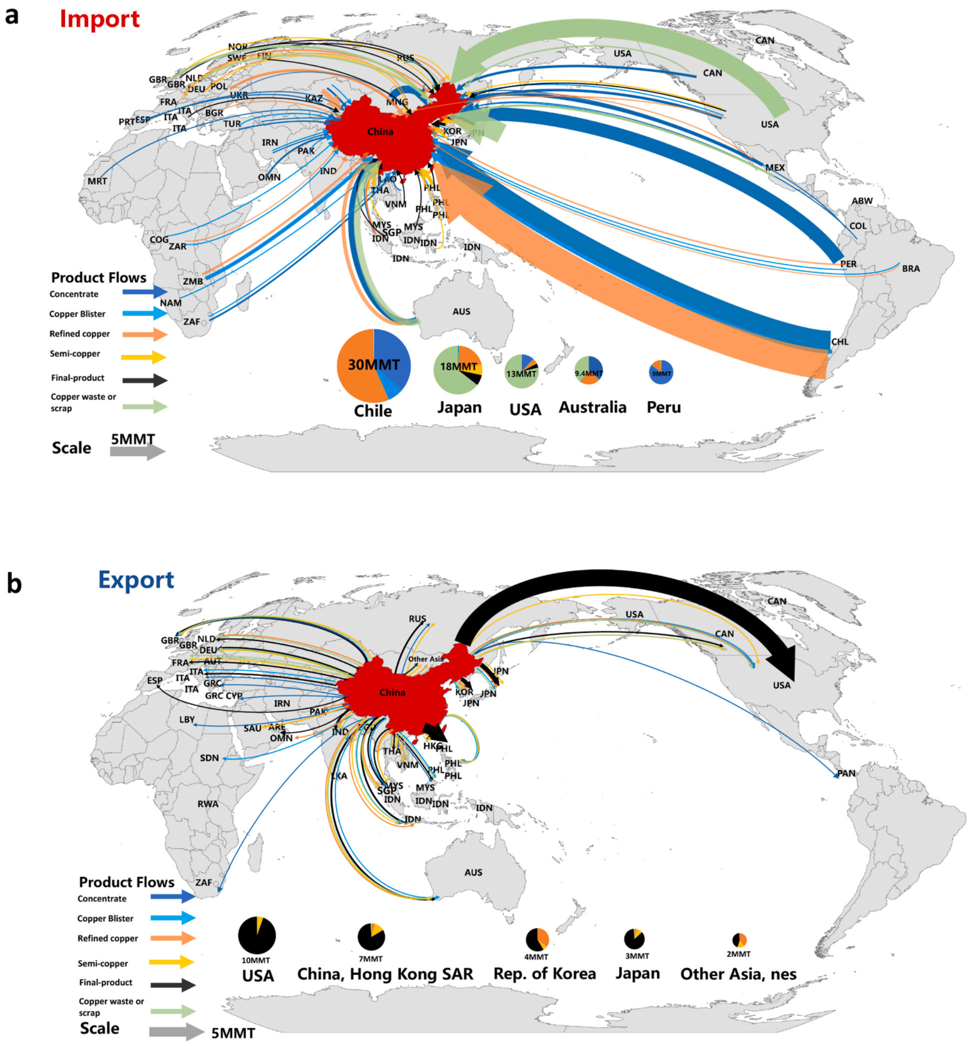

Fig. 7. Trade pattern of copper-containing products and cumulative trade flows from 1990 to 2015. (a) Import; (b) Export.

5. Limitations

Because data sources and product classification are based on statistical data and references, it is inevitable to have limitations, mainly reflected in the following aspects: (1) Data limitations. Information on the production of copper-containing products and their copper content was not available for all products and had to be estimated for some products based on expert information and literature. We have identified the types and quantities of final products that China trades with the world, but we have not distinguished which countries trade with China in this part. (2) Model limitations. The complete copper cycle can be quantified through the apparent consumption, stock-driven and lifetime models, and mass-balance principle triggered by the in-use stock. Each parameter will impact the results. (3) Limitations of the study area. As the world's largest developing country, the issue of the Chinese copper cycle is crucial to understanding global copper metabolism. Hence, we have first chosen China as the research scope in this paper. However, the role of other developing countries, such as Chile and Brazil, in the global copper cycle should not be overlooked. Based on the above limitations, we will focus on the following aspects in future research: first, a more detailed analysis of the trade of copper products needs to be performed, especially with a wide variety of final products. We must identify the form in which China's copper resources are exported to other countries. Second, the significant impact on the copper metabolism patterns of other countries after the ban is fully implemented on copper scrap must be assessed. Thirdly, a study on the copper ore, semi-products, final -products, and waste footprint of Chinese domestic and international trade needs to be performed. Finally, the global resource trade must be considered by modelling the copper metabolism of each country, which is of great significance for the sustainable utilisation of copper resources in human society.

6. Conclusions

With a dynamic material cycle analysis, this study conducts a high-resolution investigation of China's copper stocks and flows in China from 1950 to 2015. This study helps to uncover the importance of international trade of copper-containing products in national copper metabolism, seek solutions for eliminating the external dependence on copper resources, and realise the sustainable development of copper resources. The framework and information presented in this paper can form the basis for future work in the field of material flow analysis for other critical materials. Key conclusions are summarised as follows:

Firstly, our study indicates that international copper scraps have significantly contributed to China's copper industry. Especially international copper scrap accounts for more than half of China's copper scrap consumption, which should be considered an important supplementary source of copper raw materials. Thus, there is an urgent need for China to resolutely ban the import of waste with lower quality but appropriately import copper scrap of higher quality.

Secondly, our study speculates that the accumulation of copper in in-use stocks in China will likely continue to increase in the future; while domestic EoL waste will increase with ageing stocks, domestic secondary copper resources cannot meet the growing demand for copper. Even if there is no import of copper scrap based on the copper cycle in Chinese metabolism, the resource gap of this part will be transferred to the import of copper primary products. However, China's waste management system of copper is far from recycling EOL copper efficiently, which highlights the need for policymakers to build an effective recycling system and improve the utilisation rate of copper scrap flow into the manufacturing process.

Finally, the high-resolution investigation of China's copper flows reveals that China dominates the global copper market, and the copper resource trade accounts for 50% of the world's copper consumption and has become a significant factor affecting global copper demand. Furthermore, China's copper consumption is enabled by imports of copper-containing products, and such high dependence on international trade is becoming a pressing challenge to its resource security. China is the largest recipient of copper scrap in the world. Chinese government and enterprises should be fully prepared to deal with the ban's impact. It is suggested to actively participate in constructing the global copper recycling system and continuously improve the domestic copper waste recycling system.

CRediT authorship contribution statement

Min Hao: Writing – original draft, Methodology, Software. **Linbin Tang:** Writing – original draft, Conceptualization, Visualization. **Peng Wang:** Conceptualization, Writing – review & editing, Supervision. **Heming Wang:** Writing – review & editing. **Qiao-Chu Wang:** Writing – review & editing. **Tao Dai:** Writing – review & editing. **Wei-Qiang Chen:** Writing – review & editing, Supervision.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106700.

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