Improved sustainability assessment of the G20's supply chains of materials, fuels, and food

Journal Article

Author(s):
Cabernard, Livia ⓘD; Pfister, Stephan ⓘD; Hellweg, Stefanie ⓘD

ACCEPTED MANUSCRIPT

Improved sustainability assessment of the G20's supply chains of materials, fuels, and food

Title: Improved sustainability assessment of the G20's supply chains of materials, fuels, and food

Authors: Livia Cabernard[1,2,*], Stephan Pfister[1,2], Stefanie Hellweg[1,2]

Affiliations:

[1]Swiss Federal Institute of Technology, ETH Zurich

Department of Civil, Environmental and Geomatic Engineering

Institute of Environmental Engineering

Ecological Systems Design

John-von-Neumann-Weg 9

8093 Zurich, Switzerland

[2]Swiss Federal Institute of Technology, ETH Zurich

Department of Humanities, Social, and Political Sciences

Institute of Science, Technology, and Policy (ISTP)

Universitätstrasse 41

8092 Zurich, Switzerland

Corresponding Author:

*Livia Cabernard

livia.cabernard@istp.ethz.ch

Contacts of Co-Authors:

Dr. Stephan Pfister

stephan.pfister@ifu.baug.ethz.ch

Prof. Dr. Stefanie Hellweg

stefanie.hellweg@ifu.baug.ethz.ch

Abstract

Transparency in global value chains of materials, fuels, and food is critical for the implementation of sustainability policies. Such policies should be led by the G20, who represent more than 80% of global material, fuel, and food consumption. Multi-regional input-output (MRIO) analysis plays an important role for consumption-based assessment, including supply chains and their environmental impacts. However, previous accounting schemes were unable to fully assess the impacts of materials, fuels, and food. To close this gap, we provide an improved method to map key aspects of sustainability along value chains of materials, fuels, and food. The results show that the rise in global coal-related greenhouse gas (GHG) emissions between 1995 and 2015 was driven by the G20's metals and construction materials industry. In 2015, the G20 accounted for 96% of global coal-related GHG emissions, of which almost half was from the extraction and processing of metals and construction materials in China and India. Major drivers include China's rising infrastructure and exports of metals embodied in machinery, transport and electronics consumed by other G20 members. In 2015, the vast majority (70–95%) of the GHG emissions of metals consumed by the EU, USA, Canada, Australia, and other G20 members were emitted abroad, mostly in China. In contrast, hotspots in the impact displacement of water stress, land-use related biodiversity loss, and low-paid workforce involve the G20's food imports from non-G20 members. Particularly high-income members have contributed to the G20's rising environmental footprints by their increasing demand for materials, food and fuels extracted and processed in lower-income regions with less strict environmental policies, higher water stress and more biodiversity loss. Our results underline the G20's importance of switching to renewable energy, substituting high-impact materials, improving supply chains, and using site-specific competitive advantages to reduce impacts on water and ecosystems.

1. Introduction

In the United Nations Agenda for sustainable development, climate change, air pollution, water stress, and biodiversity loss are considered as the most important global environmental impacts that need to be addressed in the coming decades[1-8]. These environmental problems need to be tackled together with the socioeconomic pillar of sustainability, such as promoting decent work and economic growth and ensuring responsible consumption of material resources. In this study, we rely on the International Resource Panel (IRP) definition, where material resources include metals, non-metallic minerals, biomass and fossil resources that are processed into materials (steel, cement, textiles, plastics, paper, etc.), food products, and fossil fuels (coal, oil, etc.)[1]. In a recent report, the IRP has shown that the extraction and processing of material resources into ready-to-be used materials, food products, and fuels, summarized as material production in this study, causes about half of global greenhouse gas (GHG) emissions, one-third of global particulate matter (PM) health impacts and more than 90% of global water stress and land-use related biodiversity loss[9, 10]. With the global material demand expected to more than double by 2050[11, 12], strategies for a more sustainable production and consumption are crucial to comply with the Paris Agreement and many Sustainable Development Goals.

1

To ensure sustainable production and consumption, joint action must be undertaken at both the bilateral and multilateral levels to facilitate negotiations among related nations, foster decision making, and promote international agreements[13]. The meeting of the Group of Twenty, called the G20, is a regular international gathering. It brings together the leaders of both high-income countries and emerging economies[14-16]. Altogether, the G20 represent about two-thirds of the world's population, 80% of the world's GDP, three-quarters of international trade[17], and more than 80% of total global material production and consumption[14]. There is a process in which G20 members discuss challenges and actions related to sustainable material production and consumption[18, 19]. Due to the high policy level, the international meeting of the G20 could be very effective in mitigating material-related impacts, if dedicated to develop joint actions for sustainable production and consumption.

When evaluating various sustainability actions, it is most effective to address the impacts caused along the entire value chain, including the upstream, midstream, and downstream chain[20-23]. Here, the upstream chain refers to all economic activities in the upstream (supply) chain of material production, such as the supply of electricity or transport activities to the mining or processing stages. The midstream chain refers to the extraction and processing of material resources into ready-to-be used materials, food, and fuels, grouped under the collective term materials here. The downstream chain refers to all activities afterwards, such as further manufacturing into finished products, use for construction, service, heating, and the associated supply of electricity and transport activities in the downstream chain. Each step can cause a set of environmental and socioeconomic impacts. The latter can also be beneficial, such as by employing workforce and creating value added. In the GHG protocol[24, 25], the so-called scope 3 emissions includes upstream and midstream (direct) emissions, while the inclusion of downstream emissions is optional[26]. In this study, scope 3 refers to the cumulative upstream and midstream impacts of material production for any type of impact category (as done in ref[10]), while downstream emissions are separately addressed for GHG emissions.

One form of life-cycle assessment that allows assessing impacts along global value chains is environmentally-extended multi-regional-input-output (MRIO) analysis[27-35]. However, none of the standard accounting schemes in MRIO analysis[13, 15, 20, 21, 30-60] was capable of accurately assessing the impacts of sectors and regions situated in the middle of the global value chain, called intermediate or midstream sectors and regions (SI Paragraph S1)[10, 61-64]. This implied a particular lack in information for material sectors and regions strongly connected by international trade, which have both an upstream and downstream chain. Recently, a method was developed to analyze the impacts of materials on a national level[61-63], and extended to assess the impacts of any intermediate sector and region for any impact category of any MRIO database[10]. It was applied to assess the environmental and socioeconomic impacts of global material production[10, 64-69], plastics production[64], ICT manufacturing[68], and the EU's food consumption[69]. However, an application to the G20's material production and consumption is missing in the scientific literature despite its importance for policy making, given the G20's key role in collective action to promote sustainable material production and consumption.

Although the inclusion of downstream impacts is optional in scope 3 assessment[26], downstream emissions are critical for fossil resources as their combustion causes the vast majority of global GHG emissions[70, 71]. Previous studies[10, 64-69] have tracked the use of

materials (and the impacts related to their production) in the downstream chain, such as to analyze which fraction of the emissions of steel production were attributed to steel used in construction. Also, one study has allocated GHG emissions of global plastics production to the type of fossil fuel that is combusted[64]. Finally, one study used a monetary-based downstream allocation of materials (SI Paragraph S2).[61-63] However, the emissions released by the use of materials in the downstream chain, such as the GHG emissions released by fossil fuels combustion in the construction sector, were not attributed to the material that releases the emissions (physical allocation).

To address these research gaps, we create an MRIO database with high sectoral resolution and indicator coverage for each G20 member (based on ref[69]), apply the methodology of ref[10] to assess the scope 3 impacts of the G20's material value chain, and extend it to downstream emissions. This allows us to address the following research questions (RQ):

RQ 1) How to design an accounting system that fully considers the impacts of material value chains (Section 3.1)?

RQ 2) Which material value chains drive the G20's rising GHG emissions (Section 3.2)?

RQ 3) How does the G20's trade in materials affect key aspects of sustainability (Section 3.3)?

2. Methods and Data

2.1 Database compilation

Our methodology is based on multiregional input-output (MRIO) analysis, which aggregates the global economy into a specific number of regions and industrial sectors. It records their transactional flows and environmental and socioeconomic accounts for a specific time frame. To address the research gaps highlighted in the introduction, we compiled an MRIO database covering each of the G20 members, including China, the USA, the EU (with Germany, France, and Italy as single members), the United Kingdom, India, Russia, Japan, Brazil, Indonesia, Mexico, South Korea, Canada, Australia, Turkey, Saudi Arabia, South Africa, and Argentina (see e.g., Figure 6). The G20 database is based on EXIOBASE3[27], which was extended to Saudi Arabia and Argentina by integrating data from Eora26[29], FAOSTAT[72] and previous work[73-76], following the procedure described in Cabernard & Pfister[69] (see this publication and Paragraph S3 for further details). It distinguishes 163 sectors for 51 regions, covering each G20 member, and time series from 1995 to 2015. It includes the key environmental issues listed by the UN's Agenda for sustainable development, namely GHG emissions, PM-related health impacts, water stress, land-use related biodiversity loss, which were implemented based on the impact assessment methods recommended by UNEP-SETAC[77], as done before[10, 69] (Paragraph S3). Furthermore, it adds the socioeconomic indicators workforce and value added.

2.2 Assessment

We applied the following four steps to the G20 database: First, we used the common Leontief framework[78] to assess the total environmental and socioeconomic impacts from a production and consumption perspective (SI Paragraph S4). Second, we split the production and consumption-based impacts into scope 3 impacts of material production (including upstream

3

and midstream impacts) and the impacts caused in the downstream chain by the remaining economy and households, based on the methodology of ref[10, 61, 62] (SI Paragraph S5). Third, we split the scope 3 GHG emissions of material production and the GHG emissions released in the downstream chain by the process of GHG emissions and type of fuel combustion, by extending the approach of ref[64] to downstream emissions (SI Paragraph S6). Finally, we decomposed the respective equations related to scope 3 and downstream emissions to map the intermediate steps in the G20's material value chain, called carbon flow analysis here (SI Paragraph S7). The intermediate steps are illustrated by showing the G20's GHG emissions from different perspectives (e.g., consumption region, end-use sector; material groups; upstream, midstream, and downstream emissions; process of GHG emissions release; production region) and by mapping the linkages between these perspectives (e.g., the end-sectors' use of metals, non-metallic minerals, biomass, and fossil resources; the impacts of these material groups split by upstream, midstream and downstream emissions; the link to the emission sources such as fossil fuel combustion).

3. Results and Discussion

In the following, Section 3.1 explains why none of the previous standard accounting schemes was suitable to assess the G20's material-related scope 3 GHG emissions (RQ 1). Moreover, it reveals the effects of including downstream emissions and mapping the intermediate steps in the G20's material value chain. Based on our improved accounting scheme for material-related impacts, Section 3.2 identifies key drivers of the G20's rising GHG emissions (RQ 2). Finally, Section 3.3 shows the degree of the G20's displacement of impacts to other G20 members and the rest of the world (RQ 3).

3.1 Methodical improvements

In this section, we explain the differences of our method compared to previous accounting schemes for both scope 3 and downstream GHG emissions of materials produced and consumed by the G20. In contrast to this study's method, standard production-based accounting focuses on direct impacts of resource extraction and processing, and thus neglects upstream impacts (e.g., the upstream impacts of material production caused by the electricity or transport sector are allocated to the electricity and transport sector instead of the material sectors). This would result in an underestimation of scope 3 GHG emissions by 60% for metals, and by more than 25% for nonmetallic-minerals, biomass, and fossil resources (30% for all materials, Figure 1a vs 1d). On the other hand, standard consumption-based accounting[13, 15, 20, 30-33, 35-40, 58, 79] allocates all impacts to end-use sectors, and hence misses the impacts of intermediate uses of materials (e.g., the impacts of metals in electronics, cement in construction, food in restaurants, and fossil resources in transport are allocated to these end-use sectors instead of the material sectors). This would result in an underestimation of scope 3 GHG emissions by 20% for biomass, and more than a factor of two, five, and ten for fossil resources, metals, and non-metallic minerals, respectively (Figure 1b vs 1d). Vice versa, standard scope 3 accounting[20, 58, 59] would overestimate the GHG emissions by more than 40% for biomass and fossil resources, and more than 100% for metals and nonmetallic minerals (80% for all materials, Figure 1c vs 1d). This is attributed to double-counting of the emissions

of those material sectors situated in each other's supply chain (e.g., part of the scope 3 impact of material A is double counted in the scope 3 impacts of material B because part of material A is used to produce material B). Thus, none of the previous MRIO approaches allowed for a comprehensive and accurate assessment of the G20's material-related scope 3 GHG emissions.

A comparison of this study's downstream approach to the monetary-based downstream allocation of Dente et al[61-63] is shown in Figure 1e–f, where scope 3 emissions are the same as in Figure 1d (based on the method of Cabernard et al[10]), but downstream emissions were calculated based on the approach of Dente et al[61-63] and this study's approach, respectively. In the approach of ref[61-63], downstream GHG emissions of material resources are comparably small and distributed among all material resource types (Figure 1e). Due to the monetary allocation in ref[61-63], more than one-third of the G20's GHG emissions are attributed to the remaining economy (e.g., further manufacturing, public transport, service, etc.) and households (private transport and heating), and thus not related to materials. The approach taken in this study allows emissions of the remaining economy and households to be fully attributed to material resources causing the emissions, mainly fossil fuels through combustion and, to a lesser extent, biomass through decomposition (Figure 1f). Thus, the inclusion of downstream GHG emissions increases the G20's scope 3 GHG emissions of biomass by 5% and those of fossil resources by a factor of three. Further comparison of this study's results with those of Dente et al[61-63] are shown in the SI by the example of Japan's material value chain (Figure S2 and S3, Paragraph S8).
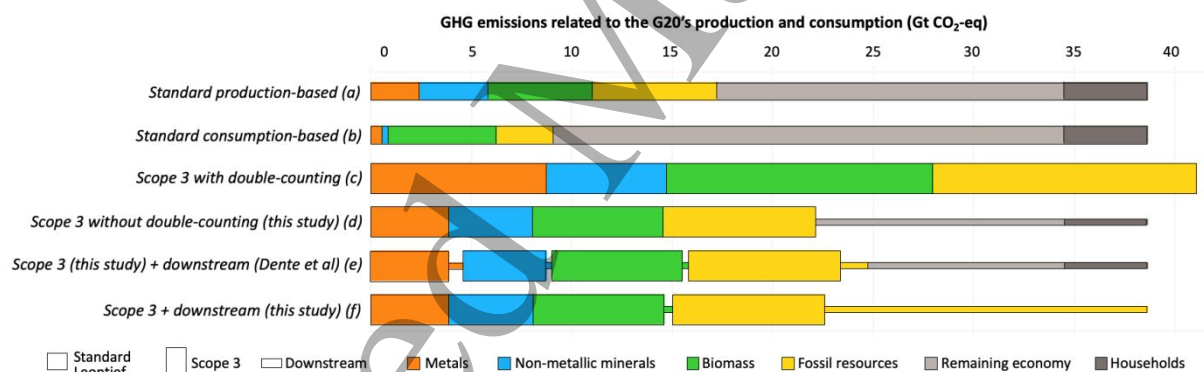

Figure 1. Greenhouse gas (GHG) emissions related to the G20's production and consumption of materials calculated with the standard Leontief model (a and b) [20, 30-33, 36-40, 58, 79], scope 3 accounting with double-counting (c)[20, 58, 59] and without double-counting (d–f, based on Cabernard et al[10]) combined with the downstream allocation of Dente et al[61-63] (e) and this study's downstream approach (f). The intermediate steps in the G20's material value chain based on this study's method (f) are shown in Figure 2.

The carbon flow analysis of the G20's material value chain is shown in Figure 2. It extends the standard Leontief model[20, 30-33, 35-40, 58, 79] where GHG emissions are allocated to either the region and sector of production and consumption (Figure 2a–b and 2f) by showing the intermediate steps in the G20's material value chain (Figure 2b–f). It differs from the method of Dente et al[61-63] by fully allocating the emissions of the end-sectors to the type of material resource causing the emissions (Figure 2b–c). Moreover, it extends the method of Cabernard et al[10] by including not only upstream and midstream emissions (scope 3: Figure 2d1–d2), but

also downstream emissions (Figure 2d3) and the link to the emission source (Figure 2d–e). The split of the four material groups by upstream, midstream, and downstream emissions shows that 14% of the G20's GHGs were emitted in the upstream chain, 24% and 21% were released midstream by extraction and processing, respectively, and 41% were released in the downstream chain (Figure 2c–d). The link to the emission sources shows that upstream emissions were mainly released by coal electricity (Figure 2d–e). Most emissions of the processing stage were related to metals and non-metallic minerals, whose emissions were released by calcification and fossil fuel combustion (Figure 2c–e). Fossil fuels combustion caused not only the vast majority of the emissions in the downstream chain of materials, such as by heating and transport through households (27% of the G20's carbon footprint, Figure 2b–d), but also in the upstream and midstream chain of material production (Figure 2d–e). The analysis of the end-sector's use of materials reveals that half of the carbon footprint of the G20's electronics, machinery and car industry is attributed to metals, while the other half is attributed to fossil resources (Figure 2b–c). For the G20's construction industry, more than half of its carbon footprint is attributed to cement, bricks, and other concrete elements, and the remaining fraction is attributed to metals (20%) and fossil resources (25%).
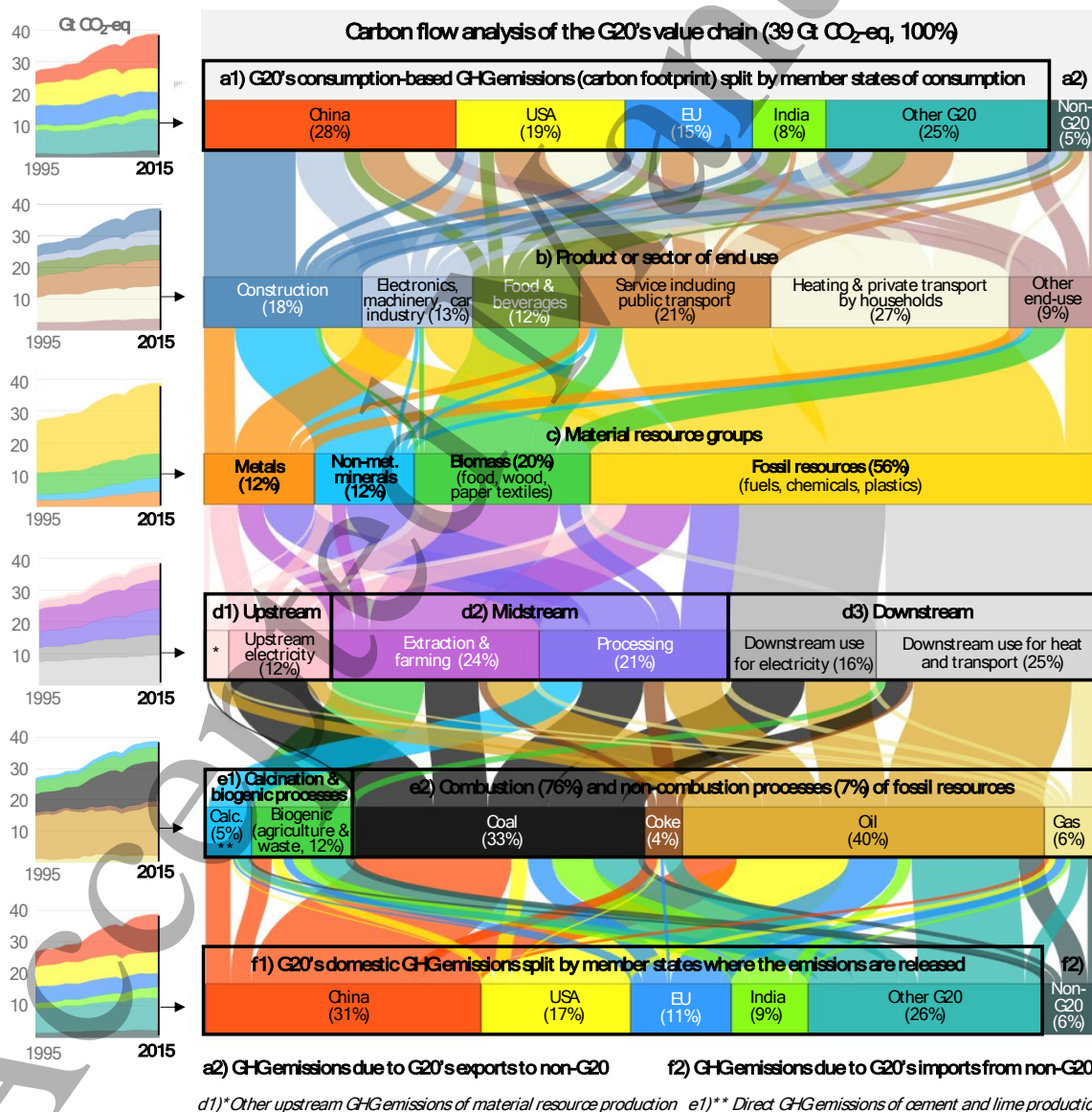
Figure 2. Carbon flow analysis of the G20's material value chain, including their consumption (a1, carbon footprint) and production for exports to non-G20 members (a2) in 2015 (totally 39 Gt CO_2-equivalents, 100%). Each bar sums up to 100% and shows the G20's GHG emissions from different perspectives in the global value chain, such as a) the regions where materials are finally used, b) the product or sector where materials are finally used for supplying final consumption, c) the four material groups, d) the split by upstream, midstream, and downstream impacts, e) the processes which release GHG emissions, and f) the regions where GHG emissions are released, which includes the G20's domestic GHG emissions (f1) and those released by non-G20 members due the G20's imports (f2). The small graphs to the left show the temporal development from 1995 to 2015.

3.2 Key materials driving the G20's GHG emissions

Based on the methodical improvements discussed above, this section provides new insights on the drivers of the G20's rising GHG emissions, which have increased by 44% from 1995 to 2015 (Figure 2). The increasing reliance on coal to extract and process materials, especially metals and construction materials in China and India, was a key driver of the G20's rising GHG emissions. As a result, the G20's coal-based GHG emissions have more than doubled, while the G20's oil-based GHG emissions increased only slightly over the past two decades (+15%, Figure 2e). In 2015, the G20 were responsible for 96% of global coal-related GHG emissions, whereof two-thirds were emitted during electricity and heat generation for material production (upstream and midstream emissions), while the remaining third was released in the downstream chain (downstream emissions, Figure 2d–e). Almost half of the G20's coal-based GHG emissions were related to the extraction and processing of metals and construction materials, mostly in China and India (Year 2015). The G20's GHG emissions of metals and construction materials have more than doubled since 1995, contributing to a quarter of the G20's total GHG emissions in 2015 (Figure 2c). From a demand side, this increase was mainly driven by China's growing infrastructure. China's GHG emissions related to the production of metals and construction materials have more than quadrupled since 1995 (both from a production and consumption perspective). The same growth rate applies for the GHG emissions of China's construction, electronics, machinery and car industry, which relied on these materials (Figure 2a–c).

In the following, we focus on the use of coal for the extraction and processing of metals and construction materials, as Figure 2 had shown the pivotal role of these materials for the rise in global GHG emissions. The use of coal for the G20's production of metals and construction materials has increased sixfold between 1995 and 2015 (Figure 3). In contrast, the global use of coal for everything else than these materials has increased by only 16%. In 2015, half of global coal was used for the G20's production of metals and construction materials, mostly steel and cement in China and India (Figure 3b, Figure S4). From 1995 to 2015, the use of coal for the production of metals and construction materials in China and India has increased by a factor of 12 and six, respectively. Moreover, coal used for China's cement production has increased by a factor of more than hundred. In 2015, almost half of global coal was combusted for the production of metals and construction materials in China and India. As most of this coal was extracted domestically, China used two-thirds of its entire coal for the production of these materials in 2015. In India, even 85% of the total domestic coal was used for the production of metals and construction materials.
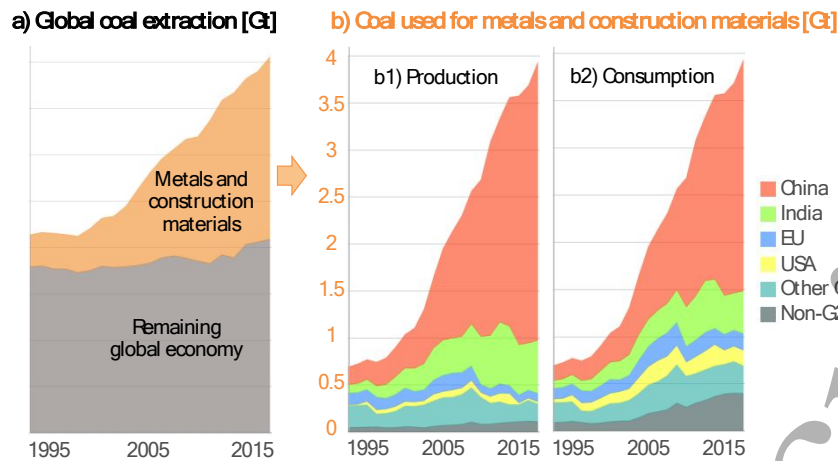
7

Figure 3. a) Global coal extraction split by its use for minerals production and the remaining economy (everything else than minerals production), and b) region where coal is used for minerals production (b1) and where minerals are finally consumed (b2).

As global coal mining is driven by the G20's production of metals and construction materials, the combustion of that coal drove the rising carbon footprint of these materials. An in-depth analysis on the carbon footprint of metals and the role of coal combustion is shown in Figure 4. The split by the type of fuel combusted shows that coal-based GHG emissions for metals production have tripled since 1995, while the remaining GHG emissions increased by only 20% (Figure 4b). Consequently, coal-based emissions contributed to 60% of the global carbon footprint of metals in 2015. The split into upstream and midstream emissions reveals that more than half of coal-based emissions were released in the upstream chain of metals production, mostly by coal mining and electricity generation (Figure 4a–b). The link to the region where metals are produced and consumed shows that the vast majority of the carbon footprint of metals was attributed to the G20, both from a production (92%) and a consumption perspective (82%, Figure 4c–d). This explains why the G20's metals carbon footprint was three times higher compared to the non-G20 average on a per-capita level (year 2015, Figure 5).

The link between metals producer and consumer shows that most metals produced in China and India were also consumed in China and India, mostly in construction, machinery, and transport (Figure 4c–e). Still, one third of the GHG emissions released by China's and India's metals production were attributed to exports (Figure 4c–e). China's and India's rising exports of metals (and strong reliance on coal to produce these metals) explains why the share of coal-based emissions in the metals carbon footprint has considerably increased for all G20 members (except Brazil and South Korea) and the non-G20 regions from a consumption perspective (Figure 5). In 2015, the vast majority (70–95%) of the GHG emissions of metals consumed by the EU, USA, Canada, Australia, and other G20 members were emitted abroad, mostly in China, due to coal combustion in the supply chain.
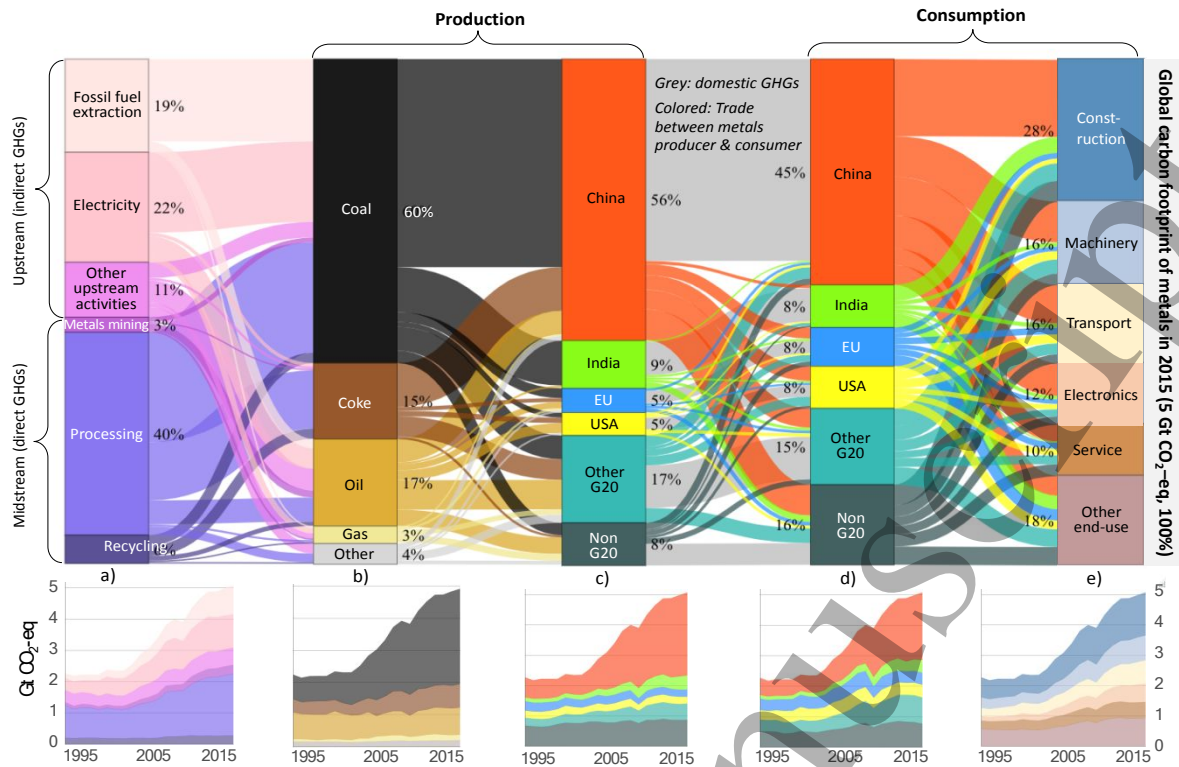
Figure 4. Carbon flow analysis of the metals value chain in 2015 (5 Gt CO2-eq, 100%, flow chart) and temporal evolution from 1995 to 2015 (small graphs at the bottom) shown from different perspectives: a) the sector where GHG emissions related to metals production are released, b) the fossil fuel type which releases GHG emissions, c) the region where GHG emissions are released, d) the region where metals are finally consumed, and e) the end-sector where metals finally end up.
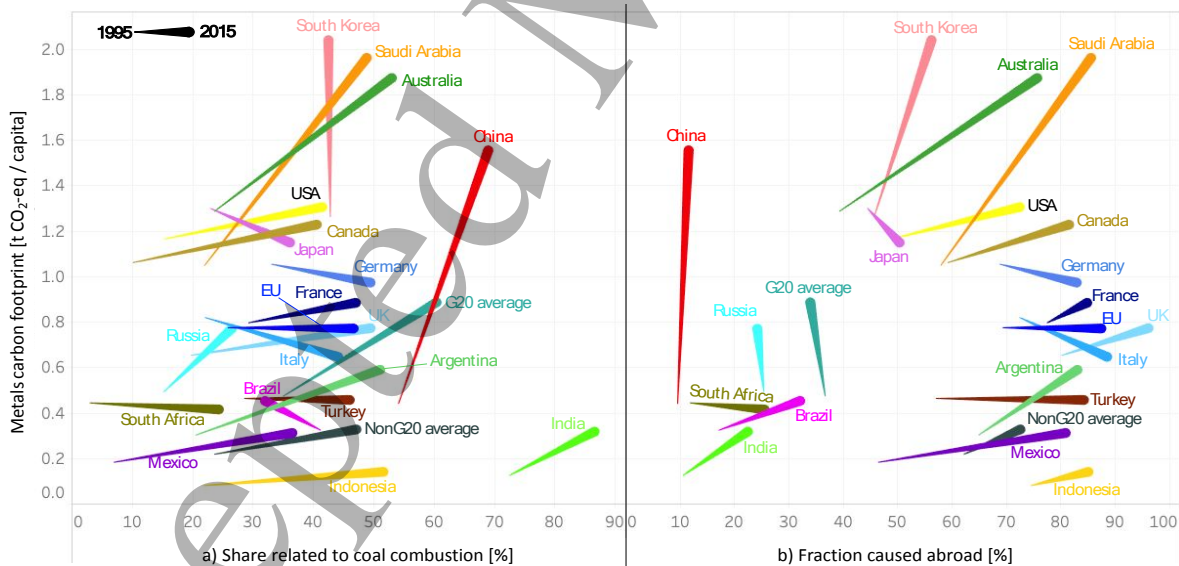
Figure 5. Change in the G20's metals-related GHG emissions from a consumption perspective (metals carbon footprint) on a per-capita level plotted against a) the share of coal-based emissions in total GHG emissions and b) the fraction of the metals carbon footprint caused abroad (due to metals imports, either as raw material or embodied in other products) plotted against the GDP for all G20 members. The metals carbon footprint includes all GHG emissions related to a region's metals consumption (including the emissions embodied in metals imports, but excluding the emissions of metals embodied in exports).

3.3 The G20's rising impacts and role of material trade

As Section 3.2 has shown that high-income members increasingly consume metals produced in coal-based economies, this section analyzes how trade in materials affects the G20's total impacts, considering not only GHG emissions but also other key aspects of sustainability. Our results show strong differences in the per-capita footprints among the G20 members, and that international trade in materials adds to this imbalance (Figure 6 and 7, see SI Paragraph S9–S11 for further results). EU countries, the USA, and Canada are the only members who managed to decrease their carbon and PM health impact footprints while simultaneously improving the economic wealth, called absolute decoupling (Figure 6a). Nevertheless, their per-capita carbon footprints are still several times higher compared to China, whose carbon footprint has more than doubled since 1995. The decoupling achievements of EU countries, the USA, and Canada were entirely attributed to domestic technology improvements, which compensated for the rising GHG emissions and PM health impacts caused abroad due material imports (Figure 6b). In 2015, EU countries induced more than a third of their carbon and PM health footprint abroad, and this was largely (>85%) attributed to imports of metals (particularly steel and aluminum), fuels (oil and gas), and plastics. These imports occurred either as raw materials (e.g., oil, gas, plastics) or were embodied in other products, such as metals embodied in imported electronics, machinery, and transport equipment.

Outsourcing of material production from higher-income to lower-income regions with less stringent environmental policies, higher water stress, and more biodiversity loss has contributed to the G20's rising environmental footprints since 1995 (Figure 6 and 7, SI Figure S8–S12). Similar to the carbon and PM health footprint, EU countries induced more than half of their water stress and land-use related biodiversity loss footprint abroad, largely (>80%) attributed to material imports. Consequently, the EU's water stress and land-use related biodiversity loss was two times higher from a consumption than a production perspective (Figure 7). While the EU's carbon and PM health footprint caused abroad was mainly related to imports of metals and fossil-based products from G20 members, the EU's water stress and biodiversity loss footprint induced abroad was mainly attributed to biomass products. These were mostly food imports from non-G20 members (SI Figure S13 and S14). Similar to the environmental impacts, almost 80% of the workforce required for the EU's material demand was occupied abroad and this primarily involved low-paid agricultural work in non-G20 members (SI Figure S10e, Figure S15). Consequently, the number of workers required for the EU's consumption was two times higher than the EU's domestic workforce (Figure 7f). Nevertheless, the vast majority of the value added created to supply the EU's material demand was generated within the EU (Figure 7g, SI Figure S10g).
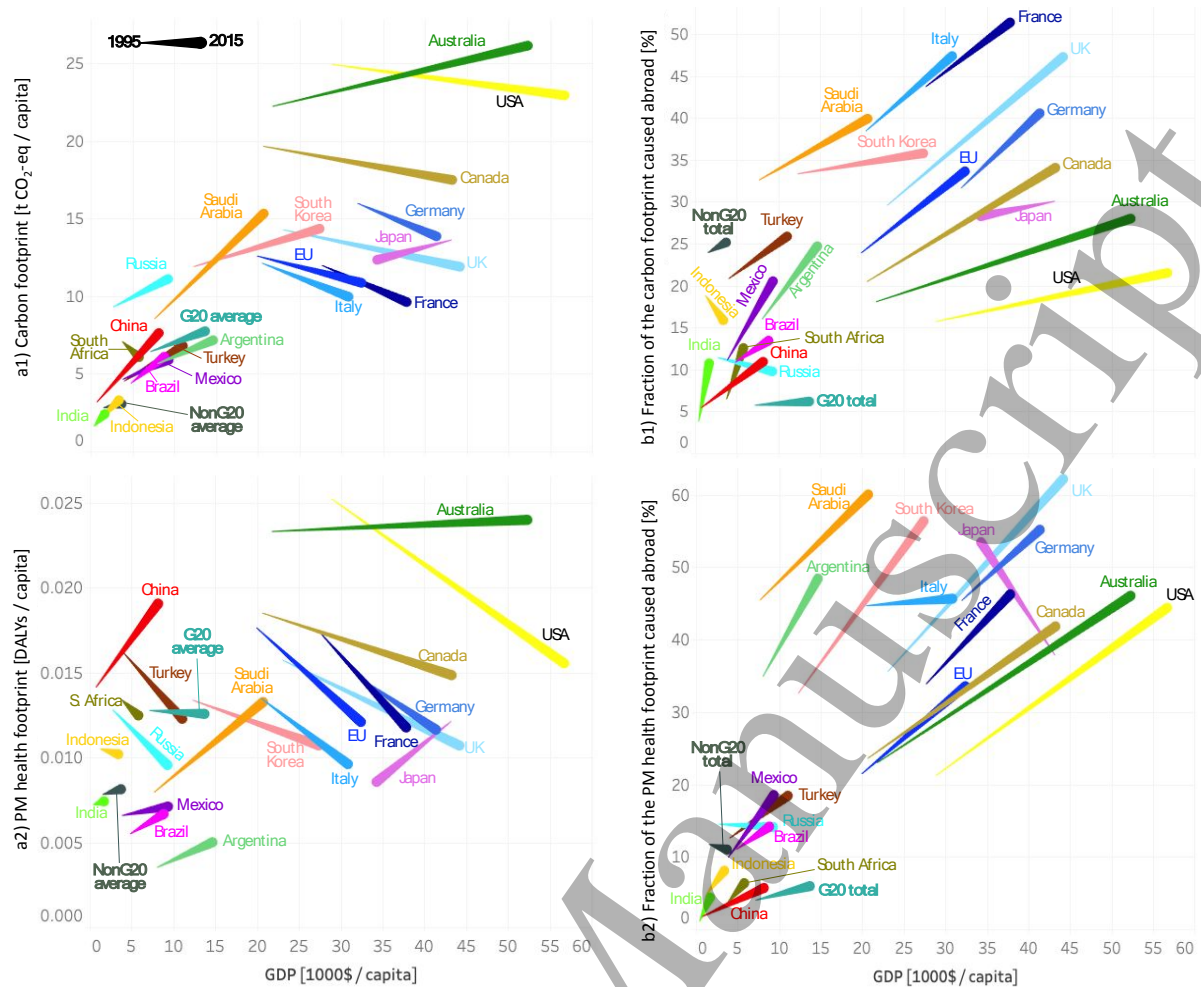
Figure 6. Change in a) the G20's GHG emissions and PM health impacts from a consumption perspective (carbon footprint) on a per-capita level and b) share of the G20's carbon and PM health footprint caused abroad, mainly due to material imports (SI Figure S6a–b) in 1995 and 2015 (as single data points for these two years) plotted against the GDP for all G20 members. The carbon and PM health footprint includes all emissions related to a region's consumption (including the emissions of imports, but excluding the emissions of exports).

Footprints of other high-income regions like Australia, Canada, Japan, and South Korea show a similar pattern of high domestic value creation and increased outsourcing of environmental impacts and low-paid workforce due to material imports (Figure 7, Figure S8–S12). Australia stands out as the region with the highest per-capita impacts from both a production and consumption perspective for all environmental indicators except domestic PM health impacts (Figure 7). On a per-capita level, Australia further stands out as the region with most raw material exports (mainly iron and steel, aluminum, copper, coal, and cattle meat), but the highest reliance on foreign low-paid workforce in the agriculture, farming, and mining sector of non-G20 regions to produce food, textiles, metals, chemicals, plastics, and other materials for export to Australia (Figure S17). Overall, three workers (in full-time-equivalents) are needed to supply the consumption of two people in Australia in 2015. The number of workers occupied worldwide to supply Australia's material and food demand is bigger than the number of people working in Australia's entire economy.
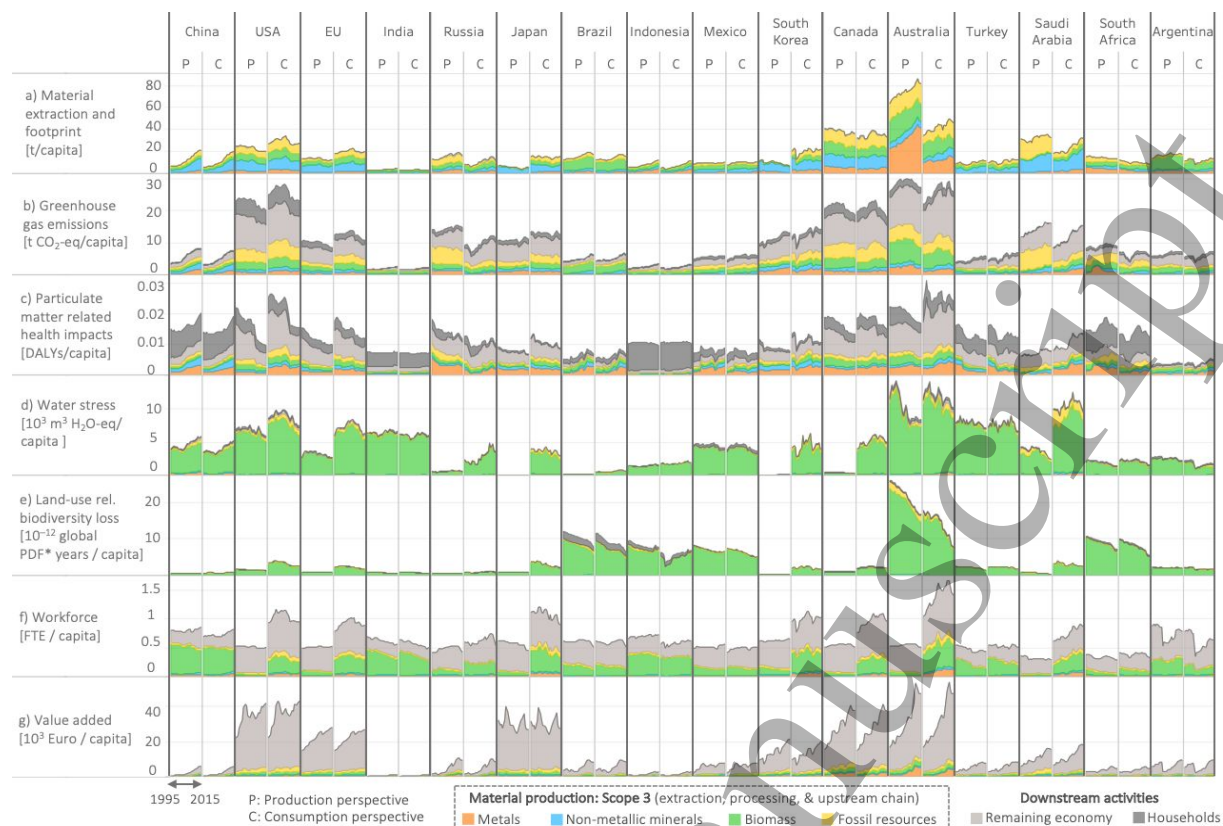
11

Figure 7. Temporal development of the environmental and socioeconomic impacts of the G20 members on a per-capita level split by scope 3 impacts of material production (metals, non-metallic minerals, biomass, fossil resources) and the remaining downstream economy and by households (mainly fossil fuels for GHG emissions, see Figure 2c) from a production (P) and consumption (C) perspective. G20 members with higher production than consumption accounts are net exporter of impacts, while countries with higher consumption than production accounts are net importer of impacts. Note that global land-use related biodiversity loss shows a decreasing trend in EXIOBASE3[27, 33], which is in contrast to other studies[44].

4. Conclusion and Outlook

This is the first study assessing the intermediate steps in the G20's material value chains, contrasting key aspects of sustainability, and highlighting the relevant hotspots, trade patterns, and key materials. Our analysis shows that previous standard accounting schemes in MRIO analysis would have either underestimated or overestimated the G20's material-related scope 3 GHG emissions (by more than 60% for metals and more than 20% for non-metallic minerals, biomass, and fossil resources). The inclusion of downstream emissions further increases the G20's scope 3 GHG emissions of fossil resources by a factor of three (compared to ref[10]). However, this study's downstream approach should be improved for analyzing GHG emissions related to biomass combustion, especially due to their importance for the future energy transition[80]. In addition to the analysis of GHG emissions performed here, this study's downstream approach could be applied to PM health impacts (e.g., as done in ref[64] for plastics). Also, further work is needed to include GHG emissions related to land use and related changes and forestry, as these data are lacking in EXIOBASE3[27]. Due to the limited quality and availability of mining-related water and land use data, future work should also improve mining-related water and land impacts. Moreover, future research is needed to

analyze this study's results for uncertainty, which could be addressed by extending the approach of Lenzen et al[81] and Zhang et al[82] to this study's methodology and database.

This study reveals that the rise in global coal emissions was mainly driven by the G20's production of metals and construction materials. In 2015, half of global coal was used for the production of metals and construction materials (while the other half was used for everything else than the production of these materials). We further conclude that the G20's displacement of climate and PM health impacts is mainly attributed to trade in materials within the G20, mostly high-income members such as the EU and USA who increasingly consume coal-intensive metals produced in China and India. In contrast, hotspots in the impact displacement of water stress, biodiversity loss, and low-paid workforce involve the G20's food imports from non-G20 members. An important countermeasure would be to internalize the external costs of supply chain impacts in the prices of commodities. A carbon price, such as carbon taxes, cap-and-trade emissions schemes, and renewable energy subsidies, would strongly improve the environmental performance of the production of metals and construction materials. Monetary incentives are also crucial to reduce the other key environmental impacts listed by the UN agenda. The internalization of external costs into end-users price should be discussed at the multilateral level, such as the G20 meeting due to its high policy level[18, 19], and implemented at the national and bilateral level, such as in bilateral trade agreements among the G20 members for reducing climate and health impacts (e.g., between the EU and China)[83] (see SI Paragraph S11 for further conclusions).

Conclusively, our results show that materials produced and consumed by the G20 play a pivotal role in complying with the Paris Agreement and many sustainable development goals. However, current trends are not sufficient to reach these targets. In the coming decades, the large build-up of infrastructure and the growing population anticipated for emerging economies will result in strong demands for materials, especially metals and construction materials, identified here as the main driver of coal emissions. Material-efficient urban design and circular economy solutions are of utmost importance to reduce the environmental impacts (e.g. sustainably sourced wood to substitute cement and steel[84, 85]). A fast exit from coal, a switch to renewable energies, and the electrification and emergence of carbon-capturing technologies is pivotal, but will also increase the demand for materials, particularly metals[86-88]. As shown here, most of the G20's GHG emissions are ultimately attributed to fossil fuels combustion (Figure 2e), and thus the potential of renewable energies is substantial. This requires investment along the entire value chain and thus the engagement of producer and consumer, both represented in the G20. Major producers involve China and India, whose production of metals and construction materials drove the rise in global coal emissions. Major consumers involve high-income countries, such as the EU and USA, who have the financial power, but have increasingly outsourced their material production to regions with less strict environmental policies, higher water stress, and more biodiversity loss. This study's method, database, and results support sustainable policy making by allowing for greater transparency in the supply chain assessment of nations, sectors, and materials, including the associated impacts. This information is important for estimating external costs and identifying consumer responsibilities to compensate or mitigate them.

13

Acknowledgements

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Author contributions: All authors designed the research and interpreted the results. Livia Cabernard wrote the manuscript with inputs from Stephan Pfister and Stefanie Hellweg. Livia Cabernard developed the method, extended the MRIO database to all G20 members, and performed the calculations.

Competing interests: The authors declare no competing interests.

Additional Information: PDF document with figures supporting the results of the research article: *"SupportingInformation_G20.pdf"* and classification of the sectors in EXIOBASE3 *"SI_Classification_G20.xlsx"*

References

1.   *United Nations (UN). The Sustainable Development Goals Report 2020*; 2020.

2.   *International Panel of Climate Change (IPCC). Global warming of 1.5 C*; World Meteorological Organization, Geneva, Switzerland: 2018.

3.   Hoegh-Guldberg, O.; Jacob, D.; Taylor, M.; Bolaños, T. G.; Bindi, M.; Brown, S.; Camilloni, I. A.; Diedhiou, A.; Djalante, R.; Ebi, K., The human imperative of stabilizing global climate change at 1.5 C. *Science* **2019,** *365*, (6459).

4.   WHO, Health statistics and information systems: the Global Burden of Disease (GBD) project. **2020**.

5.   *United Nations (UN) and World Bank Group. Making Every Drop Count: An Agenda for Water Action.* ; 2018.

6.   Sustainable Development Goals (SDGs). UN report: Nature's Dangerous Decline 'Unprecedented'; Species Extinction Rates 'Accelerating'. **2019**.

7.   Díaz, S. M.; Settele, J.; Brondízio, E.; Ngo, H.; Guèze, M.; Agard, J.; Arneth, A.; Balvanera, P.; Brauman, K.; Butchart, S., The global assessment report on biodiversity and ecosystem services: Summary for policy makers. **2019**.

8.   Ceballos, G.; Ehrlich, P. R.; Raven, P. H., Vertebrates on the brink as indicators of biological annihilation and the sixth mass extinction. *Proceedings of the National Academy of Sciences* **2020,** *117*, (24), 13596-13602.

9.   Hellweg, S.; Pfister, S.; Cabernard, L.; Droz-Georget, H.; Froemelt, A.; Haupt, M.; Mehr, J.; Oberschelp, C.; Piccoli, E.; Sonderegger, T., Environmental impacts of natural resource use. In *Global Resources Outlook 2019,* United Nations Environment Programme: 2019; pp 64-96.

10.   Cabernard, L.; Pfister, S.; Hellweg, S., A new method for analyzing sustainability performance of global supply chains and its application to material resources. *Science of the Total Environment* **2019,** *684*, 164-177. https://doi.org/10.1016/j.scitotenv.2019.04.434.

11.   OECD *Global Material Resources Outlook to 2060 - Economic Drivers and Environmental Consequences*; OECD Publishing, Paris, 2018.

12.   UNEP *Assessing global resource use: a systems approach to resource efficiency and pollution reduction*; Nairobi, Kenya, 2017.

13.   Nansai, K.; Tohno, S.; Chatani, S.; Kanemoto, K.; Kagawa, S.; Kondo, Y.; Takayanagi, W.; Lenzen, M., Consumption in the G20 nations causes particulate air pollution resulting in two million premature deaths annually. *Nature Communications* **2021,** *12*, (1), 1-12.

14.   IRP *Resource efficiency for sustainable development: key messages for the Group of 20*; 2018.

15.   Foran, B.; Lenzen, M.; Moran, D.; Alsamawi, A.; Geschke, A.; Kanemoto, K., Balancing the G20's Environmental Impact. **2014**.

16.   IRP, Natural resource use in the group of G20. Cabernard, L. Pfister, S. Hellweg, S. Baptista, M.J. *https://www.resourcepanel.org/reports/natural-resource-use-group-20* **2019**.

17.   G20. G20 Saudi Arbia 2020, https://g20.org/en/Pages/home.aspx (2020).

18.   Ghose, J.; Kapur, S., Policies and Practices to Enable Business Models for Resource Efficiency and a Circular Economy. In *G20 Summit Japan. Policy area: Climate Change and Environment.*, 2019.

19.   Klepper, G.; Peterson, S., The G20 Countries Should Lead the Way in Decarbonizing their Economies and Making the Paris Climate Agreement Work. In *G20 Summit Germany. Policy area: Climate Change and Environment.*, 2017.

20.   Hertwich, E. G.; Wood, R., The growing importance of scope 3 greenhouse gas emissions from industry. *Environmental Research Letters* **2018,** *13*, (10), 104013.

21.   Hoekstra, A. Y.; Wiedmann, T. O., Humanity's unsustainable environmental footprint. *Science* **2014,** *344*, (6188), 1114-1117.

22.   Peters, G. P., Carbon footprints and embodied carbon at multiple scales. *Current Opinion in Environmental Sustainability* **2010,** *2*, (4), 245-250.

23.   Hellweg, S.; i Canals, L. M., Emerging approaches, challenges and opportunities in life cycle assessment. *Science* **2014,** *344*, (6188), 1109-1113.

24.   Fong, W. K.; C40, M. D.; Deng-Beck, C., Global protocol for community-scale greenhouse gas emission inventories. **2014**.

25.   Bhatia, P.; Cummis, C.; Rich, D.; Draucker, L.; Lahd, H.; Brown, A., Greenhouse gas protocol corporate value chain (scope 3) accounting and reporting standard. **2011**.

26.   Pelletier, N.; Allacker, K.; Pant, R.; Manfredi, S., The European Commission Organisation Environmental Footprint method: comparison with other methods, and rationales for key requirements. *The International Journal of Life Cycle Assessment* **2014,** *19*, (2), 387-404.

27.   Stadler, K.; Wood, R.; Bulavskaya, T.; Södersten, C.-J.; Simas, M.; Schmidt, S.; Usubiaga, A.; Acosta-Fernández, J.; Kuenen, J.; Bruckner, M.; Giljum, S.; Lutter, S.; Merciai, S.; Schmidt, J. H.; Theurl, M. C.; Plutzar, C.; Kastner, T.; Eisenmenger, N.; Erb, K.-H.; de Koning, A.; Tukker, A., EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. *Journal of Industrial Ecology* **2018,** *22*, (3), 502-515.

28.   Andrew, R. M.; Peters, G. P., A multi-region input–output table based on the global trade analysis project database (GTAP-MRIO). *Economic Systems Research* **2013,** *25*, (1), 99-121.

29.   Lenzen, M.; Moran, D.; Kanemoto, K.; Geschke, A., Building Eora: a global multi-region input–output database at high country and sector resolution. *Economic Systems Research* **2013,** *25*, (1), 20-49.

30.   Wiedmann, T.; Lenzen, M., Environmental and social footprints of international trade. *Nature Geoscience* **2018,** *11*, (5), 314-321.

31.   Steen-Olsen, K.; Weinzettel, J.; Cranston, G.; Ercin, A. E.; Hertwich, E. G., Carbon, land, and water footprint accounts for the European Union: consumption, production, and displacements through international trade. *Environmental science & technology* **2012,** *46*, (20), 10883-10891.

32.   Weinzettel, J.; Pfister, S., International trade of global scarce water use in agriculture: Modeling on watershed level with monthly resolution. *Ecological Economics* **2019,** *159*, 301-311.

33.   Wood, R.; Stadler, K.; Simas, M.; Bulavskaya, T.; Giljum, S.; Lutter, S.; Tukker, A., Growth in Environmental Footprints and Environmental Impacts Embodied in Trade: Resource Efficiency Indicators from EXIOBASE3. *Journal of Industrial Ecology* **2018,** *22*, (3), 553-564.

34.   Meng, B.; Peters, G. P.; Wang, Z.; Li, M., Tracing CO2 emissions in global value chains. *Energy Economics* **2018,** *73*, 24-42.

35.   Ottelin, J.; Ala-Mantila, S.; Heinonen, J.; Wiedmann, T.; Clarke, J.; Junnila, S., What can we learn from consumption-based carbon footprints at different spatial scales? Review of policy implications. *Environmental Research Letters* **2019,** *14*, (9), 093001.

36.   Lenzen, M.; Moran, D.; Kanemoto, K.; Foran, B.; Lobefaro, L.; Geschke, A., International trade drives biodiversity threats in developing nations. *Nature* **2012,** *486*, (7401), 109.

37.   Kanemoto, K.; Moran, D.; Lenzen, M.; Geschke, A., International trade undermines national emission reduction targets: New evidence from air pollution. *Global Environmental Change* **2014,** *24*, 52-59.

38.   Tukker, A.; Pollitt, H.; Henkemans, M., Consumption-based carbon accounting: sense and sensibility. In Taylor & Francis: 2020.

39.   Wood, R.; Moran, D. D.; Rodrigues, J. F.; Stadler, K., Variation in trends of consumption based carbon accounts. *Scientific Data* **2019,** *6*, (1), 1-9.

40.   Peters, G. P.; Hertwich, E. G., Post-Kyoto greenhouse gas inventories: production versus consumption. *Climatic Change* **2008,** *86*, (1-2), 51-66.

41.   Los, B.; Timmer, M. P.; de Vries, G. J., How global are global value chains? A new approach to measure international fragmentation. *Journal of regional science* **2015,** *55*, (1), 66-92.

42.   Timmer, M. P.; Erumban, A. A.; Los, B.; Stehrer, R.; De Vries, G. J., Slicing up global value chains. *Journal of economic perspectives* **2014,** *28*, (2), 99-118.

43.   Wiedmann, T. O.; Schandl, H.; Lenzen, M.; Moran, D.; Suh, S.; West, J.; Kanemoto, K., The material footprint of nations. *Proc Natl Acad Sci U S A* **2015,** *112*, (20), 6271-6.

44.   UNEP *Global material flows and resource productivity*; 2016.

45.   Bruckner, M.; Giljum, S.; Lutz, C.; Wiebe, K. S., Materials embodied in international trade–Global material extraction and consumption between 1995 and 2005. *Global Environmental Change* **2012,** *22*, (3), 568-576.

46.   Feng, K.; Chapagain, A.; Suh, S.; Pfister, S.; Hubacek, K., Comparison of bottom-up and top-down approaches to calculating the water footprints of nations. *Economic Systems Research* **2011,** *23*, (4), 371-385.

47.   Lenzen, M.; Moran, D.; Bhaduri, A.; Kanemoto, K.; Bekchanov, M.; Geschke, A.; Foran, B., International trade of scarce water. *Ecological Economics* **2013,** *94*, 78-85.

48.   Lutter, S.; Pfister, S.; Giljum, S.; Wieland, H.; Mutel, C., Spatially explicit assessment of water embodied in European trade: A product-level multi-regional input-output analysis. *Global environmental change* **2016,** *38*, 171-182.

49.   Weinzettel, J.; Hertwich, E. G.; Peters, G. P.; Steen-Olsen, K.; Galli, A., Affluence drives the global displacement of land use. *Global Environmental Change* **2013,** *23*, (2), 433-438.

50.   Yu, Y.; Feng, K.; Hubacek, K., Tele-connecting local consumption to global land use. *Global Environmental Change* **2013,** *23*, (5), 1178-1186.

51.   Hertwich, E. G.; Peters, G. P., Carbon footprint of nations: A global, trade-linked analysis. *Environmental science & technology* **2009,** *43*, (16), 6414-6420.

52.   Davis, S. J.; Caldeira, K., Consumption-based accounting of CO2 emissions. *Proceedings of the National Academy of Sciences* **2010,** *107*, (12), 5687-5692.

53.   Kanemoto, K.; Moran, D.; Hertwich, E. G., Mapping the Carbon Footprint of Nations. *Environ Sci Technol* **2016,** *50*, (19), 10512-10517.

54.   Moran, D.; Kanemoto, K., Tracing global supply chains to air pollution hotspots. *Environmental Research Letters* **2016,** *11*, (9).

55.   Verones, F.; Moran, D.; Stadler, K.; Kanemoto, K.; Wood, R., Resource footprints and their ecosystem consequences. *Sci Rep* **2017,** *7*, 40743.

56.   Moran, D.; Kanemoto, K., Identifying species threat hotspots from global supply chains. *Nat Ecol Evol* **2017,** *1*, (1), 23.

57.   Zimdars, C.; Haas, A.; Pfister, S., Enhancing comprehensive measurement of social impacts in S-LCA by including environmental and economic aspects. *The International Journal of Life Cycle Assessment* **2018,** *23*, (1), 133-146.

58.   Li, M.; Wiedmann, T.; Hadjikakou, M., Enabling Full Supply Chain Corporate Responsibility: Scope 3 Emissions Targets for Ambitious Climate Change Mitigation. *Environmental science & technology* **2019,** *54*, (1), 400-411.

59.   Wiedmann, T.; Chen, G.; Owen, A.; Lenzen, M.; Doust, M.; Barrett, J.; Steele, K., Three-scope carbon emission inventories of global cities. *Journal of Industrial Ecology* **2020**.

60.   Roelfsema, M.; van Soest, H. L.; Harmsen, M.; van Vuuren, D. P.; Bertram, C.; den Elzen, M.; Höhne, N.; Iacobuta, G.; Krey, V.; Kriegler, E., Taking stock of national climate policies to evaluate implementation of the Paris Agreement. *Nature Communications* **2020,** *11*, (1), 1-12.

61.   Dente, S. M. R.; Aoki-Suzuki, C.; Tanaka, D.; Hashimoto, S., Revealing the life cycle greenhouse gas emissions of materials: The Japanese case. *Resources, Conservation and Recycling* **2018,** *133*, 395-403.

62.   Dente, S. M.; Aoki-Suzuki, C.; Tanaka, D.; Kayo, C.; Murakami, S.; Hashimoto, S., Effects of a new supply chain decomposition framework on the material life cycle greenhouse gas emissions—the Japanese case. *Resources, Conservation and Recycling* **2019,** *143*, 273-281.

63.   Aoki-Suzuki, C.; Dente, S. M.; Tanaka, D.; Kayo, C.; Murakami, S.; Fujii, C.; Tahara, K.; Hashimoto, S., Total environmental impacts of Japanese material production. *Journal of Industrial Ecology* **2021**.

64.   Cabernard, L.; Pfister, S.; Oberschelp, C.; Stefanie, H., Growing environmental footprint of plastics driven by coal combustion. *accepted in Nature Sustainability*.

65.   IRP, Global Resources Outlook 2019: Natural Resources for the Future We Want. Oberle, B. et al. A Report of the International Resource Panel. United Nations Environment Programme. Nairobi, Kenya. **2019**.

66.   Hertwich, E. G., Increased carbon footprint of materials production driven by rise in investments. *Nature Geoscience* **2021**, 1-5.

67.   Itten, R.; Hischier, R.; Andrae, A. S.; Bieser, J. C.; Cabernard, L.; Falke, A.; Ferreboeuf, H.; Hilty, L. M.; Keller, R. L.; Lees-Perasso, E., Digital transformation—life cycle assessment of

digital services, multifunctional devices and cloud computing. *The International Journal of Life Cycle Assessment* **2020**, 1-6.

68.   Freitag, C.; Berners-Lee, M.; Widdicks, K.; Knowles, B.; Blair, G. S.; Friday, A., The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations. *Patterns* **2021,** *2*, (9), 100340.

69.   Cabernard, L.; Pfister, S., A highly resolved MRIO database for analyzing environmental footprints and Green Economy Progress. *Science of The Total Environment* **2020**, 142587. https://doi.org/10.1016/j.scitotenv.2020.142587.

70.   Vohra, K.; Vodonos, A.; Schwartz, J.; Marais, E. A.; Sulprizio, M. P.; Mickley, L. J., Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem. *Environmental Research* **2021,** *195*, 110754.

71.   International Energy Agency (IEA). CO2 Emissions from Fuel Combustion: Overview, IEA, Paris *https://www.iea.org/reports/co2-emissions-from-fuel-combustion-overview* **2020**.

72.   FAOSTAT, Data. **2019,** *https://www.fao.org/faostat/en/#data*.

73.   Pfister, S.; Lutter, S. F., How EU27 is outsourcing the vast majority of its land and water footprint. **2016**.

74.   Pfister, S.; Bayer, P., Monthly water stress: spatially and temporally explicit consumptive water footprint of global crop production. *Journal of Cleaner Production* **2014,** *73*, 52-62.

75.   Pfister, S.; Bayer, P.; Koehler, A.; Hellweg, S., Environmental impacts of water use in global crop production: hotspots and trade-offs with land use. *Environmental science & technology* **2011,** *45*, (13), 5761-5768.

76.   Chaudhary, A.; Verones, F.; de Baan, L.; Pfister, S.; Hellweg, S., 11. Land stress: Potential species loss from land use (global; PSSRg). *Transformation* **2016,** *1000*, 2.

77.   UNEP-SETAC *Life Cycle Initiative. Global guidance for life cycle impact assessment indicators*; 2016.

78.   Miller, R. E.; Blair, P. D., *Input-output analysis: foundations and extensions*. Cambridge university press: 2009.

79.   Muller, S.; Lai, F.; Beylot, A.; Boitier, B.; Villeneuve, J., No mining activities, no environmental impacts? Assessing the carbon footprint of metal requirements induced by the consumption of a country with almost no mines. *Sustainable Production and Consumption* **2020,** *22*, 24-33.

80.   Cozzi, L.; Gould, T.; Bouckart, S.; Crow, D.; Kim, T.; Mcglade, C.; Olejarnik, P.; Wanner, B.; Wetzel, D., World Energy Outlook 2020. *Paris: IEA* **2020**.

81.   Lenzen, M.; Wood, R.; Wiedmann, T., Uncertainty analysis for multi-region input–output models–a case study of the UK's carbon footprint. *Economic Systems Research* **2010,** *22*, (1), 43-63.

82.   Zhang, H.; He, K.; Wang, X.; Hertwich, E. G., Tracing the uncertain Chinese mercury footprint within the global supply chain using a stochastic, nested input–output model. *Environmental science & technology* **2019,** *53*, (12), 6814-6823.

83.   European Commission. Negotiations and agreements. https://ec.europa.eu/trade/policy/countries-and-regions/negotiations-and-agreements/.

84.   Churkina, G.; Organschi, A.; Reyer, C. P.; Ruff, A.; Vinke, K.; Liu, Z.; Reck, B. K.; Graedel, T.; Schellnhuber, H. J., Buildings as a global carbon sink. *Nature Sustainability* **2020**, 1-8.

85.   Tripathi, N.; Hills, C. D.; Singh, R. S.; Atkinson, C. J., Biomass waste utilisation in low-carbon products: harnessing a major potential resource. *npj Climate and Atmospheric Science* **2019,** *2*, (1), 1-10.

86.   Sovacool, B. K.; Ali, S. H.; Bazilian, M.; Radley, B.; Nemery, B.; Okatz, J.; Mulvaney, D., Sustainable minerals and metals for a low-carbon future. *Science* **2020,** *367*, (6473), 30-33.

87.   Hertwich, E. G.; Gibon, T.; Bouman, E. A.; Arvesen, A.; Suh, S.; Heath, G. A.; Bergesen, J. D.; Ramirez, A.; Vega, M. I.; Shi, L., Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences* **2015,** *112*, (20), 6277-6282.

88.   Yokoi, R.; Watari, T.; Motoshita, M., Future greenhouse gas emissions from metal production: gaps and opportunities towards climate goals. *Energy & Environmental Science* **2021**.

19