Emission impacts of supply chain disruptions for COVID and China's solid waste import ban

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| Citation       | Ryter, John et al. “Emission impacts of supply chain disruptions for COVID and China’s solid waste import ban.” Under review in Nature Portfolio (2021): dx.doi.org/10.21203/rs.3.rs-86991/v1. © 2021 The Author(s) |
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| As Published   | http://dx.doi.org/10.21203/rs.3.rs-86991/v1                                                                                                                                                           |
| Publisher      | Research Square                                                                                                                                                                                     |
| Version        | Final published version                                                                                                                                                                             |
| Citable link   | https://hdl.handle.net/1721.1/131052                                                                                                                                                                 |
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Climate change will increase the frequency and severity of supply chain disruptions and large-scale economic crises, also prompting environmentally protective local policies. Here we use econometric time series analysis, inventory-driven price formation, dynamic material flow analysis, and life cycle assessment to model each copper supply chain actor’s response to China’s solid waste import ban and the COVID-19 pandemic. We demonstrate that the economic changes associated with China’s solid waste import ban increase primary refining within China, offsetting the environmental benefits of decreased copper scrap refining and generating a cumulative increase in CO₂-equivalent emissions of up to 13 Mt by 2040. Increasing China’s refined copper imports reverses this trend, decreasing CO₂e emissions in China (up to 180 Mt by 2040) and globally (up to 20 Mt). We test sensitivity to supply chain disruptions using GDP, mining, and refining shocks associated with the COVID-19 pandemic, showing the results translate onto disruption effects.
The transition toward a zero-carbon society is coupled with increasing electrification, prompting projections that demand for copper, the third most-consumed metal, will increase by >300% and consume ~2.5% of the world’s energy by 2050, with greater increases under more equitable global development scenarios. At the same time, copper ore grades continue to decline and extraction operations are increasingly concentrated in low-income regions with decreased enforcement of best practices. These regions are also expected to experience the most intense effects of climate change, and copper resources in particular are concentrated in areas of high water scarcity risk. These conflicting issues necessitate an integrated assessment of the copper material system and further emphasize the need for recycling and other resource efficiency principles in this supply chain.

In an effort to address air pollution and limit soil and water toxicity while maintaining economic progress, China has implemented resource efficiency policies centering the circular economy as a national development strategy. While much of this legislation has garnered broad international support and improved local health outcomes, China’s Green Fence (2013) and National Sword (2017) policies, which restrict nearly all solid waste imports, have also caused disruption across a variety of supply chains and led to increased landfiling and buildup of recyclables in high-income, waste-exporting countries. Chinese companies facing consequent scrap supply shortages have reinvested in recycling facilities throughout Southeast Asia, Australia, and the United States, indicating a redistribution of scrap processing environmental impacts.

Studies to date have emphasized the ban’s impact on plastic waste streams, primarily addressing geographical redistribution, increased landfiling, and environmental impacts. Several authors have shown that China’s domestic secondary copper supply is insufficient to meet its increasing metals demand, where Zeng et al., Wang et al., and Dong et al. explicitly account for changes in scrap imports. With prior studies relying on top-down material flow analyses limited to China and primarily addressing potential scrap availability changes, a significant research gap remains in understanding global supply chain reactions stemming from the solid waste import ban, the resulting environmental impacts, and mechanisms for maximizing environmental benefits in China and globally. We demonstrate that the solid waste import ban causes increased primary refining and copper concentrate imports within China to account for refineries’ loss of secondary material, generating effects throughout the material system that produce increasing environmental impacts both in China and globally.

The coronavirus disease 2019 (COVID-19) pandemic has introduced a supply chain shock alongside the solid waste import ban. Macroeconomic effects have decreased global copper demand, while recent outbreaks have increased death among miners and halted production at some of the world’s largest copper mines, reduced refinery production, and limited scrap trade. Simultaneous demand rebound in China is expected to produce supply deficits and price increases in 2021. Relevant recent studies have addressed pandemic effects at the macroeconomic level, emphasizing short-term effects, and have been unable to comment on medium- to long-term impacts on individual supply chains, the impacts of combined supply–demand (SD) shocks, or external policy resilience to these shocks.

This study uses econometric time series analysis, inventory-driven price formation, dynamic material flow analysis (dMFA), and life cycle assessment (LCA) to estimate copper supply chain and environmental impact evolution under differing regional policy change and global economic shock scenarios. The model architecture (Fig. 1) differentiates supply chain behavior between China and the rest of the world (RoW) and considers differences in scrap composition, availability, and price in those two regions. We estimate the evolution of cathode and scrap prices, refinery processing fees (treatment and refining charges (TCRC)), and production and consumption of copper scrap, concentrate, and refined material through 2040, primarily reporting results as cumulative departure from baseline. The explicit modeling of mine-level opening, closing, and capacity utilization (CU) decisions; the economic modeling accounting for cascading effects throughout the copper supply chain; and the cost-driven optimization model determining scrap consumption changes between China and RoW highlight the contributions this methodology makes to material supply chain modeling.

Results
Current impacts of the China solid waste import ban. China’s major recent solid waste legislation includes the Green Fence action in 2013, the National Sword policy at the beginning of 2017, and the Implementation Plan on Banning Entry of Foreign Garbage and Reforming the Administrative System of Solid Waste Importation in July 2017. Recent policies affecting copper scrap include the announcement of the ban on Category 7 copper scrap in May 2017 and the imposition of tariffs on US copper scrap imports in August 2018. The ban on Category 7 copper scrap was implemented in December 2018 alongside the announcement of additional restrictions on Category 6 copper scrap imports, set to begin June 2019. These policies have produced a redistribution of copper scrap trade and compositional changes in China’s scrap imports (Fig. 2a). The gross weight of China’s copper imports has declined over the past several years, with a corresponding increase in copper fraction producing a near-constant copper content by mass. These data reflect the success of China’s policy goal of decreasing low-grade scrap imports and processing and coincide with the redistribution of global scrap trade and processing.

According to industry experts, Rep. of Korea, India, Germany, Taiwan, Belgium, Malaysia, Canada, and Vietnam have begun importing the majority of this newly available low-grade scrap, with some fraction simply being upgraded and re-exported to China (Supplementary Tables 9 and 10). This behavior is particularly evident in Rep. of Korea, Taiwan, Malaysia, Canada, and Indonesia; these regions have dramatically increased both copper scrap exports to China and copper scrap imports (Fig. 2b). Simultaneously, the fraction of US gross weight copper scrap exports going to China fell from 68 to 10% from 2017 to 2019, while the fraction of EU copper scrap exports to China fell from 29 to 15% in the same period. While the copper fraction of China’s copper scrap imports nearly doubled from 2017 to 2019, within Indonesia, India, and Malaysia this value decreased 10, 15, and 39%, respectively, indicating more contaminated scrap streams. For the remaining nations listed above, the copper fraction of copper scrap imports changed no more than 5% over this period.

Future impacts of the China solid waste import ban. We simulate projected import restrictions for cases where scrap with less than 94 or 99% copper content would not be permitted for import. Such restrictions would eliminate imports of alloyed scrap grades, No.2 scrap, or both, with <99% copper content restricted and only No.1 copper scrap (Institute of Scrap Recycling Industries (ISRI) grade Barley) permitted to enter China. We analyze scrap import reductions of 50% year over year for each category with ±25% as sensitivity while other imports remain constant (Fig. 3a). Following China’s reclassification of copper scrap to recycled copper or brass solid waste material on
July 1, 2020, the No.2 ban scenario approximates reality; industry experts predict free trade of high-quality recycled copper and brass raw materials and consequent policy stability in the near future. We provide additional granularity surrounding the No.2 scrap ban scenario.

In an effort to highlight relative changes, results are presented as the cumulative departure from the baseline scenario as a percentage of the projected 2020 value for that parameter; absolute responses (in thousand metric tonnes) may be found in Supplementary Figs. 5–7. The solid waste import ban shifts scrap availability from China to RoW, increasing prices in China and decreasing prices for RoW, prompting a redistribution of primary and secondary refining production (Fig. 3b). Due to time delays and differing magnitudes of scrap availability shifts, the decrease in RoW primary refining and increase in RoW secondary refining lag the opposing responses in China, producing a global increase...
in primary refining production and decrease in secondary refining production (Fig. 3d). Increasing scrap demand in RoW is unable to offset the increasing prices and decreasing demand in China, generating a net decrease in global scrap demand. Resulting changes in cathode price are insufficient to drive a significant departure from baseline and the small increases in mining and primary refining production are erased by market corrections by 2040. While scrap consumption appears approximately linear as a function of scrap quantity restricted, the No.2 ban generates a larger system response than the ban on alloyed scraps for refining, mining, and CO₂ emission responses (Fig. 3e).

Global parameters either decrease or remain effectively unchanged relative to baseline by 2040, leading to the expectation of negligible changes in environmental impacts. However, the redistribution of primary and secondary refining between China and RoW, coupled with higher unit impacts of China’s primary refining, produces an increase in global CO₂-e emissions of 13 Mt, or 6.1% of current annual emissions due to copper production (Fig. 3c). This result corresponds with a 29% (25 Mt, 12% of global) increase in CO₂-e emissions from copper within China, equivalent to the annual CO₂ emissions of 5.4 million gasoline vehicles. Without the significant decarbonization of China’s electricity grid predicted by the U.S. Energy Information Administration’s reference case35, global emissions increase by as much as 35 Mt by 2040. This large emissions increase is the result of increased primary refining production, while the decreases in scrap use and fabrication account for the smaller contributions toward decreasing emissions (Fig. 3f).

Increasing primary refining production requires increased concentrate imports—determined endogenously—due to limited domestic copper ore bodies, continuing the present logistic growth trend (Supplementary Fig. 3).

All 12 environmental impact indicators considered in this study follow trends similar to the CO₂-e emission response (Supplementary Figs. 8 and 9). Given the pollution reduction goal of China’s solid waste policies, smog-, respiratory-, and human toxicity-related emissions are of particular importance and these results show 34% (5.5 Mt O₃ eq), 53% (450 kt PM2.5 eq), and 44% (1.2 million comparative human toxicity units (MCTUh)) increases above the baseline 2020 value within China. Without further action, economic responses to this policy will produce unintended negative environmental consequences.

Responding to the China solid waste import ban. Higher Chinese refined copper imports may mitigate the effects of the scrap ban and take advantage of the newly available scrap available outside China and correspond with some of China’s foreign investment strategies to date8,14,15,36. We increase or decrease China’s refined copper imports at rates of 100 or 200 kt/year (Fig. 4a) coincident with the No.2 scrap ban. We assumed that China would not begin exporting refined copper and the minimum value was set to zero. We show that increasing China’s refined copper imports redistributes both primary and secondary refining production from China to RoW by shifting regional refined copper demand (Fig. 4c). Globally, this shift enables better use of displaced scrap material (cumulative 10% of 2020 value,
1.0 Mt), resulting in increased secondary refining (6.4%, 1.3 Mt), decreased primary refining (6.3%, 1.3 Mt), and decreased mining production (5.9%, 1.2 Mt; Fig. 4b). This global decrease in primary refining and mining production (Fig. 4b), coupled with the redistribution of refining from China to RoW (Fig. 4c), enables a cumulative global reduction in CO\textsubscript{2}e emissions equal to 9% of 2020 copper production emissions. This value exceeds that of the mining reduction alone due to the differences in unit environmental impacts of refining within China and the global average. Within China, CO\textsubscript{2}e emissions decrease a cumulative 210% (180 Mt or 87% of global) of the estimated 2020 emissions in China by 2040, smog-related emissions decrease 215% (34 Mt O\textsubscript{3} eq.), respiratory-related emissions decrease 250% (2.1 Mt PM2.5 eq.), and human toxicity-related emissions decrease 220% (6 MCTUh). These values assume significant decarbonization of global electrical grids in the baseline scenario, particularly in China. Given their dependence on the relative unit impacts of primary and secondary refining in and outside of China, emission reductions relative to baseline are greater still if China’s carbon intensity of electricity remains high or RoW implements similarly ambitious decarbonization.

Decreasing China’s refined copper imports represents a continuation of the 2015–2018 trend, while increasing imports represents the case where China acts to redistribute primary refining activities outside its borders alongside scrap refining activities. Further decreasing China’s refined copper imports exacerbates the negative effects of the scrap ban by causing China to increase refining further still, while reversing that trend produces environmental benefits both within China and globally. Increasing China’s refined copper imports does, however, increase environmental impacts for RoW. While much of the redistribution to date has been to regions with reduced environmental regulations, these localized impacts can be minimized if smelting and refining investment prioritizes regions and technologies with better environmental practices and electrical grid emissions intensities. The relative inelasticity of total refining production, the nearly equal and opposite changes in global mining production, and scrap consumption stemming from increasing China’s refined copper imports indicate a market-stable transition in the direction of a circular economy and at minimum lower unit emissions for the copper material system (Fig. 4b).

**Sensitivity to supply chain disruptions.** To understand how these policies evolve in the face of future climate- and social unrest-induced supply chain disruptions, we simulate the impact of major system shocks using production and consumption changes stemming from the COVID-19 pandemic. We use 2019–2021 gross domestic product (GDP) changes from the International Monetary Fund (IMF; Fig. 5a) and calculate copper demand endogenously from GDP per capita evolution (Fig. 5b). We account for operational discontinuities by adjusting mine Cu, refinery CU, and refinery secondary ratio (SR; the fraction of secondary material used in secondary refineries) for 2020 according to data from the International Copper Study Group (ICSG). We use mean year over year changes from the first 5 months of 2019 and 2020 ±50%, producing large, moderate,
and small responses for each of these four parameters. The annual timescale of this model necessitates that evolution of copper price and other market indicators begins in 2021, the year following the shock. Nonetheless, the near-term evolution of the demand, primary and secondary refining production, mine production, and cathode price align well with projections from Roskill, ICSG, S&P Global, and GlobalData. See Supplementary Methods: Near-term system response to COVID-19 shocks.

In testing supply chain resilience to such shocks, we found a reduction in cumulative total refining production (Fig. 5c), indicating that post-shock recovery effects may not sufficiently compensate for short-term production disruption. Demand rebound prompts a period of high copper cathode prices, incentivizing mining and primary refining production at the expense of scrap consumption and secondary refining production (Fig. 5c). China exhibits a more muted CO₂e emission response due to its more limited GDP growth reductions and low fraction of global mining production, with the bulk of China and RoW declines attributable to manufacturing contraction (Fig. 5d). Among small GDP shocks, incorporating larger mine and refinery shocks generates CO₂e emission reductions equivalent to those of large GDP shocks (Fig. 5e). Further analysis has shown that these reductions stem from the SR shock specifically (Supplementary Figs. 14 and 15). This shock produces an increase in primary refining production, leading to a copper concentrate supply deficit, mine overproduction, and eventually a price collapse that promotes mine closure and delays mine concentration. For secondary refining, GDP changes produce near-equal violin plots and here the data are grouped by the three levels of refinery shock instead, with the color bars representing changes in mine and GDP/capita shocks. Underlying data for this figure may be found in a data repository https://doi.org/10.6084/m9.figshare.14390489.v3.
emissions increase 22–36 Mt (10–12% of global 2020 value, 24–29% of China 2020 value) relative to the supply chain shock-centered scenarios, overlapping the 25 Mt increase in the no-shock scenarios above. Relative to baseline, mean emissions in China increase by up to 0.8–26 Mt. These results indicate that, within China, the environmental benefits stemming from these supply chain disruptions are insufficient to offset the increasing emissions resulting from the solid waste import ban even for the largest economic and trade disruptions.

When refined copper import changes are coincident with the solid waste import ban and supply chain disruptions, we again observe a redistribution of primary and secondary refining. These changes result in decreased primary refining and mining production, increased secondary refining and scrap consumption, and near-constant total refining production indicating a decrease in copper system unit impacts amid business-as-usual demand growth following the shock. For a large increase in China’s refined copper imports (+200 kt/year), mean global CO₂e emissions decrease a cumulative 22–29 Mt (10–13% of 2020 value) relative to supply chain shocks alone (compared with 20 Mt decrease without supply chain shocks above), or 33–81 Mt relative to baseline, doubling even the largest shock-induced emission reductions. These impact reductions are concentrated within China, with China’s cumulative CO₂e emissions decreasing ∼190 Mt (90% of global 2020 value, 210% of China 2020 value) relative to supply chain shocks alone or 180–210 Mt relative to baseline (39–46 million vehicles).

For both the scrap and refined copper import policies explored here, their modeled impacts manifest as an approximately additive effect when combined with the supply chain disruption scenarios. The modeled responses therefore remain valid for large-scale supply chain shocks, including those that vary in regional severity, given that the GDP per capita shock is more intense in RoW than in China. Large supply chain shocks such as those associated with the COVID-19 pandemic may partially mask the environmental impacts associated with the solid waste import ban, but it will not erase them, and a redistribution of primary refining activity to RoW remains a viable mechanism for mitigating these effects. Under circumstances where these shocks produce additional restrictions on environmentally harmful industries26, environmental impact reductions beyond those shown here may occur.

Discussion
China’s solid waste import ban has induced a shift in the location of scrap processing, with Malaysia and other Southeast Asian nations accounting for the majority of recent scrap processing investment (Fig. 2b). With the bulk of scrap being upgraded and re-exported to China, it is clear that these nations are not benefiting from the efficient allocation of raw materials typically ascribed to the free trade of solid waste40. While economy-scale analyses provide evidence for the environmental Kuznets curve—that per-capita emissions follow an inverted U-shaped trajectory as per-capita income increases—accounting for trade has been shown to produce a linearly increasing curve instead41. These results, in combination with the estimated future impacts of the solid waste import ban, provide the first system-level evidence supporting these conclusions. When increasing China’s refined copper imports, ∼80% of the emissions reduction within China is redistributed to RoW, generating a net global decrease in emissions due to economic effects and lower unit impacts in RoW. This value is consequently dependent on the relative environmental impacts of industrial activities for each trade partner, explicitly demonstrating that individual nations’ environmental impact reductions may be directly accomplished via burden shifting. To maximize the benefits of this burden shifting, new refineries must be constructed with best available technologies in place and located within low-emission electricity grids.

Zeng et al.20, Dong et al.23, Eheliyagoda42, Liu et al.17, and Wang et al.31 show that China’s domestic copper scrap generation cannot meet its increasing raw material demand and we confirm these results. We also demonstrate that the solid waste import ban results in increased primary refining and concentrate imports within China to account for refineries’ loss of secondary material, generating effects throughout the material system that produce increasing environmental impacts. The solid waste import ban’s impacts on scrap availability, and consequently regional prices, drive a redistribution of primary refining from RoW to China and of secondary refining from China to RoW. Even as China’s scrap- and manufacturing-related emissions decrease, increasing primary refining production offsets these benefits (Fig. 3f) and generates a net increase in environmental impacts by 2040 across all impact categories considered in this study, both in China and globally (Fig. 3e). The RoW response rate keeps the reallocation of refining activities from being even proportioned, and secondary refining is projected to decrease globally. The RoW must act quickly to limit this redistribution and develop low-impact secondary processing and refining capacity such that the environmental impacts of the copper supply chain do not increase further still.

Increasing China’s refined copper imports acts to mitigate these effects and capitalizes on the newly available scrap outside China (Fig. 4b), mirroring some of China’s current foreign investment strategies8,14,15,36. The nearly equal and opposite resulting changes in global mining production and scrap consumption indicate a market-stable transition toward a circular economy and lower unit emissions for the copper material system. Given their compositional similarities and that this study includes smelting within refining processes, model results would be similar for increased imports of copper blister, anode, or fabricated products. Potential mechanisms for increasing imports of these materials therefore include limiting China’s concentrate imports below 10 Mt (see Supplementary Fig. 3) and increasing China’s refined copper imports above 2018 levels. To limit the adverse environmental impacts of the solid waste import ban, China could prioritize investment in increasing domestic scrap collection and the implementation of refining and fabrication technologies with best available techniques.

Our analysis of global economic and supply chain shocks shows that the long-term environmental impacts of the solid waste import ban and refined copper import policies remain valid even with disruptions in mining and refining production. Elevated sensitivity exists for changes in GDP growth and refinery SR, where GDP growth shocks dominate at high values. We also show that the impacts of policies such as the China solid waste import ban and increasing China’s refined copper imports translate approximately linearly onto such shocks, indicating the results of these policies are robust in the face of supply chain disruption. Additionally, we observe that, because mines respond to longer-term market trends, primary production is more robust to these supply chain shocks than secondary production. The resulting decline in secondary demand indicates that further emission reductions could be enabled by implementing policies supporting the recovery of secondary markets.

Future research surrounding regional differences in refinery and scrap price behavior, scrap import–export compositions, future copper mining production, and mine opening and closing behavior would address model assumptions and reduce the associated uncertainty. Additional geographical granularity would permit a coincident increase in the degree of localization accessible to the model, both in terms of policies and associated...
Table 1 Scenario descriptions.

| Scenario                             | Description                                                                 |
|--------------------------------------|-----------------------------------------------------------------------------|
| Future impacts of the China solid    | Alloacted scrap ban                                                        |
| waste import ban                     | Alloacted scraps are barred from import to China, leading to 25, 50, or 75% |
|                                      | declines in alloacted scrap imports relative to the previous year, starting |
|                                      | in 2019. No.1 and No.2 copper scrap imports remain constant. Decline of 50% |
|                                      | year over year was selected as the mean ban rate, with 25 and 75% included  |
|                                      | as sensitivities                                                             |
| No.2 scrap ban                       | Scraps requiring refining are barred from import to China, leading to 25, 50, |
|                                      | or 75% declines in No.2 scrap imports relative to the previous year, starting |
|                                      | in 2019. No.1 and alloyed copper scrap imports remain constant. Decline of 50% |
|                                      | year over year was selected as the mean ban rate, with 25 and 75% included  |
|                                      | as sensitivities                                                             |
| <99% Cu scrap ban                    | Alloacted scraps and scrap requiring refining are barred from import to China, |
|                                      | leading to 25, 50, or 75% declines relative to the previous year, for all scrap |
|                                      | imports except No.1 copper scrap, starting in 2019. No.1 scrap imports remain |
|                                      | constant. Decline of 50% year over year was selected as the mean ban rate,   |
|                                      | with 25 and 75% included as sensitivities                                     |
| Responding to the China solid        | Change in China’s refined copper imports                                    |
| waste import ban                     | China’s refined copper imports change by −200, −100, 0, 100, 200kt/year     |
|                                      | relative to the prior year’s value, starting in 2019. We assume China does   |
|                                      | not become a net exporter of refined copper and negative refined import values |
|                                      | are not permitted. In scenarios without refined copper import changes, China’ |
|                                      | s refined copper imports remain constant at the 2018 level                  |
| Sensitivity to supply chain          | GDP/capita reduction                                                         |
| disruptions                           | Due to the economic disruption associated with COVID-19, changes in GDP/     |
|                                      | capita relative to the prior year were evaluated in line with Fig. 5a, where  |
|                                      | the global reduction from 2019 to 2020 was 2, 4, 6%, increasing 2.35, 4.7,  |
|                                      | 7.05% from 2020 to 2021. Mean changes were −4 and 4.7% for 2019-2020 and   |
|                                      | 2020-2021, respectively. All years beyond 2021 use baseline GDP/capita      |
|                                      | evolution                                                                   |
| Refinery shock                        | Due to factory closures and shipping restrictions associated with COVID-19,  |
|                                      | two simultaneous changes in refinery operation occurred, respectively. First,  |
|                                      | refinery capacity utilization was reduced by 114, 2,29, 3.93% for 2019–2020,  |
|                                      | with mean value 2.29%. Second, shipping restrictions reduced scrap use,      |
|                                      | causing refinery secondary ratios to decrease 3.46, 6.93, 10.4% for 2019–2020, |
|                                      | with 6.93% used as mean. Both these shocks are implemented simultaneously    |
|                                      | except in Supplementary Fig. 15, where the secondary ratio shock was removed |
|                                      | to highlight result dependence on this component of the refinery shock over  |
|                                      | the capacity utilization reduction. For 2021 onward, and the rest of the      |
|                                      | simulation, these parameters were not constrained and evolve in accordance    |
|                                      | with the model                                                               |
| Mine supply shock                     | Due to the suspension of mining operations due to COVID-19 outbreaks,       |
|                                      | mining capacity utilization decreased 1.31, 2.62, 3.93% globally, with mean  |
|                                      | 2.62%. For 2021 onward, mine capacity utilization changes were not            |
|                                      | constrained and evolve in accordance with the model                         |

| Unalloyed scrap grades include No.1 and No.2 copper scrap, while alloyed scrap grades include yellow brass, leaded yellow brass, red brass, leaded yellow brass, cartridge, manganese bronze, nickel silver, ocean, aluminum bronze, tin bronze, and leaded tin bronze. |

Environmental impacts. Alternative environmental impact reduction strategies may be explored as scenarios, including carbon pricing, minimum recycled content policies, and material lifetime extension. The regional aspect of this model enables comparison of local and global variations on such policy, further informing the benefit of global efforts toward emission reduction.

Methods

Trade data. Import data for each country were obtained from UN Comtrade using HS commodity code 7404, “copper; waste and scrap.”45 We subtracted exports from imports to calculate net imports for each region and its trade partners, using individual trade partners for China and the global sum for all other countries. Copper content values were calculated using the reported monetary value of the trade and year average London Metal Exchange (LME) copper cathode price. We considered changes in net import copper content from 2017 to 2018 and from 2018 to 2019, selecting countries with 2017–2018 changes of >300 tonnes, excluding those with unavailable 2018–2019 data with the exception of Taiwan. Monthly China copper scrap import data for Fig. 2a were obtained from Big Trade Data (www.bigtradedata.com), with copper content calculated using the monetary value of trade and the monthly LME copper cathode price.

Scenarios and scenario implementation. To evaluate the future impacts of the China solid waste import ban, methods for response, and sensitivities to supply chain disruptions such as COVID-19, several exogenous and endogenous model parameters were constrained. In the absence of scrap and refined import policy changes, China’s scrap and refined copper imports were held constant at the 2018 values, with scrap imports broken into 14 categories representing the most common ISRI post-consumer scrap grades as described below. The scrap import distribution among these categories was assumed equivalent to that of old scrap generation in RoW in that year. In the absence of COVID-19-related shocks, GDP/capita changes proceed according to IMF projections made prior to any COVID-19 outbreaks, while refinery and mining operations evolve according to their relevant elasticities. Scenario definitions are given in Table 1.

The range of scenarios explored here reflects the uncertainty surrounding the potential market impacts of COVID-19, including cases of supply surplus and deficit and the resulting reverberations through the material system. These changes included GDP/capita changes in 2020 and 2021, mining CU change in 2020, and refinery CU and SR changes in 2020. Each change was implemented in the model by manually inserting the respective value, rather than using its exogenous (GDP/capita) or endogenously determined (all others) value. GDP/capita reductions result from the economic shock induced by COVID-19, while the remaining changes stem from supply chain interruptions associated with viral outbreaks.46 Outside these years, the SD imbalances emanating from these shocks were permitted to evolve in accordance with the model.
GDP/capita changes were implemented in agreement with Fig. 5a, with mean global reduction in GDP/capita of 4% from 2019 to 2020 followed by a 4.7% increase from 2020 to 2021.14 Refinery operations were affected by plant closures and slowdowns in scrap collection, processing, and transportation, resulting in Cu falling 2.29% for 2019–2020 and Sr falling 6.93%.25 Mining operations were suspended in efforts to slow or avoid outbreaks, resulting in mine Cu falling 2.62% for 2019–2020.25 Sensitivities were explored by adjusting the values above ±50%. The resulting near-term changes in demand, primary and secondary refining production, mine production, and cathode price are detailed in Supplementary Methods: Near-term system response to COVID-19 shocks and align with projections from Roskill,17 ICSC,18 S&P Global,19 and GlobalData.30

**Model framework.** The copper material system model described in previous work formed the basis of this model. The production of copper and consumption of four material stages within the copper system—ore, scrap, refined copper cathode, and semifabricated goods—were modeled based on MFA and inventory-driven force models, where econometric time series analysis of historical data was used to determine the price, production, and consumption responses that minimize SD imbalances for each material stage. As such, the original model flow can be characterized as follows, starting from model initialization in 2018 with iteration on an annual basis through 2040:

1. Cathode price, TCRC, and scrap spreads (differences between scrap and cathode prices) are determined based on SD imbalances from the previous year;
2. Traditional (concentrate) and solvent extraction and electrowinning (SX-EW) mines respond to the market state—cathode price and TCRC—by alternating, opening, or closing;
3. Total copper demand is estimated based on exogenous GDP per capita and sectoral (e.g., construction, automotive, or industrial) volume projections, coupled with copper intensity (kg Cu per kg product) response to price, as developed from collaborator Karan Bhuvakula;5
4. Primary and secondary refining production are estimated based on TCRC and No.2 (ISRI grade Birch) scrap spread. Smelters are included within the refinery module;
5. Post-consumer (old) and post-industrial (new) scrap supply are estimated using standard DMAF procedure, using previous years’ demand values, lognormal distribution (lognormal(m = 0.1) sectoral product lifetimes, estimated scrap collection rates, technical recycling efficiencies, and home and exchange scrap ratios from Glöser et al.46, SMM39, and previous work;47
6. Refined copper and direct melt scrap consumption are estimated based on the prior demand prediction, the ratio between the allayed and unalloyed copper products, and scrap conversion efficiencies.

Several components required further development to enable regional and scrap composition considerations for system evolution under the China solid waste import ban. The prior global model was separated into two co-evolving components—China and the RoW—where the distribution of refined and scrap material consumption between these regions was determined by a linear programming optimization model. For this optimization model to operate, additional granularity surrounding semi-fabricator compositional requirements and scrap composition, availability, and demand were required. Each of these model expansions are described below. A brief discussion of the model base is also given. The additions to the model in previous work47–49 were performed using the production data resulting from scenario analysis. A comprehensive outline of model iteration is shown in Supplementary Fig. 16.

**Price formation.** In all cases, prices are adjusted for inflation. Cathode price evolution is based on the balance between cathode supply (refinery production and SX-EW mining production) and demand (semi-fabricator cathode consumption). We used spot price rather than future contract data because spot price is believed to be a better indicator of SD balance than future price for commodities.48–50 With minimal difference between commodity exchange prices due to arbitrage,51 we used only LME cathode spot price in developing this model due to its higher historical liquidity. Factors influencing copper cathode price have been studied extensively,48–52 with short-term price changes particularly vulnerable to factors outside SD balance. We focus only on the effects of SD imbalance, developing an autoregressive distributed lag model that uses oil price to account for other market effects, with more details in prior work.47,48 Cathode price then evolves according to Eq. (1).

$$P_{\text{cathode}} = P_{\text{cathode}, t-1} - 0.461(S_{\text{concentrate}, t-1} - D_{\text{cathode}, t-1})$$

where $P_{\text{cathode}}$ is the cathode price, $S_{\text{concentrate}}$ and $D_{\text{cathode}}$ represent cathode price, supply, and demand in the preceding year, respectively. TCRC are a component of mining cash costs and a source of revenue for smelters and refineries, serving as an indicator of copper concentrate SD imbalance. With annual TCRC determined by negotiation among the world’s largest smelting and mining corporations and spot TCRC highly correlated with annual TCRC, we assumed that annual TCRC is more representative of the concentrate market.56 An ordinary least squares (OLS) regression model was constructed using SNL and ICSC data from 1982 to 201857,58, resulting in TCRC evolution following Eq. (2).

$$TCRC_t = TCRC_{t-1} + 0.164(C_{\text{cumulative}, t-1} - D_{\text{concentrate}, t-1})$$

where TCRC is the annual TCRC of year $t$ (in USD/t payable copper), $C_{\text{cumulative}, t-1}$ is the world concentrate supply (concentrate mine production) in year $t-1$, and $D_{\text{concentrate}, t-1}$ is concentrate demand (primary refinery concentrate consumption) in year $t-1$.

To the high correlation between cathode price and scrap price, as well as the expectation that scrap balance impacts only the price of scrap relative to cathode, we model the difference between cathode price and scrap price, the scrap spread. With SD data lacking for individual scrap grades, we estimated spread evolution based on the imbalance of total scrap supply and demand. With No.2 copper scrap opening (ISRI grade Birch), the most significant predictor within other modules, we present only the No.2 scrap results here. We developed an OLS model using monthly scrap price data (1995–2018) from Fastmarkets AMM, resulting in No.2 spread evolution according to Eq. (3). We assumed that the SD effect was equal to the cathode SD effect on No.2 spread via cathode price effects (cathode SD effect on cathode price multiplied by the cathode price effect on No.2 spread). This assumption was explored using sensitivity analysis in previous work.47,56

$$\text{Spread}_{\text{Birch}, t} = \text{Spread}_{\text{Birch}, t-1} + 0.184 \Delta P_{\text{Cu}} + 0.0845(S_{\text{scrap}, t-1} - C_{\text{scrap}, t-1})$$

where Spread_{Birch} is the No. 2 spread at time $t$, $\Delta P_{\text{Cu}}$ is the change in cathode price from year $t-1$ to year $t$, $S_{\text{scrap}, t-1}$ is the scrap supply in year $t-1$, and $C_{\text{scrap}, t-1}$ is scrap consumption (demand) in year $t-1$.

**Primary supply module.** We model evolution of individual mines, with currently operating mines from SNL and an incentive pool of potential mines created by resampling with perturbation mines that have opened during 2015–2018. Ore grade elasticities (OGEs) to cumulative ore production were determined on an individual mine basis. OGEs were determined by simulating mine life, iteratively changing OGE until cumulative ore production from 2017 to closure was within 5% of 2017 reserves, or until the closure year matches SNL’s projected closure year if reserves were not reported. Mineseite costs, transport and offsite costs, TCRC, and royalties are components of the mine’s total cash cost, where the difference between the realized metal price and the total cost gives the total cash margin (TCM), which determines mine profitability.45 We assume hedging profits and losses to be constant, approximating the realized metal price with cathode price. Mineseite costs, transport and offsite costs, and royalties are exogenous mine parameters that were held constant throughout these simulations. Short-run ore production changes as mines alter Cu, which is modeled according to Eq. (4) following a generalized method of moments dynamic panel regression model performed in previous work.47

$$\text{Mine capacity utilization} = \begin{cases} 0.4, & \text{if in ramp up or ramp down} \\ 0.75, & \text{if not in ramp and TCM}=0 \\ \text{CU}* \left\{ \begin{align} 0.34 & , & \text{else} \end{align} \right. & \end{cases}$$

where mine CU is assumed equal to 0.4 in ramp up and ramp down periods, which last 3 years after the opening decision and 1 year after the closing decision, respectively. While TCM less than zero indicates that the mine was not profitable in that year, mines are unlikely to shut down or halt production before the depletion of reserves. CU was tuned such that the 2018 average CU in the simulation was equal to the average CU reported by the ICSC,55 while TCM was assumed to be the median TCM of all operating mines in 2018.57

Mine closure decision making is modeled based on anticipated cashflows and maximizing net present value (NPV), comparing the NPVs of entering the 1-year ramp down period in the current year or the next year, incurring reclamation costs in the following year for both cases. If the projected cash flow for the following year is calculated using the maximum value of cathode price from the preceding 5 years, NPV is calculated following Eq. (5).

$$\text{NPV} = \sum_{t=0}^{T} \frac{C_t}{(1 + r)^t}$$

where $C_t$ is the total cashflow expected in year $t$, $r$ is the discount rate set at 10%61,62, $T$ is 1 for ramp down beginning in year 0 and 2 for ramp down beginning in year 1, where $C_t$ is equal to the reclamation cost in year $T$. In all other years, $C_t$ is a function of cathode price, TCRC, Cu, ore grade, and several mine-level exogenous variables described in previous work.47

Mine opening decision making is significantly more complex than closure, as it is dependent on legal, political, environmental, and economic feasibility. In this simulation model, we rely solely on economic feasibility, assuming that non-economic conditions are either intrinsic to available economic data or do not act as bottlenecks to mine opening. The decision to develop a mine from the incentive pool opening $m$ is based on maximizing net present value (NPV) considering the internal rate of return (IRR) exceeds a cutoff value of 15%, a common guideline for assessing new mining projects.63,64 IRR is calculated by solving for $r$ in Eq. (6).

$$\text{NPV} = \sum_{t=0}^{T} \frac{C_t}{(1 + r)^t} = 0$$

where $C_t$ includes 3 years of development capital expenditures, estimated cashflows, and reclamation costs, while $T$ is the year of mine closure. Cashflows are estimated...
by simulating the lifetime of the mine using the trailing 3-year average of cathode price and TCRC. The number of mines selected from the incentive pool for opening evaluation was tuned such that annual mining production of 2018–2040 approximated a benchmark future mining supply, with cathode price and TCRC held constant. This future mine supply was calculated assuming linear growth in copper mine production, with the same growth rate as 2001–2011. This growth rate is slower than that of 2011–2018, which we assumed could not be sustained based on demand projections. The resulting time series of subsample size was held constant in all other scenarios.

**Refinery module.** Estimate cathode production from refineries as a function of cathode price, TCRC, and scrap spread, outputting concentrate demand, refined scrap demand, and cathode supply. Smelters are treated as part of the refining process. Wrought SX-EW mines also produce concentrates, so, whether or not they are included in the primary supply module and their production is directly added to total cathode production. Here primary refineries process only copper concentrate, while secondary refineries process both concentrate and scrap, with the fraction of raw material from scrap defined as the SR. We conducted generalized method of moments dynamic panel regression models of primary refinery CU, secondary refinery CU, and secondary refinery SR as functions of TCRC and No.2 scrap spread. Individual-level refinery data and TCRC from 1992 to 2016 was obtained from SNL95 and No.2 spread from Fastmarkets AMM56. We model refineries as one primary and secondary refinery each for both China and RoW. Refinery production is the product of capacity and CU, where capacity was assumed to follow cathode consumption with a 1-year lag, following the direction of industry interviews. The resulting evolution of primary CU, secondary CU, and SR are described by Eqs. (7)–(9).

\[
PCU_t = PCU_{t-1} \times \frac{TCRC}{TCRC_{t-1}}
\]

(7)

\[
SCU_t = SCU_{t-1} \times \frac{TCRC}{TCRC_{t-1}}
\]

(8)

\[
SR_t = SR_{t-1} \times \frac{TCRC}{TCRC_{t-1}} - \frac{\text{Spread}_{t-1}}{\text{Spread}_{t-1-1}}
\]

(9)

where PCU is the primary refinery CU at time t, SCU is secondary refinery CU at time t, SR is the secondary refinery SR at time t, and Spread_{t-1}/Spread_{t-1-1} is the difference between cathode price and No.2 scrap price at time t. For more details, see previous work56,58.

**Regional evolution.** Historical values for production and consumption both in China and globally were compiled from data provided by the ICSG, the International Copper Association, Minnir, Glöser et al. at Fraunhofer ISI, the International Wrought Copper Council, CRU Group, S&P Global Market Intelligence57, Wood Mackenzie, the Shanghai Metals Market, American Metal Market, and UN Comtrade (see Supplementary Table 2 for full list of data sources and their applications).

In developing the China–RoW regional model, cathode prices, TCRC, and mining evolution were assumed to behave as global parameters due to market liquidity, while scrap spreads, copper demand, primary and secondary refined copper production and consumption, and scrap production and consumption required regionalization. China’s scrap and refined copper imports were specified as exogenous variables, while concentrate imports were implicit in regional refinery operation. Scrap spreads evolve as a function of the scrap SD balance and the change in cathode price, and scrap spread elasticities to changes in these values retained their global values from the previous model. However, scrap spreads were modeled at the regional level to enable changes in regional scrap availability to impact scrap consumption and thus regional refinery evolution. The deviation of China and RoW scrap prices from the calculated global values was further explored as a model sensitivity as discussed in Supplementary Methods: Sensitivity to scrap spread. Global refinery production was previously modeled as a combination of 99% primary metal production and the remaining 1% secondary metal. For China, the remaining 1% is unalloyed products, which is a function of a sector-specific incentive \(\beta_t\), representing dematerialization, sector- and region-specific copper price coefficients \(\beta_0\) and \(\beta_1\), where \(\beta_t = \frac{\text{Spread}_{t-1}/\text{Spread}_{t-1-1}}{\text{Spread}_{t-1}}\) is the first lag of trailing 2-year average cathode price, and \(\beta_t\) representing the intensity response to regional GDP per capita. For more details, see our previous work57,59.

The resulting regional demand values were then converted to regional demand by shape (e.g., copper or alloyed wire or tube) using global parameters based on data from Glöser et al., which permitted distinction between alloyed and unalloyed products, including refined copper use at the global scale. Unalloyed products were assumed on average 99.98% Cu by weight, while refined product compositions were determined based on Copper Development Association supplier databases and industry expert interviews as described in Supplementary Methods: Semi-fabricator alloy distribution framework. As such, alloyed semi-fabricator production was broken into 190 representative UniNumber System alloy categories, and the Regional Committee on Standardization and Certification recommended that the overall distribution of alloying elements within each shape remains constant over time, and consequently the fraction of each shape occupied by each alloy was held constant for each year of production. Since each sector is composed of different fractions of each shape, and that sectors evolve independently as shown in Eq. 1, demand for individual alloys does not, however, remain constant. Alloy compositional requirements across eight impurity elements were considered for the blending component of the linear programming optimization model described in the following section.

Scrap generation was broken down into 14 categories representing the most common ISRI post-consumer scrap grades and 191 categories representing post-industrial scrap produced by alloyed semi-fabricators, with 190 categories representing alloyed post-industrial scrap and the single additional alloy representing unalloyed post-industrial scrap. Annual post-consumer scrap generation values for China and RoW were calculated using standard DMFA methods with lognormal sectoral lifetime distributions, with sectoral collection rates and recycling efficiencies for both regions. Refined metal markets were assumed to be sufficiently liquid to permit any quantity to be consumed at the same unit price globally, but given availability concerns associated with post-consumer scrap consumption, post-consumer scrap prices were determined using an order book formulation, where average purchasing prices increased with total quantities consumed within each region. Given that inventories were sufficiently large that each scrap grade was not fully consumed each year, this formulation permitted an increase in regional scrap availability in a given year to produce an increase in scrap consumption in that region. The resulting equations describing scrap generation relative to quantities consumed for each scrap grade as functions of scrap availability and scrap price, which was determined using econometric time series analysis. Following the assumption that scrap markets
illiquid, scrap prices were allowed to change based on regional SD imbalances. Additional details surrounding order book, scrap price formation, and additional data for scrap generation were described in Supplementary Methods: Scrap price, availability, and their interplay. With regional manufacturer production and scrap availability determined at the compositional level, a linear programming optimization model was developed within Gurobi Optimization software66, where composition and production quantities of electrolyte were maximized and price was minimized. The model was further constrained to consume the total quantity of refined copper determined at the global level above, with the distribution between China and RoW a result of scrap and refined metal prices and determined by the optimization model (see Supplementary Methods: Linear programming optimization model).

**Life cycle assessment.** This work was primarily performed using the Ecoinvent 3 database within the software package SimaPro, using the environmental damage indicators offered by the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) 2.1 midpoint life cycle inventory analysis method, which provides the following ten damage categories: Ozone depletion (kg CFC-kk), Global warming (kg CO2 eq), Smog (kg O3 eq), Acidification (kg SO2 eq), Eutrophication (kg N eq), Carcinogenicity (CTUh), Non carcinogenicity (CTUh), Respiratory effects (kg PM2.5 eq), Ecotoxicity (CTUe), and Fossil fuel depletion (MJ surplus). We also considered total energy consumption using Cumulative Energy Demand V1.11, and water use following Berger et al. For mines, we calculated CO2e emissions, water use, and energy consumption as a function of ore grade as described in relationships established by Northey et al. Average regional ore grades for concentrate and SX-EW mines were calculated using SNL data, average regional CO2e emissions, water use, and energy consumption were calculated following Eq. (12), and the resulting values were multiplied by regional scaling factors (Supplementary Table 11) to reach the regional values from Ecoinvent 3, TRACI 2.1, Cumulative Energy Demand V1.11, and Berger et al. (Supplementary Table 12).

\[ C = R \cdot AgR \]  
(12)

where \( C \) is the calculated impact for the category applied, and \( A \) and \( B \) are empirically determined constants using a power series trendline on global concentrate and SX-EW mine data for CO2 emissions, water consumption, and energy use from Northey et al. with values in Supplementary Table 15 and \( g \) is the ore grade of the mine67. Additional regional scaling factors, \( R \), were implemented such that the calculated ore grade was scaled according to regional average ore grade as described in Supplementary Table 11. The regional unit CO2e emissions, energy, or water value for Ecoinvent processes for copper concentrate (sulphide ore) or copper (from SX-EW). Regions include Oceania, Africa, Europe, North America, China, other Asia, and Latin America. Further details are described in previous work37. These processes were used to develop the emissions or consumption for each model region, where the remaining nine TRACI indicators were calculated based on the ratio of CO2e emissions to each indicator for the respective region in Ecoinvent 3. We assume that the global distribution of mining activities remains constant from 2018 through 2040.

Regional SX-EW mining environmental impacts were determined using the SimaPro global value for copper from SX-EW, scaled by the impacts of regional concentric mining relative to global average concentrate impacts. Due to the exponential nature of the mine impact calculations, individual mine unit impacts were capped according to the highest values from Northey et al. for concentrate, mines49,50. Copper cathode prices of $5500/ton (Cu, 1590 MJ/kg, 1.56 kg CO2eq/kg Cu, 450 MJ/kg, and 0.27 m3 water/kg). Impacts for the refining supply chain components follow values from Ecoinvent 3, TRACI 2.1, Cumulative Energy Demand V1.11, Berger et al.68, Giurco et al.69, and Chen et al.70. Here primary refining includes smelting impacts as well, and both primary and secondary refining are treated at the regional level. Direct melting of scrap is treated globally due to data limitations but is a function of scrap grade (Supplementary Table 15). Semi-finished goods manufacturing unit impacts are semi-regional, with global impacts from wire drawing on ~56% of production based on data from Glöser et al.66. The remainder is treated using metal working impacts, with Europe and North America using one set of impacts and other regions using impacts for RoW (Supplementary Table 17). For all of these impacts, we assume the regional distribution within RoW remains constant, with the fraction of primary refining, secondary refining, direct melt scrap consumption, and manufacturing occurring in China and RoW being results of model evolution. We assume that refining impacts do not change as functions of ore grade and that manufacturing and scrap direct melting impacts do not change over time, in alignment with previous studies37.

We modeled regional changes in CO2e emission intensity of electricity generation following the U.S. Energy Information Administration’s reference case, which projects a 14% decline globally from 2018 to 2040 (Supplementary Table 20)52. This reference case indicates a 22% decline in global CO2e emission intensity of electricity generation using the 2010–2050 range of Giurco et al.37, which falls between their “market rules” (10% decline) and “toward resilience” (32% decline) scenarios. Industrial sources generally state that comminution accounts for at least 50% of mine energy consumption, while academic studies have reported 46% of copper mine CO2 emissions from comminution57, 48–62% of mine energy as electricity57, and 70% of all mine energy for comminution57. With comminution requiring electricity for the operation of mechanical grinding apparatuses, we assume that 55% of copper mining activity energy consumption is in the form of electricity, with the remainder being primary energy unaffected by decreased emission intensity of electricity. Annual CO2e emissions calculated using the original parameters were scaled according to the regional emission intensity change relative to 2018.

**Data availability**

The data that support the findings of this study are available from the corresponding author upon request. Source data are provided in the figshare repository https://doi.org/10.6084/m9.figshare.14390489.v3#5, with additional detail available upon request.

Received: 2 October 2020; Accepted: 20 May 2021; 
Published online: 18 June 2021

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Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41467-021-23874-7.

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Peer review information Nature Communications thanks Xianlai Zeng and other anonymous reviewers for their contributions to the peer review of this work. Peer review reports are available.

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