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Creating transparency in global value chains and their environmental impacts to support sustainability policies

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Zurich, December 2021 Livia Cabernard

Abstract

Climate change, air pollution, water stress, and biodiversity loss are the most important global environmental impacts that need to be addressed in the coming decades. This thesis shows that most of these impacts are caused by the extraction and processing of materials, food, and fuels, summarized as "materials" here. With the demand for materials expected to double by 2050, improved sustainability policies are critical. As many materials are produced in another country than ultimately consumed, such policies require detailed information on global value chains and their environmental impacts. Multi-regional input-output (MRIO) analysis plays a key role in providing this information, but several research gaps exist. One gap is the lack of an accurate method for assessing scope 3 impacts of materials, industries, and nations, including cumulative upstream and direct impacts (for any impact category). Also, no method exists for analyzing downstream impacts, which is a particular issue for greenhouse gas (GHG) and particulate matter (PM) emissions of fuels, such as coal. Another gap is the limited spatial and sectoral resolution and the incomplete coverage of sustainability indicators in current MRIO databases. This includes the lack of regionalized assessment of water and land use impacts. Due to these gaps, an accurate and extensive environmental assessment of materials is missing both globally and nationally.

The objective of this thesis was to provide an improved MRIO method and database for creating transparency in global value chains and their impacts, to support sustainable policy-making. For this purpose, a method was developed that allows assessing the scope 3 impacts of any sector and region of an MRIO database (Chapter 2), tracking them along the global value chain (for GHG emissions and any other impact category), and analyzing downstream impacts (for GHG and PM emissions of fuels, Chapter 4 and 5). Furthermore, an automated, transparent, and time-efficient approach was developed to improve the resolution and quality of an existing MRIO database (Chapter 3). It was applied to merge the global MRIO databases EXIOBASE3 and Eora26 and add data from FAOSTAT and previous studies to create an MRIO database with high spatial (189 countries), sectoral (163 sectors), and temporal resolution (year 1995–2015). Finally, a set of sustainability indicators was implemented into the database: Climate change from GHG emissions, health impacts from PM emissions (primary and secondary particles), water stress and land-use-related biodiversity loss (both regionalized), value added, and number of workers (Chapter 2–5).

The importance, versatility, and broad applicability of the improved method and database was illustrated by several application examples. These include a case study on material production globally (Chapter 2) and for the G20 (Chapter 4). An in-depth analysis of the role of coal combustion is provided in Chapter 4 for the production of metals and construction materials, and in Chapter 5 for global plastics production. A detailed analysis of the food supply chain and the related water and land footprint is shown in Chapter 3 for the European Union (EU).

The case study on global material production (Chapter 2) showed that previous MRIO methods either underestimated or overestimated the environmental impacts of material production by 20–60%. The improved method found that material production causes half of global GHG emissions, one-third of global PM health impacts, and, because of biomass production, more than 90% of global water stress and land-use related biodiversity loss. Since 1995, global material-related impacts have increased by 52% (GHG emissions), 56% (PM health impacts), and 22% (water stress). While high-income regions mainly use materials for private consumption, emerging economies use a large share of materials for infrastructure build-up. Although the latter was the main driver of the rising material-related GHG emissions, material-related carbon footprints of high-income regions are still several times higher than those of emerging economies on a per-capita level (year 2015). This underscores the need to decouple environmental impacts from economic growth and to promote sufficiency measures.

Material production for building infrastructure in emerging economies, mainly China, has also driven the increase in the G20's overall carbon footprint (Chapter 4). Since 1995, China's carbon footprint of metals and construction materials has quadrupled, causing more than 10% of global GHG emissions in 2015. Similarly, the case study on plastics (Chapter 5) showed that plastics-related carbon footprints of China's transportation, Indonesia's electronics industry, and India's construction sector have increased more than 50-fold. Thus, measures to reduce, reuse, recycle, and substitute high-impact materials are critical to mitigate the environmental impacts of the expected economic growth in developing countries.

Reliance on coal to produce materials has been another key driver of the G20's rising carbon footprint (Chapter 4). In 2015, half of global coal was used for the G20's production of metals and construction materials, the majority in China and India. Thus, 85% of India's total domestic coal was used for the production of these materials in 2015. This points to the need for a rapid phase-out of coal and a shift to renewables in the G20's material production chain. Similarly, it was found that due to the growth in plastics production in coal-based economies, the carbon and PM health footprint of plastics has doubled since 1995 (Chapter 5). In 2015, 6% of global coal electricity was used for plastics production. Moreover, plastics accounted for 4.5% of global GHG emissions. This is higher than expected, as previous studies did not account for the increased reliance on coal energy in the plastics sector. It was also assumed that equal amounts of oil were used as fuel and feedstock in plastics production, while this thesis shows that twice as much fossil carbon is combusted as fuel than contained as feedstock. Even in a worst-case scenario where all plastics were incinerated, the production stage would still contribute most to plastics-related GHG and PM emissions. This means that previous studies have underestimated the relative significance of the production versus the disposal phase, and thus the enormous potential to reduce the carbon and PM health footprint of plastics by renewable energy investments.

High-income regions have significantly contributed to the rising environmental impacts by outsourcing the extraction of resources and processing into materials to lower-income regions with less stringent environmental policies, more water stress, and high biodiversity (Chapter 2–5). Due to increasing imports of plastics from coal-based economies, the share of the plastic-related carbon footprint generated abroad increased to 67% in the EU, 79% in the USA, 90% in Canada, and 95% in Australia in 2015 (Chapter 5). Similarly, the case study on the EU's water-stress and land-use related biodiversity loss footprint found that most of the associated impacts are caused abroad (Chapter 3). This is mainly attributed to food imports from emerging and developing countries where water is scarce (e.g. Egypt) and biodiversity is high (e.g. Madagascar). The improved spatial resolution (189 countries instead of 49 regions) and regionalized impact assessment led to a significant increase in the EU's water and land impact footprint induced abroad. These results highlight the need for expanding environmental policy initiatives (e.g., the Paris Agreement and the EU's Green Deal) from production-based to consumption-based accounting to foster improved supply chain management. This includes the investment in clean energy production throughout the supply chain and the use of regional comparative advantage for reducing water stress and biodiversity loss.

In addition to environmental impacts, the value added and workforce associated with material production are also unequally distributed around the world. Trade in materials reinforces this imbalance (Chapter 2–5). It was shown that although high-income regions strongly rely on low-paid work abroad due to material imports (mainly food), they generate most of the associated value added inland (e.g., due to food processing). The extent of this imbalance was highlighted, e.g., in the G20 case study: Since 2011, the number of workers employed globally to meet Australia's material demand is greater than the number of workers employed in the entire Australian economy (Chapter 4). Similarly, the plastics case study found that although 70% of the workforce required for plastics consumption in the EU was employed abroad, 80% of the associated value added was generated domestically (year 2015), as only the low-paid steps in the plastics value chain have been outsourced (Chapter 5).

The method and database of this thesis are open access and can be applied by researchers, industries, and policy makers for a more accurate impact assessment of various materials, commodities, industries, and nations. The method is available as a software tool that can be used to track the scope 3 impacts of industries and nations for a range of sustainability indicators along the global value chain (Chapter 2). Future work can apply the approach of Chapter 3 to improve the spatial, sectoral, and temporal resolution and quality of the database by integrating further MRIO databases and data sources. Also, future work is needed to incorporate detailed bottom-up inventories and use remote sensing data to improve the resolution and coverage of life-cycle inventories.

Zusammenfassung

Klimawandel, Luftverschmutzung, Wasserstress und Biodiversitätsverlust sind die wichtigsten globalen Umweltprobleme, die in den kommenden Jahrzehnten angegangen werden müssen. Diese Doktorarbeit zeigt, dass diese Umweltprobleme mehrheitlich bei der Gewinnung und Verarbeitung von Materialien, Nahrungsmitteln und Brennstoffen entstehen, die hier als "Materialien" zusammengefasst werden. Da sich die Nachfrage nach Materialien bis 2050 voraussichtlich verdoppeln wird, sind verbesserte Nachhaltigkeitsstrategien von zentraler Bedeutung. Da viele Materialien in einem anderen Land produziert als letztendlich konsumiert werden, erfordern solche Strategien detaillierte Daten über globale Wertschöpfungsketten und deren Umweltwirkungen. Die multiregionale Input-Output-Analyse (MRIO) spielt eine Schlüsselrolle bei der Bereitstellung dieser Daten, doch gibt es mehrere Forschungslücken. Eine Lücke ist das Fehlen einer genauen Methodik zur Bewertung von Scope-3-Auswirkungen von Materialien, Sektoren und Ländern, einschließlich kumulativer vorgelagerter und direkter Umweltwirkungen (für jede Wirkungskategorie). Zudem gibt es keine Methode zur Analyse der nachgelagerten Umweltwirkungen, was insbesondere für Treibhausgas-(THG) und Feinstaubemissionen von Brennstoffen wie beispielsweise Kohle zentral wäre. Eine weitere Lücke ist die begrenzte räumliche und sektorale Auflösung und die unvollständige Abdeckung von Indikatoren zur Nachhaltigkeitsbewertung in aktuellen MRIO-Datenbanken. Dazu gehört die fehlende regionalisierte Bewertung der Auswirkungen von Wasser- und Landnutzung. Aufgrund dieser Forschungslücken fehlt eine genaue und umfassende Quantifizierung der Umweltwirkungen von Materialien sowohl auf globaler als auch auf nationaler Ebene.

Ziel dieser Arbeit war es, eine verbesserte MRIO-Methode und -Datenbank zur Schaffung von Transparenz in globalen Wertschöpfungsketten und deren Umweltwirkungen bereitzustellen, um nachhaltige politische Entscheidungen zu unterstützen. Zu diesem Zweck wurde eine Methodik entwickelt, die es erlaubt die Scope-3-Auswirkungen beliebiger Sektoren und Regionen einer MRIO-Datenbank zu bewerten (Kapitel 2), sie entlang der globalen Wertschöpfungskette zu verfolgen (für THG-Emissionen und beliebige andere Umweltwirkungskategorien) sowie die nachgelagerten Emissionen zu analysieren (für THG- und Feinstaubemissionen von Brennstoffen, Kapitel 4–5). Weiterhin wurde ein automatisierter, transparenter und zeiteffizienter Ansatz entwickelt, um die Auflösung und Qualität einer bestehenden MRIO-Datenbank zu verbessern (Kapitel 3). Mit diesem Ansatz wurden die globalen MRIO-Datenbanken EXIOBASE3 und Eora26 zusammengeführt, Daten aus FAOSTAT und früheren Studien integriert und eine MRIO-Datenbank mit hoher räumlicher (189 Länder), sektoraler (163 Sektoren) und zeitlicher Auflösung (Jahr 1995–2015) erstellt. Schließlich wurde eine Reihe von Nachhaltigkeitsindikatoren in die MRIO Datenbank implementiert: Klimawandel durch THG-Emissionen, Gesundheitsauswirkungen durch Feinstaub (primäre und sekundäre Partikel), Wasserstress und landnutzungsbedingter Biodiversitätsverlust (beides regionalisiert), Wertschöpfung und Anzahl der Arbeitskräfte (Kapitel 2–5).

Die Bedeutung, Vielseitigkeit und breite Anwendbarkeit der verbesserten Methodik und Datenbank wurde anhand mehrerer Anwendungsbeispiele veranschaulicht. Dazu gehört eine Fallstudie zur Materialproduktion weltweit (Kapitel 2) und für die G20 (Kapitel 4). Eine

eingehende Analyse der Rolle der Kohleverbrennung wird in Kapitel 4 für die Produktion von Metallen und Baumaterialien und in Kapitel 5 für die weltweite Kunststoffproduktion vorgenommen. Eine detaillierte Analyse der Lebensmittelversorgungskette und des damit verbundenen Wasser- und Land-Fußabdrucks wird in Kapitel 3 für die Europäische Union (EU) präsentiert.

Die Fallstudie zur globalen Materialproduktion (Kapitel 2) hat gezeigt, dass frühere MRIO-Methoden die Umweltauswirkungen der Materialproduktion entweder unter- oder überschätzt haben, und zwar um 20–60%. Die verbesserte Methodik ergab, dass die Materialproduktion die Hälfte der globalen THG-Emissionen, ein Drittel der globalen Feinstaub-Gesundheitsauswirkungen und aufgrund der Biomasseproduktion mehr als 90% des globalen Wasserstresses und des landnutzungsbedingten Biodiversitätsverlustes verursacht. Seit 1995 sind die globalen materialbedingten Auswirkungen um 52% (THG-Emissionen), 56% (Feinstaub-Gesundheitsauswirkungen) und 22% (Wasserstress) gestiegen. Während reiche Länder Materialien hauptsächlich für den privaten Konsum verwenden, werden sie in Schwellenländern vor allem für den Bau der Infrastruktur genutzt. Obwohl Letzteres die Hauptursache für den Anstieg der materialbedingten THG-Emissionen war, sind die materialbedingten THG-Fußabdrücke von reichen Ländern auf Pro-Kopf-Ebene immer noch um ein Vielfaches höher als die von Schwellenländern. Dies unterstreicht die Notwendigkeit, die Umweltauswirkungen vom Wirtschaftswachstum abzukoppeln und Maßnahmen zur Suffizienz zu fördern.

Die Materialproduktion für den Bau von Infrastruktur in Schwellenländern, vor allem in China, hat auch am stärksten zum THG-Fußabdruck der G20 beigetragen (Kapitel 4). Seit 1995 hat sich Chinas THG-Fußabdruck von Metallen und Baumaterialien vervierfacht und verursachte im Jahr 2015 mehr als 10% der globalen THG-Emissionen. In ähnlicher Weise zeigte die Fallstudie zu Kunststoffen (Kapitel 5), dass die kunststoffbedingten THG-Fußabdrücke des chinesischen Verkehrssektors, der indonesischen Elektronikindustrie und des indischen Bausektors um mehr als das 50-fache gestiegen sind. Daher sind Maßnahmen zur Verringerung, Wiederverwendung, zum Recycling und zur Substitution besonders umweltschädlicher Materialien von entscheidender Bedeutung, um die Umweltauswirkungen des erwarteten Wirtschaftswachstums in Entwicklungsländern einzudämmen.

Die Abhängigkeit von Kohle zur Herstellung von Materialien war ein weiterer Schlüsselfaktor des steigenden THG-Fußabdrucks der G20 (Kapitel 4). Im Jahr 2015 wurde die Hälfte der weltweit abgebauten Kohle für die Produktion von Metallen und Baumaterialien in den G20 verbrannt, vor allem in China und Indien. In Indien wurde damit 85% der gesamten Kohle nur für die Produktion dieser Materialien eingesetzt. Dies verdeutlicht, wie zentral der rasche Ausstieg aus Kohle und die Umstellung auf erneuerbare Energien in der Materialproduktionskette der G20 ist. Ebenso wurde festgestellt, dass sich der THG- und Feinstaub-Fußabdruck von Kunststoffen aufgrund des Wachstums der Kunststoffproduktion in kohlebasierten Volkswirtschaften seit 1995 verdoppelt hat (Kapitel 5). Im Jahr 2015 wurden 6% des weltweiten Kohlestroms für die Kunststoffproduktion verwendet. Darüber hinaus waren Kunststoffe für 4.5% der weltweiten THG-Emissionen verantwortlich. Dies ist höher als erwartet, da die zunehmende Abhängigkeit von Kohleenergie im Kunststoffsektor bisher nicht berücksichtigt wurde. Auch wurde davon ausgegangen, dass Öl in der Kunststoffproduktion zu gleichen Teilen als Brennstoff und als Ausgangsstoff verwendet wird, während hier gezeigt wird, dass doppelt so viel fossiler Kohlenstoff als Brennstoff verbrannt wird, wie als Ausgangsmaterial enthalten ist. Selbst in einem Worst-Case-Szenario, in dem alle Kunststoffe verbrannt würden, würde die Produktionsphase immer noch weitaus am stärksten zu den THG-und Feinstaub-emissionen von Kunststoffen beitragen. Damit wurde die relative Bedeutung der Produktions-phase gegenüber der Entsorgungsphase unterschätzt und somit auch das enorme Potential zur Verringerung des Kohlenstoff- und Feinstaub-Fußabdrucks von Kunststoffen durch Investitionen in erneuerbare Energien.

Reiche Länder haben erheblich zu den steigenden Umweltauswirkungen beigetragen, indem sie den Abbau von Ressourcen und deren Verarbeitung in Materialien in Länder mit tieferem Einkommen, weniger strengen Umweltrichtlinien, mehr Wasserstress und höherer Arten-vielfalt verlagert haben (Kapitel 2–5). Aufgrund zunehmender Importe von Kunststoffen aus kohlebasierten Volkswirtschaften stieg der Anteil des im Ausland verursachten kunststoff-bedingten THG-Fußabdrucks im Jahr 2015 auf 67% in der EU, 79% in den USA, 90% in Kanada und 95% in Australien (Kapitel 5). Auch die Fallstudie zum Wasserstress und landnutzungs-bedingten Biodiversität-Fußabdruck der EU ergab, dass die meisten dieser Auswirkungen im Ausland anfallen (Kapitel 3). Dies ist vor allem auf Lebensmittelimporte aus Schwellen- und Entwicklungsländern zurück zu führen wo Wasser knapp (z. B. Ägypten) und die Artenvielfalt hoch ist (z. B. Madagaskar). Aufgrund der verbesserten räumlichen Auflösung der MRIO-Datenbank (189 Länder statt 49 Regionen) und der regionalisierten Wirkungsabschätzung ist der im Ausland verursachte Wasser- und Land-Fußabdruck der EU deutlich gestiegen. Diese Ergebnisse unterstreichen die Notwendigkeit, politische Umwelt-Zielvereinbarungen (z. B. das Pariser Abkommen und der Europäische Grüne Deal) von einer produktionsbasierten auf eine konsumbasierte Bilanzierung auszuweiten, um das Lieferkettenmanagement zu fördern. Dazu gehören Investitionen in saubere Energieerzeugung in der Lieferkette und die Nutzung regionaler komparativer Vorteile zur Reduktion von Wasserstress und Artenverlust.

Neben den Umweltwirkungen sind auch die Wertschöpfung und die mit der Material-produktion verbundenen Arbeitskräfte weltweit ungleich verteilt. Der Handel mit Materialien verstärkt dieses Ungleichgewicht (Kapitel 2–5). Es wurde gezeigt, dass Regionen mit hohem Einkommen aufgrund von Materialimporten (vor allem Lebensmittel) zwar stark auf schlecht bezahlte Arbeit im Ausland angewiesen sind, den größten Teil der damit verbundenen Wertschöpfung aber im Inland erwirtschaften (z. B. durch die Lebensmittelverarbeitung). Das Ausmaß dieses Ungleichgewichts wurde beispielsweise in der G20-Fallstudie aufgezeigt: Seit 2011 ist die Zahl der weltweit beschäftigten Arbeitskräfte zur Deckung der australischen Nachfrage nach Materialien größer als die Zahl der in der gesamten australischen Wirtschaft beschäftigten Arbeitskräfte (Kapitel 4). In ähnlicher Weise ergab die Fallstudie zu Kunststoffen, dass zwar 70% der für den Kunststoffverbrauch in der EU benötigten Arbeits-kräfte im Ausland beschäftigt waren, aber 80% der damit verbundenen Wertschöpfung im Inland erwirtschaftet wurde, da lediglich die schlechtbezahlten Schritte in der Plastikwert-schöpfungskette ausgelagert wurden (Jahr 2015, Kapitel 5).

Die Methodik und Datenbank dieser Arbeit sind öffentlich verfügbar und können von Forscher/Innen, Industrien und politischen Entscheidungsträgern/Innen für eine genauere Folgenabschätzung diverser Materialien, Produkte, Industrien und Länder angewendet werden. Die Methodik ist als Software-Tool verfügbar, mit dem die Scope-3-Auswirkungen beliebiger Industrien und Länder für eine Reihe von Nachhaltigkeitsindikatoren entlang der globalen Wertschöpfungskette verfolgt werden können (Kapitel 2). Zukünftige Arbeiten können den Ansatz aus Kapitel 3 anwenden, um die räumliche, sektorale und zeitliche Auflösung und Qualität der Datenbank durch die Integration weiterer MRIO-Datenbanken und Datenquellen zu verbessern. Außerdem sind künftige Arbeiten erforderlich, um detaillierte Bottom-up-Inventare zu integrieren und Fernerkundungsdaten zu nutzen, um die Auflösung und den Erfassungsbereich von Lebenszyklusinventaren zu verbessern.

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Glossary

Carbon footprint of a material	Cumulative upstream and direct GHG emissions of a *material*. This is the same as the scope 3 GHG emissions of a material (see *scope 3 impacts*)
Carbon footprint of a region	*Consumption-based* GHG emissions of a region
Climate change impacts	Greenhouse gas emissions (assessed in this thesis based on the IPCC 2013 Global Warming Potentials for 100 years)[1]
Consumption-based impacts of a region, footprint of a region	*Impacts* related to the consumption of a region, including impacts of imports and excluding impacts of exports
Downstream impacts of materials	Greenhouse gas and particulate-matter impacts related to the combustion of fossil fuels, waste incineration, and composting of biomass
Footprint of a material	Cumulative upstream and direct impacts of a material. This is the same as the *scope 3 impacts* of a *material*
Impacts	Collective term for different environmental and socioeconomic impacts
Materials, material resources	Metals, non-metallic minerals, biomass, and fossil resources that are processed into materials (steel, cement, textiles, plastics, paper, etc.), food, and fossil fuels (coal, oil, etc.) based on the definition of the International Resource Panel[2]
Material-related impacts	Environmental *impacts* related to the extraction and processing of *materials*
Midstream impacts of materials	Direct *impacts* of *materials*
Production-based impacts of a region and sector	Domestic *impacts* of a region (excluding impacts related to imports) and direct *impacts* of a sector
Scope 3 impacts	Cumulative upstream and direct *impacts* for any impact category. This terminology has been used for scope 3 GHG emissions[3–5] but was extended to any type of impact category in this thesis.
"Tracking material-related impacts in the downstream chain"	Tracking the use of materials and the *impacts* related to their production in the downstream chain (e.g., the impacts related to the production of steel used in construction) →not to be confused with *downstream impacts of materials*
Upstream / supply chain impacts	Impacts caused in the upstream chain / supply chain

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Abbreviations

BGS	British Geological Survey
CF	Characterization factors
DALYs	Disability adjusted life years
EE-MRIO analysis	Environmentally-extended multi-regional input-output analysis
EU	European Union (EU-27)
GDP	Gross domestic product
GEP	Green Economy Progress
GHG emissions	Greenhouse gas emissions
HDI	Human Development Index
ICT	Information and communication technology
IEA	International Energy Agency
IRP	International Resource Panel
ISTP	Institute of Science, Technology and Policy
LCA	Life-cycle analysis
MR impacts	Material-related impacts
MRIO analysis	Multi-regional input-output analysis
MRIO database	Multi-regional input-output database
NGO	Non-governmental organizations
Obj.	Objectives
PAGE	Partnership for Action on Green Economy
pdf	Potentially disappeared fraction
PGM	Platin group metals
PM emissions	Particulate-matter emissions
PM health impacts	Particulate-matter related health impacts
R-MRIO database	Highly resolved MRIO database
RG	Research Gaps
RoW regions	Rest of the World regions
SETAC	Society of Environmental Toxicology and Chemistry
UN	United Nations
UNEP	United Nations Development Program
USA	United States of America

Chapter 1

Introduction

1.1 Background

In the United Nations' (UN) agenda 2030 for sustainable development[1], climate change, air pollution, water scarcity, and biodiversity loss are listed as the major global environmental problems that need to be addressed in the coming decades. Climate change threatens the survival of millions of people, plants, and animals by sea level rise, sea acidification, and more frequent and extreme meteorological events, such as droughts, fires, and floods[2, 3]. Air pollution affects 90% of the global population, causing millions of deaths per year due to respiratory illness[4]. The lack of water, vital to human, animal, and plant survival, affects more than 40% of the world population[5], and the destruction of natural habitat is the main reason why the world is in the process of the sixth mass extinction[6-8]. Thus, the International Panel for Climate Change demands drastic reductions in greenhouse gas (GHG) emissions[2, 3] and the World Health Organization urges strong reductions in air pollution[4]. The UN call for actions on improved sustainability policies to address these environmental challenges along with the economic and social pillar of sustainability, such as fostering economic growth and education, and reducing poverty and inequality[1].

Improved sustainability policies require transparency in global value chains[9-14]. A value chain refers to the set of economic activities needed to deliver a valuable product, good, or service for the market[15]. For example, the value chain of materials, food, and fuels, grouped under the term "materials" in this thesis, comprises resource extraction (e.g., iron mining), material processing (e.g. steel processing), further manufacturing (e.g., a car), and final use (e.g., by households). Each step in the global value chain can cause a set of environmental and socioeconomic impacts, summarized as "impacts" in the following. Since value chains have become increasingly globalized, the impacts caused in one country are linked to the production of goods consumed in another[16-25]. This has led to a displacement of impacts due to international trade, particularly from higher to lower-income regions with lower environmental standards and less financial strength to implement clean technologies. Therefore, sustainability policy must look at the entire value chain[9-14]. However, many environmental policies, such as the Paris Agreement, aim to reduce a country's domestic environmental impacts, but neglect the impacts outside the national boundaries to satisfy domestic demand with imports.

When evaluating measures and technologies to support sustainability policies, it is most effective to address the emissions and impacts caused along the entire value chain of an industrial activity (e.g., steel processing) of a region, including the upstream, midstream, and downstream chain[14, 26-28]. The upstream chain refers to all activities in the upstream supply chain of an industrial activity (e.g., iron and coal mining, transport, and the supply of electricity up to steel processing), the midstream chain refers to the industrial activity itself (e.g., steel processing), and the downstream chain refers to all activities afterwards (e.g., further manufacturing of steel into finished products). In the greenhouse gas (GHG) protocol[29, 30], the so-called scope 3 emissions include upstream and midstream (direct) emissions, while the inclusion of downstream emissions is optional[31]. In the following, scope 3 impacts refer to the cumulative upstream and midstream impacts, while downstream impacts are separately addressed. Furthermore, the terminology of scope 3 impacts is extended in this thesis from GHG emissions[2–4] to any type of impact category.

One form of life-cycle analysis that allows assessing impacts along global value chains is multi-regional input-output (MRIO) analysis [32-37]. In MRIO analysis, the global economy is aggregated into a specific number of regions and sectors, whose transaction flows, environmental impacts, and socioeconomic accounts (e.g., employment, compensation, and skills of workforce) are captured for a given year (Figure 1). In standard MRIO analysis, the impacts of global value chains have been analyzed by production and consumption-based accounting[16-24]: In production-based accounting, the impacts are allocated to the producing sector or region, where emissions are released and impacts are caused, referring to direct impacts of sectors and domestic impacts of regions. In standard consumption-based accounting, the environmental impacts are allocated to the final sector or region of consumption, meaning the sector and region situated at the end of the supply chain[16-24, 35-37]. Thus, the consumption-based impacts of a country include the impacts related to imports, but exclude the impacts of exports. Based on this concept, many studies have linked the region where environmental and socioeconomic impacts are caused to the region where final products are consumed to address the importance of supply chain management[16-20, 25, 38-51].

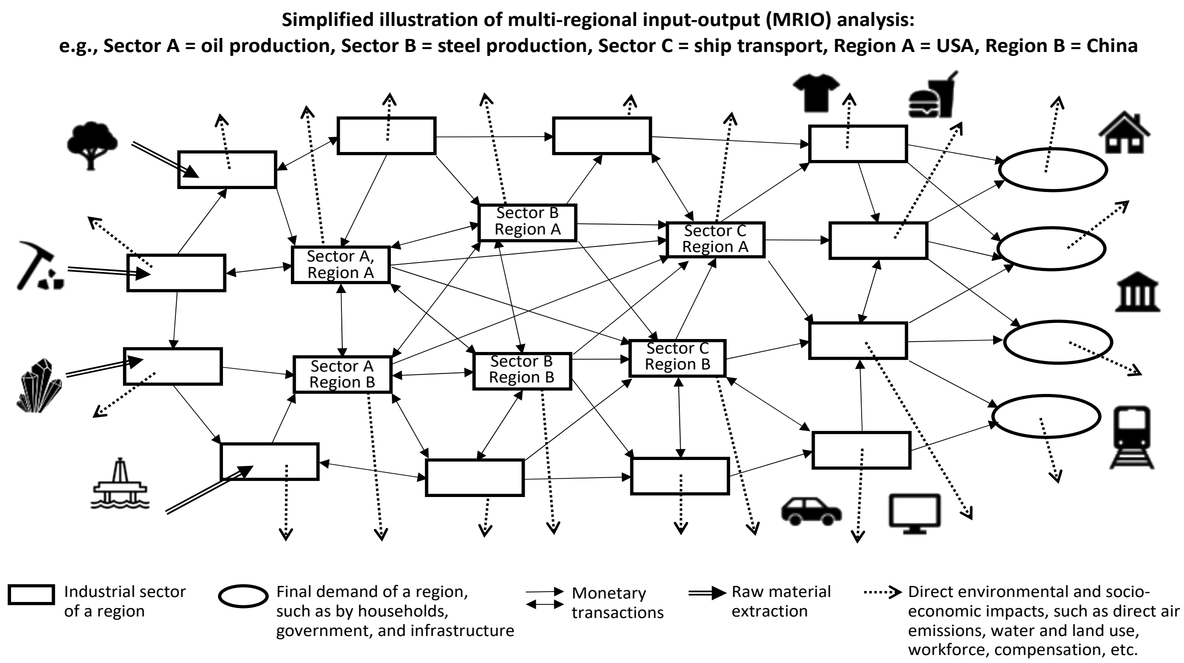

Figure 1.1. Simplified illustration of environmentally and socially extended multi-regional input-output (MRIO) analysis.

1.2 Research Gaps (RG)

RG 1: The lack of a method for assessing and tracking scope 3 impacts in MRIO analysis

Assessing the scope 3 impacts along the entire value chain is important to identify how actions can be taken at different steps in the global value chain to reduce impacts most efficiently[26, 52]. However, as standard MRIO methodology allocates the impacts either to the producing or consuming sector of a region, it was not suitable to assess the total scope 3 impacts of sectors and regions, nor to track these impacts upstream and downstream the global value chain. The reason for this is that production-based accounting neglects upstream impacts (as it allocates the upstream impacts to the sector in the upstream chain where they are caused), while consumption-based accounting allocates the impacts to the sector and region of end use (e.g., if steel is used for construction, the impacts of steel production are allocated to the construction sector). This implies a lack in information for sectors and regions located in the middle of the global value chain, called intermediate sectors and regions, such as material sectors and regions strongly connected to international trade.

Nevertheless, a few studies have attempted to assess the scope 3 emissions of industries[26] and cities[52, 53] in MRIO analysis. However, a major weakness of these studies was that many emissions were double counted. Double counting occurs when the scope 3 impacts of several sectors and regions located in each other's supply chain are added up[9, 10, 54, 55]: For example, part of the scope 3 emissions of oil production (Sector A, Figure 1.1) is also included in the scope 3 emissions of steel production (Sector B), because some of the oil is used for steel production (and vice versa, some of the steel is used e.g. in machinery for oil production). The same issue exists for regions due to trade. For example, part of the scope 3 emissions of Region A is also included in the scope 3 emissions of Region B due to exports from Region A to B, and vice versa (Figure 1.1). Only recently, a method was developed that handles the double-counting issue in a national input-output table and applied to assess the scope 3 GHG emissions of Japan's material production[54, 55]. However, a methodology to assess the scope 3 impacts of sectors and regions in MRIO analysis without double counting has been lacking prior to this thesis, both for GHG emissions and any other impact category.

RG 2: Limitations in assessing downstream impacts in MRIO analysis

Although the inclusion of downstream emissions is optional in scope 3 impact assessment[31], downstream emissions are critical with respect to fossil resources since their combustion causes the vast majority of global climate change and particulate-matter (PM) related health impacts[56, 57]. In MRIO analysis, downstream impacts have not been analyzed prior to this thesis due to two major reasons. One reason is that their additional inclusion leads to further double counting. For example, some of the downstream emissions of oil production (Sector A), are already counted as scope 3 emissions of steel production (Sector B, Figure 1.1). Another reason is that there is no clear allocation mechanism for downstream impacts. For example, if some of the produced oil is combusted for transporting some of the produced steel by ship, the direct emissions of transport via ship (Sector C, Figure 1.1) can be either allocated to the oil and steel producing sector depending on their monetary inputs, or to the actual resource that releases them, which would be the oil sector. Dente et al.[54] proposed a method to account for downstream emissions of materials without double counting based on the monetary inputs of materials into the downstream chain. This means that if e.g., 5% of the total monetary input of shipping is related to transporting steel, 5% of the direct emissions released by ship transport are charged as downstream emissions of transporting steel. This procedure is debatable as the emissions of shipping actually originate from oil combustion. Thus, the existing approach does not allocate the downstream impacts to the actual material resource that releases the emissions, such as oil, gas, or coal.

RG 3: The limited spatial and sectoral resolution in MRIO databases

Sustainability policies require detailed information on global value chains, but the level of detail that can be analyzed through MRIO analysis is limited by the spatial, sectoral, and temporal resolution in the MRIO database. Currently, several MRIO databases exist with different resolution, such as EXIOBASE3[32], Eora and Eora26[34, 58], GTAP[59], WIOD[60], OECD-ICIO[61] and GRAM[62, 63]. However, EXIOBASE3 and Eora26 are the only publicly available MRIO databases with harmonized country and sector resolution and time series from 1995 to 2015. The two databases complement each other in their spatial and sectoral resolution: While EXIOBASE3 features a higher sectoral resolution (163 sectors), it is limited in its regional resolution (it covers only 44 countries and aggregates the rest of the world (RoW) into five RoW regions), Eora26 features a higher regional resolution (189 countries) but is limited in its sectoral resolution (26 sectors). A few studies have been built on EXIOBASE to improve its country resolution[16, 43, 64-66]. However, these studies were limited to water stress impacts of agriculture in the year 2007[16, 43], and land use footprints[64-66], but did not capture other impacts. This implies that prior to this thesis, no MRIO databases was suitable to perform a detailed global value chain analysis with high spatial and sectoral resolution and indicator coverage.

RG 4: The incomplete coverage of a set of sustainability indicators in MRIO databases

To support sustainability policies, MRIO databases ideally need to cover a comprehensive indicator set that affect the economic, social, and environmental pillars of sustainability. To address the environmental pillar, environmental inventory data on GHG and PM emissions, water use, and land use, need to be translated into environmental impacts[11, 13], such as climate change and health impacts[67-69], water stress[70, 71], and biodiversity loss[72, 73]. Previous MRIO studies have either analyzed the environmental inventory data, such as material use[38, 74, 75], PM emissions[49], water use[18, 20, 41, 43] or land use[18, 20, 44, 45, 64-66], or focused on single impact categories, such as climate change impacts[18, 20, 46-48], water stress[16, 42], and biodiversity loss[17, 50, 51]. However, a complete set of inventory and impact indicators addressing the major global environmental issues was not available in the scientific literature prior to this thesis. To address the economic and social pillars of sustainability, several studies[19, 25, 76-78] have developed indicators that integrate hours of work, compensation, skills, risks to the workforce, and other socio-economic aspects, but all of these studies are limited in the spatial and sectoral resolution of the underlying MRIO database.

RG 5: The lack of an environmental assessment of materials

Addressing the world's environmental issues listed by the UN's Agenda for sustainable development[1] is particularly challenging given that the demand for material resources, including metals, non-metallic minerals, biomass, and fossil resources is expected to double until 2050[79, 80]. This and the fact that their extraction and processing into materials, food, and fuels, grouped under the term "materials" in this thesis, causes many environmental impacts, underlines the need for improved strategies for a sustainable production and consumption of materials[10]. Since the value chain of materials is highly interconnected and globalized[20, 38-40], such strategies require detailed information on material value chains and the related impacts. In this context, metals, construction materials, and plastics are special cases: One reason is the strong growth in the production of these materials in coal-based economies over the past decades, expected to continue in the future[80-86]. For plastics, another reason is that fossil resources are used both as feedstock and fuel to provide energy for plastics production. However, due to limitations in the MRIO methodology and database, an environmental assessment of materials has been lacking both on global and national scales prior to this thesis[87-89]. Concerning plastics, only one study has analyzed the global carbon footprint of plastics by bottom-up life-cycle analysis[90]. However, the study[90] did not correct for double counting, calculated with the global average energy mix, and did not analyze the global plastics value chain, such as regional production, consumption, and trade pattern.

RG 6: Limitations of national policy assessment schemes

Effective environmental policies also require reliable, relevant, and up-to-date indicators to measure environmental protection efforts[19]. However, current national policy assessment schemes, such as the Green Economy Progress (GEP) Measurement Framework of the UNEP[91, 92], measured these efforts mainly by production-based accounting, excluding the impacts related to a country's consumption due to imports, and neglected the impacts of water and land use. This is also an issue because many high-income regions, such as the EU, rely heavily on imports from lower-income regions with high levels of water stress and biodiversity loss[73]. Expanding national policy assessment schemes to consumption-based accounting of a wide range of environmental impact indicators is important, but has been hindered by the limited resolution and indicator coverage of MRIO databases prior to this thesis.

RG 7: Limitations in providing science-based decision support for policy and industry

An important step for the design and implementation of effective sustainability policies is for scientists to facilitate access to relevant information for industry, politics and society through flexible and comprehensive software tools, e.g. for analyzing the scope 3 impacts of industries and economies and their value chains[93]. Currently, several tools exist, such as the "Sustainable Consumption and Production Hotspot Analysis Tool"[94] which allows assessing production and consumption-based impacts of countries on a coarse sectoral level. However, no software tool exists that allows assessing the scope 3 impacts of industries and economies without double counting, mapping their global value chain, and including the most relevant up-to-date indicators and full regionalization in the impact assessment.

1.3 Objectives

In view of the scientific background and research gaps, the overall objective of this thesis is to support sustainability policies by providing an improved MRIO methodology, database, and impact assessment to create more transparency in global value chains and their impacts (RG 1–4). The thesis aims to demonstrate the importance, versatility, and broad applicability of the improved methodology and database by several application examples (RG 5–6) and by providing the improved methodology as a software tool (RG 7). The specific eight objectives (**Obj. 1–7**) to address each of the research gaps (RG 1–7) identified in Section 1.2 are to:

Obj. 1 (RG 1): Provide a methodology for assessing the scope 3 impacts of any sector and region without double counting by extending the method from Dente et al[54, 55] to MRIO analysis and enable tracking of these impacts upstream and downstream the global value chain (both for GHG emissions and any other impact category, Chapter 2).

Obj. 2 (RG 2): Develop a methodology to assess downstream GHG emissions and PM health impacts in MRIO analysis (Chapter 4 and 5).

Obj. 3 (RG 3): Provide an approach to merge MRIO databases, integrate primary data, and compile an MRIO database with high regional, sectoral, and temporal resolution (Chapter 3).

Obj. 4 (RG 4): Implement a cutting-edge set of environmental impact indicators into MRIO databases with high regional and sectoral resolution, covering the key environmental issues listed by the UN agenda[1] (climate change and PM health impacts, water stress, and land-use related biodiversity loss, Chapter 2 and 3).

Obj. 5 (RG 5): Assess the environmental and socioeconomic impacts of material production globally (Chapter 2) and for the G20 members (Chapter 4), and provide an in-depth analysis on the role of coal combustion in the production of metals, construction materials (Chapter 4), and plastics (Chapter 5)

Obj. 6 (RG 6): Improve an existing national policy assessment framework and provide an in-depth supply chain analysis on the EU's water stress and biodiversity loss footprint (Chapter 3).

Obj. 7 (RG 7): Provide a software tool that can be applied by researchers, industries, policy makers, and NGOs to assess the environmental and socioeconomic impacts of industries and economies in detail (and without double counting), such as locating the hotspots and leverages in the global chain to derive efficient policies for sustainable development (Chapter 2).

1.4 Structure of this thesis

In this thesis, the research gaps (RG) and objectives (Obj) are addressed by four research articles (**Chapter 2–5**), followed by the conclusion and outlook (**Chapter 6**) (Figure 1.2).

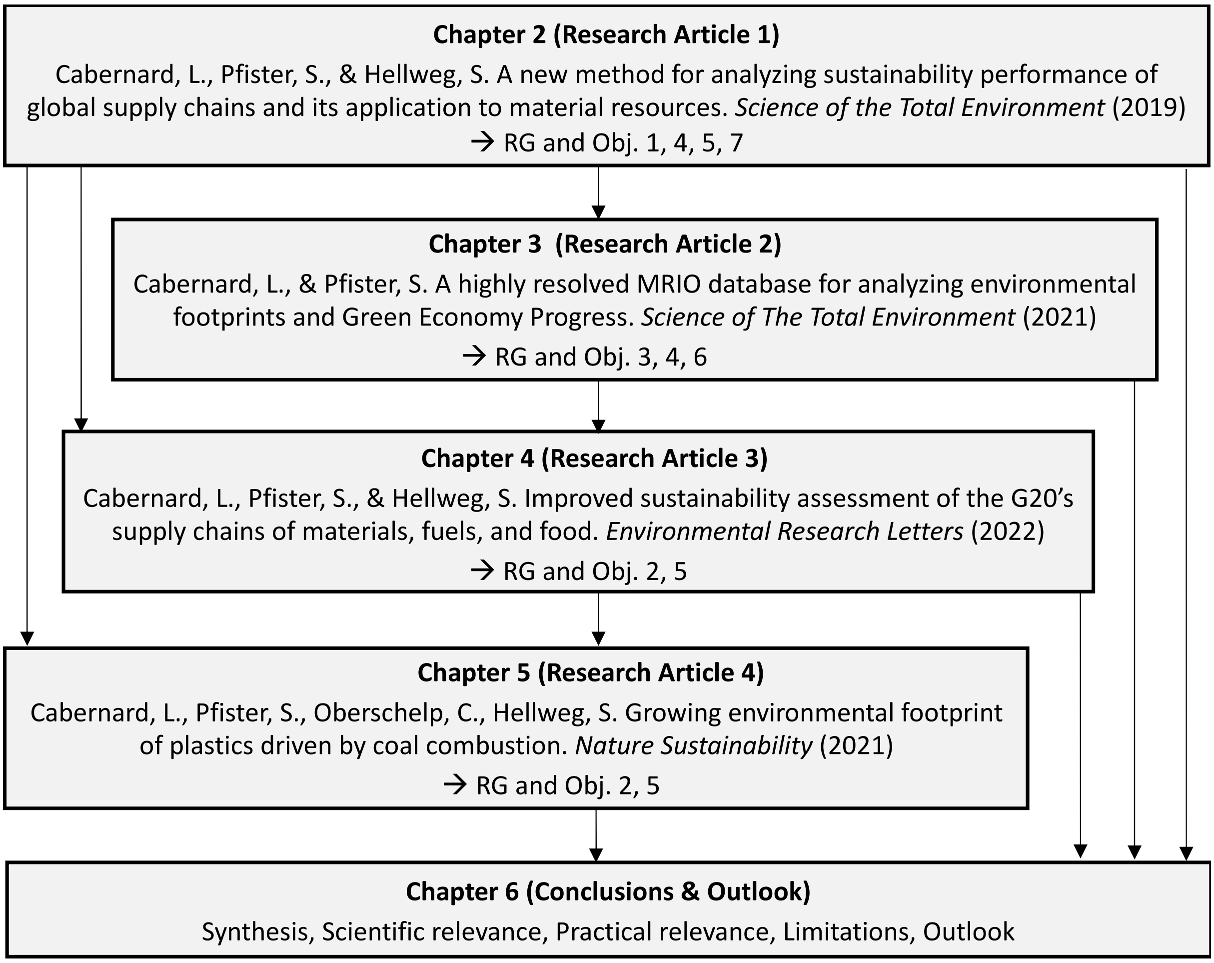

Figure 1.2. Overview, addressed research gaps (RG) and objectives (Obj.), and linkages (indicated by the arrows) of the four research articles (Chapter 2–5) and the conclusions and outlook (Chapter 6) of this thesis.

Chapter 2 covers the first research article called "A new method for analyzing sustainability performance of global supply chains and its application to material resources", published by Cabernard, Pfister & Hellweg in *Science of the Total Environment* (2019)[95]. It is the backbone of this thesis, on which the other chapters are built. It extends previous methodology[54, 55] to assess the scope 3 impacts of any sector and region of any MRIO database without double-counting, and allows tracking these impacts upstream and downstream the global value chain (RG and Obj. 1). The methodology is applied to the global MRIO database EXIOBASE3, implementing the environmental impact categories climate change impacts, PM health impacts, water stress, land-use related biodiversity loss, and covering the socioeconomic indicators value added and workforces (RG and Obj. 4). Chapter 2 illustrates the new methodology by analyzing these indicators for the case of global material production from 1995 to 2015 (RG and Obj. 5). The methodology enables mapping of sectoral and regional linkages in the global materials value chains, such as between different material types, their upstream chain, their use in the downstream chain, and the regions of material resource extraction, processing, and end use. Based on this, Chapter 2 identifies the major drivers of the increasing material-related impacts and suggests strategies for sustainable production and consumption of global materials. The methodology of Chapter 2 is provided as a software tool that can be applied to any material, industrial sector and region for analyzing the sustainability performance of global value chains to provide science-based decision support for policy makers and industry (RG and Obj. 7).

Chapter 3 includes the second research article called “A highly resolved MRIO database for analyzing environmental footprints and Green Economy Progress”, published by Cabernard & Pfister in *Science of the Total Environment* (2021)[96]. It presents an automated, transparent, and time-efficient approach to improve the resolution, quality, and indicator coverage of existing MRIO databases (RG and Obj. 3). After adding the impact assessment from Chapter 2’s database to the Eora26 database, the approach is applied to merge the EXIOBASE3 and Eora26 databases into one database with high regional and sectoral resolution, and to improve it with data on biomass production[97], water stress[70, 98], and biodiversity loss[72, 98] (RG and Obj. 4). The effect of the improved resolution is evaluated by calculating the EU’s environmental footprints and comparing them to the results from Chapter 2. To illustrate the improvements of the highly resolved MRIO database, the EU’s food supply chain and related water and land impacts are mapped by applying the method from Chapter 2 to the improved database. This allows to identify the hotspots in the EU’s food supply chain to suggest strategies for efficiently reducing the impacts on water and land. In a second application example, the resolved database is used to add carbon, water stress, and biodiversity loss footprints to the GEP framework of the UNEP (RG and Obj. 6).

Chapter 4 encloses the third research article called “Half of global coal used for the G20’s production of metals and construction materials”, published by Cabernard, Pfister & Hellweg in *Environmental Research Letters* (2022)[99]. It applies the approach of Chapter 3 to create an MRIO database with high sectoral resolution and broad indicator coverage for all G20 members. The methodology of Chapter 2 is applied to the improved database to assess scope 3 impacts of the G20’s production and consumption of materials, and extended to downstream emissions to evaluate the role of coal combustion (RG and Obj. 2). The study starts with a synthesis on the G20’s environmental and socioeconomic impacts from 1995 to 2015, discusses geographical and sectorial relationships between all G20 members and the rest of the world, and analyzes the role of trade in material resources. It continues with an in-depth analysis on the GHG emissions of the G20’s material value chain, identifies the use of coal in the G20’s production of metals and mineral materials. Based on this, Chapter 4 contrasts key aspects of sustainability, highlights the relevant hotspots in the G20’s material value chains, and suggests strategies for sustainable development (RG and Obj. 5).

In **Chapter 5** covers the fourth research article called “Growing environmental footprint of plastics driven by coal combustion”, published by Cabernard, Pfister, Oberschelp & Hellweg in *Nature Sustainability* (2021)[100]. It applies the methodology from Chapter 2 to assess the impacts of the global plastics value chain in the past and in the future, considering different climate change scenarios. In this context, the methodology from Chapter 4 is extended to PM health impacts by integrating data from previous studies[68, 69] to evaluate the role of coal combustion in global plastics production (RG and Obj. 2). The study assesses climate change and PM health impacts that occur in the global plastics value chain, and builds on the methodology from Chapter 2 to analyze fossil resources used as a fuel and feedstock for plastics production (RG and Obj. 5). To evaluate the role of trade, the link between fossil resources extracting, plastics producing, and plastics consuming regions is mapped. Further, the study analyzes the evolution of the global carbon footprint of plastics in the future, assuming the implementation of the International Energy Agency's (IEA) proposed measures for a 2-degree and 6-degree scenario[101, 102]. Finally, Chapter 4 evaluates the employed workforce and value-added created in the global plastics production chain so as to provide an overview of the socioeconomic impacts.

Chapter 6 begins with a synthesis of the main conclusions of this thesis, followed by an overarching discussion of the scientific and practical relevance, the limitations of this thesis, and an outlook.

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Chapter 2

A new method for analyzing sustainability performance of global supply chains and its application to material resources

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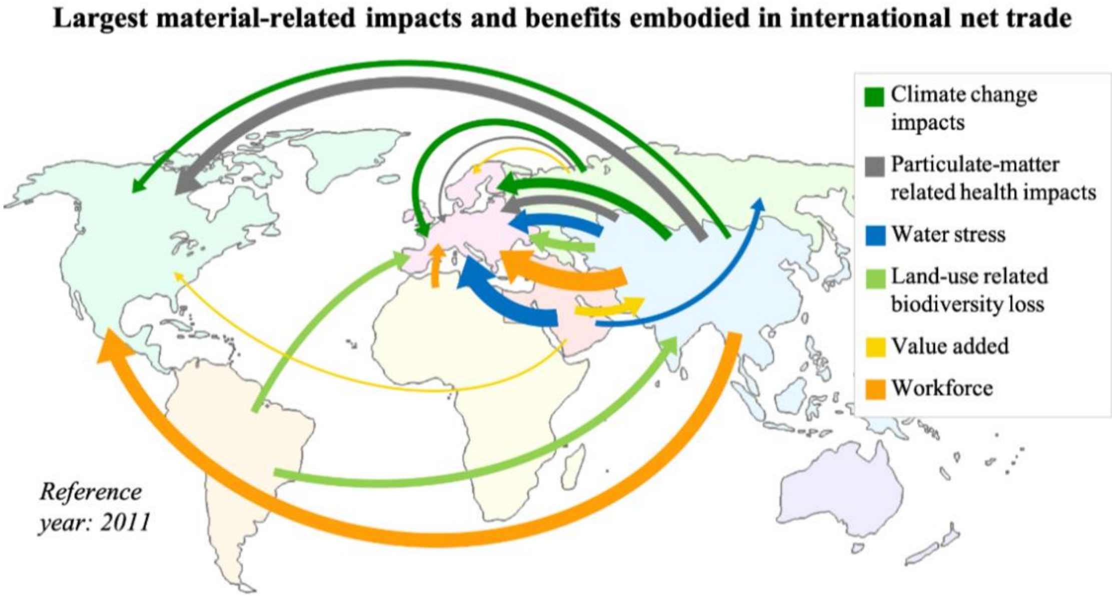
GRAPHICAL ABSTRACT



ABSTRACT

Supply chains become increasingly globalized. Multi-regional input-output databases contain all the information to assess impacts along the value chain, but standard calculation routines to track the impacts of any sector along the global upstream and downstream value chain are missing. Mapping the impacts of materials has been a particular challenge owing to difficulties with double-counting. This is attributed to the strong intertwining of the material supply chain meaning that different materials occur in the supply chains of other materials. Here, we present a new method which can be applied to any MRIO system to track the impacts of any sector or region without double counting upstream and downstream the global value chain. We apply this approach to EXIOBASE3 and implement a cutting-edge set of regionalized

environmental impact categories and socio-economic indicators. Applied to global material production, our method shows that the issue of double-counting (prevented in this study) would overestimate global impacts of materials by up to 30%. In contrast, assessing only the direct impacts would lead to an underestimation by ~20%. Our evaluation further reveals that 25–35% of global material-related impacts are embodied in trade among ten world regions. Thereby, we identify the major international trade relations of key materials and found a clear trend of industrialized nations causing impacts in less developed economies. It was further revealed that during 1995–2011, the share of materials in total global climate change impacts has remained almost constant at ~50%, but total impacts have significantly increased for minerals and fossils. Our results demonstrate the importance for improved environmental policy strategies that target several stages of the global value chain. The methodology is provided as matlab tool and can be applied to any material, industrial sector and region to track the related impacts upstream and downstream the global value chain.

2.1 Introduction

Over the past decades, the continuous growth in human population and economic welfare has increased the pressure on natural resources and the environment to an extent that is not sustainable[1-4]. Today, the equivalent of 1.7 Earths would be necessary to supply human material demand and to regenerate anthropogenic waste emissions[5]. This and the fact that the use of materials, such as biomass, metals, non-metallic minerals and fossils, is expected to more than double by 2050 demonstrates the need for a substantial increase in material efficiency[6, 7]. The importance for a more sustainable production and consumption has been recognized as a policy objective by the United Nations Environment Program, and builds the fundament for the achievement of the Sustainable Development Goals[8].

Targeting strategies for a more sustainable production and consumption of materials, commodities, and services requires regionalized assessments on the related impacts from a life-cycle perspective[9-13]. In view of the increased globalization of the economy, it is import to assess impacts along the value chain to identify the most relevant leverage points for improvement. A key step to address this issue, was the development of environmentally extended multi-regional input output tables (EE-MRIO)[4, 14-17]. Based on this concept, many studies have investigated the complex global trade pattern of material use[2, 4, 18, 19], water use[4, 20-24], land use [4, 22, 25, 26], climate change impacts[4, 22, 27-29], air pollution[30], and biodiversity loss[31-33]. In this context, different perspectives have been adopted to attribute the emissions, resource uses and impacts (summarized as '*impacts'* in the following*)* to the industrial sectors and regions covered by the respective MRIO system. In the production perspective, the impacts are attributed to the sector and region where the impacts are directly caused (also called direct impacts). In the consumption perspective, the impacts are attributed to the region of final consumption (footprint) or to the sector situated at the end of the supply chain (also called indirect impacts)[4, 21-23, 26, 27]. However, neither the production nor the consumption perspective is able to separate out and highlight the impacts of sectors situated in the middle of the supply chain, such as materials.

When evaluating measures and technologies for sustainable production and consumption, it is most efficient to address the full scope 3 impacts[34]. Thereby, the inclusion of the upstream emissions is mandatory, but the inclusion of downstream emissions is optional[35]. In the following, scope 3 refers to the cumulated upstream impacts. Until now, only one study has assessed the scope 3 greenhouse gas emissions of all individual sectors of the global industry[34], but some emissions in the supply chain were double counted. The reason for double counting is attributed to the intertwining of the supply chain, such that different sectors occur in the supply chains of other sectors[9, 10, 36, 37]. Exemplarily for materials, coke (made of coal) is used for combustion in steel production, and steel is used as machinery equipment for coke production. Therefore, the related impacts are counted twice, if they are cumulated along the upstream supply chain in both sectors (and if no correction is made for these circular flows). Methodological challenges to correct for double counting belong to the main reason for the paucity of previous scope 3 impact assessments.

Recently, a highly promising method that handles the double-counting issue on a national level has been developed by Dente et al[36, 37] . The principle of this methodology is to define all sectors of interest as *'target sectors'*. If these target sectors supply each other, double counting issue is prevented by allocating the impacts to just one of the involved target sectors. Thereby, two allocation methods (or perspectives) are distinguished. In the first allocation approach, the impacts are assigned to the upstream supply chain of the final target sector. This means that if coke is used by steel, a share of the impacts that arise during coke production (i.e. the share that is used for steel production) is attributed to the steel production and thus not accounted for in the assessment of the coke sector. In analogy, the impacts that arise during steel production used for machinery in coke production are allocated to coke production. In the second allocation approach of Dente et al[37], the impacts are attributed to the target sectors where the impacts are directly caused. This means that if coke is used by steel, the impacts that arise during coke production are assigned to the coke sector itself and are thus not accounted for in the assessment of the steel sector. So far, this methodology has been applied to a Japanese input-output database to estimate the scope 3 climate change impacts of Japan's material production by Dente et al[36, 37].

Planning strategies for a more sustainable production and consumption require the consideration of different environmental and socio-economic indicators[11, 13]. Previous studies focused either on some physical flows (e.g. material, water or land use), on single impact categories (e.g. climate change or carbon footprint, water stress, biodiversity loss) or were limited to the impacts on ecosystems[32]. However, a complete state-of-the art set of both inventory and impact indicators as recommended by UNEP-SETAC[38, 39] showing the tradeoffs between environmental interventions and impacts is lacking in the scientific literature. Also, no comprehensive and flexible software tool exists which includes the most relevant up-to-date indicators and full regionalization in the impact assessment.

Here, we further develop the method of Dente et al[36, 37] to assess the scope 3 impacts of any target sector and target region (called *target-sector-regions* in the following) without double-counting from four perspectives in the global supply chain (explained in Section 2.2.1). The multi-dimensional matrices calculation presented in this study (Section 2.2.2–2.2.4) allows to map all the linkages between these perspectives and to track the scope 3 impacts of target-sector-regions both upstream and downstream the global supply chain. The procedure can be applied to any MRIO system. We apply it to the extensive global EE-MRIO database EXIOBASE3[4, 15], and implement a set of environmental and socio-economic indicators, namely material footprint, climate change impacts, health impacts due to particulate matter emissions (PM health impacts), water stress, land-use related biodiversity loss, value added and workforce (Section 2.2.5). The methodology is provided as a matlab tool (link) and can be applied to any industrial sector(s) and region(s) of interest to trace the scope 3 environmental impacts and socio-economic benefits over the global supply chain (Section 2.2.6). We then illustrate the application of the new method analyzing the case of global material production (Section 2.2.7–2.2.8). The analysis of global materials presented in this paper is complementary to the IRP report[40], where some initial results of using the new methodology were included. To assess the methodological improvements, we assess the overestimation of the impacts of global material production (material-related impacts) if no correction for double counting is done (Section 2.3.1) and the underestimation of the impacts if only direct impacts are considered (Section 2.3.2). Next, we investigate the global impacts of the major material groups, namely biomass, metals, non-metallic minerals and fossils, and how they are linked to each other in the global supply chain (Section 2.3.3). We further investigate hotspots of locations where material-related impacts occur and the locations of the consumers of these materials, by analyzing the trade pattern (Section 2.3.4). We investigate the influence of a nation's development stage (measured by the human development index) on its production, consumption and trade pattern of materials and the related impacts (Section 2.3.5). Finally, we evaluate the temporal development of regions' material-related footprints and the temporal trajectory of the share of materials in total global impacts (Section 2.3.6–2.3.7).

2.2 Methods

2.2.1 Overview of the Methodology and Terminology

The principle of the method is to divide the global economy of the respective MRIO system into target sectors and target regions (called *'target-sector-regions'*) and the remaining economy (called *'non-target-sector-regions'*). The scope 3 impacts of target-sector-regions without double counting are composed of the direct impacts of target-sector-regions and the indirect impacts caused by non-target-sector-regions (situated in the upstream supply chain of target-sector-regions). In accordance to Dente et al[36, 37], the impacts of target-sector-regions situated in the upstream supply chain of other target-sector-regions are counted only once (instead of multiple times, as done by previous studies). In this paper we chose global material production as an illustrating example for target-sector-regions, but target sectors and target regions can refer to other cases (any of the sectors and regions included in the underlying MRIO system) depending on the interest of the method user.

Our method allows to track the scope 3 impacts of target-sector-regions along the global supply chain by adopting the following four perspectives (Figure 2.1): In the first perspective called *'production perspective'*, the scope 3 impacts of target-sector-regions are attributed to all sectors and regions where production takes place and the impacts are caused. This perspective includes the direct impacts caused by all target-sector-regions and is thus similar to the second allocation approach of Dente et al[37]. In contrast to Dente et al[37], it also indicates the impacts caused by each non-target-sector-region situated in the upstream supply chain of target-sectors-regions (which are allocated to the target-sectors in the method of Dente et al[37]). For instance, the production perspective indicates the impacts caused by electricity production (non-target sector) that is used for material production (target sector) and allows to assess where on globe these impacts are caused.

In the second approach called *'target perspective'*, the impacts are attributed to the target-sectors-regions that are supplied, which is in accordance to the first allocation method of Dente et al[37]. For example, the impacts caused by coke production (target-sector) and electricity production (non-target-sector) both used for steel production (target-sector) are attributed to steel production. The links between the production and the target perspective are called the *'upstream supply chain'* (Figure 2.1).

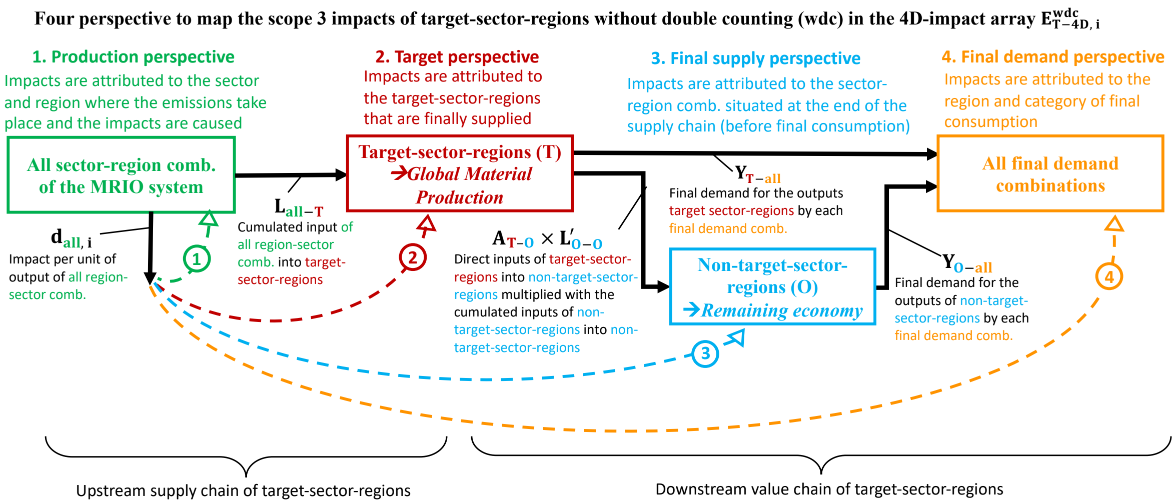


Figure 2.1. Illustration of the methodology to assess the scope 3 impacts of target-sector-regions (here illustrated with the example of global material production) without double counting. The four perspectives are connected in the four-dimensional (4D) impact array ($E^{wdc}_{T-4D,\,i}$), which allows to track the scope 3 impacts of target-sector-regions over four stages of the global supply chain.

Once produced, the target-sector-region outputs (and the impacts related to their production) are either used by non-target-sector-regions (such as construction, electrics and electronics, textiles and other finished products in the case of global material production) or they are directly consumed by households, governments, or used for capital formation (e.g. build-up of infrastructure). We distinguish these two pathways in the *'downstream value chain'* of target-sectors-regions by the following two perspectives: the *'final supply perspective'* indicates how much of the respective target-sector-regions-outputs (and the impacts related to their production) is either directly consumed or ends up in non-target-sector-regions. The *'final demand perspective'* indicates by which regions and category of final demand the target sector-region products are finally consumed (either directly or embodied in non-target-sector-regions, Figure 2.1).

2.2.2 Derivation of Variables

The first step of the procedure is to define the target-sector-regions (T) and non-target-sector-regions (O) and to build two row vectors representing the index of the target-sector regions (v_T) and the index of the non-target-sector-regions (v_O) of the respective MRIO system. Inserting these indexes into the overall coefficient matrix (A), the Leontief inverse matrix (L), the final demand matrix (Y), and the total output (x^{tot}, a column vector) of the respective MRIO system allows to derive all variables illustrated in Figure 2.1 and compiled in Table 2.1 (whereby the dimension refer to the MRIO database EXIOBASE3 for the case of global material production). Thereby, matrices are presented in capital letters, and vectors in small letters with subscripts (row vector) and superscripts (column vector). The coefficient matrix of direct inputs from target-sector-regions into non-target-sector-regions (A_{T-O}) and non-target-sector-regions into non-target-sector-regions (A_{O-O}) are derived as an excerpt of the total coefficient matrix A:

$$A_{T-O} = A(v_T, v_O) \qquad \text{Eq. 2.1}$$

$$A_{O-O} = A(v_O, v_O) \qquad \text{Eq. 2.2}$$

The direct final demand by all regions and categories of final demand for target-sector-region outputs (Y_{T-all}) and for non-target-sector region outputs (Y_{O-all}) are derived as an excerpt of the total final demand matrix Y:

$$Y_{T-all} = Y(v_T, :) \qquad \text{Eq. 2.3}$$

$$Y_{O-all} = Y(v_O, :) \qquad \text{Eq. 2.4}$$

Thereby, the colon (:) means that all regions and categories of final demand covered by the respective MRIO system are selected. The total output of target-sector-regions (x^T, a column vector) is derived as an excerpt of the total output vector x:

$$x^T = x^{tot}(v_T) \qquad \text{Eq. 2.5}$$

The cumulated input of all sector-regions into target-sector-regions (L_{all-T}) is derived as an excerpt of the total Leontief Inverse L of the respective MRIO system:

$$L_{all-T} = L(:, v_T) \qquad \text{Eq. 2.6}$$

The cumulated inputs of non-target-sector-regions into non-target-sector-regions (L'_{O-O}) are derived according to Dente et al[36, 37],

$$L'_{O-O} = (I_{O\text{-}O} - A_{O\text{-}O})^{-1} \qquad \text{Eq. 2.7}$$

Thereby, $I_{O\text{-}O}$ represents a unity matrix with the same dimension as $A_{O\text{-}O}$.

The impact coefficients ($d_{all,i}$, a row vector) indicate the direct impact per unit of output of each sector-region combination. The derivation of the impact coefficients ($d_{all,i}$) of each indicator (*i)* covered by this study is described in Section 2.2.5.

Table 2.1. List of all variables of this study.

Variables	Explanation	Dimension*	Unit
A	Total coefficient matrix	7987 x 7897	€/€
Y	Total final demand matrix	7987 x 343	€
L	Total Leontief Inverse	7987 x 7897	€/€
x^{tot}	Total output vector	7987 x 1	€
A_{T-O}	Coefficient matrix (A) of direct inputs of target-sector-regions (T) into non-target-sector-regions (O)	3675 x 4312	€/€
A_{O-O}	Coefficient matrix (A) of direct inputs of non-target-sector-regions (O) into non-target-sector-regions (O)	4312 x 4312	€/€
Y_{T-all}	Direct final demand (Y) by each region and category of final demand for target-sector-region-outputs (T)	3675 x 343	€
Y_{O-all}	Direct final demand (Y) by each regions and category of final demand for non-target-sector-region-outputs (O)	4312 x 343	€
x^T	Total output vector (x) of target-sector-regions (T)	3675 x 1	€
L_{all-T}	Excerpt of Leontief inverse (L) including the cumulated input of all sector-regions into target-sector-regions (T)	7987 x 3675	€/€
L'_{O-O}	Leontief inverse (L) of the cumulated inputs of non-target-sector-regions (O) into non-target-sector-regions (O)	4312 x 4312	€/€
$d_{all,i}$	Impact coefficient vector (d) of all sector-region-combinations of indicator i	1 x 7987	Impact/ €
$e_{T,i}$	Scope 3 impacts of target-sector-regions (including double counting) of indicator i	1 x 3675	Impact
$e_{T,wdc,i}$	Scope 3 impacts of target-sector-regions without double counting (wdc, in target perspective) of indicator i	1 x 3675	Impact
$f_{T,i}$	Double counting factor of each target-sector region of indicator i (in target perspective)	1 x 3685	–
$E^{wdc}_{T-4D,\,i}$	4-D impact array mapping the scope 3 impacts of target-sector-regions without double counting from 4 perspectives: 1. D: all sector-region combinations (constant: all 7987 sector-region combinations of EXIOBASE3) 2. D: target-sector-regions (in this paper 3675 target-sector-regions, but can be specified differently by tool user) 3. D: Direct final supply (=1st element) plus all non-target-sector-regions (in this paper 4312 non-target-sector-regions, but can be specified differently by tool user) 4. D: final demand (constant: 343 regions and categories of final demand of EXIOBASE3)	7987 x 3675 x 4313 x 343	Impact

*The dimensions refer to EXIOBASE3 in the case of global material production

2.2.3 Assessing Scope 3 Impacts Including and Without Double Counting

In previous studies, the scope 3 impacts of target-sector regions ($e_{T,i}$, a row vector) of the respective indicator (*i)* were derived from the product of the impact coefficients of all sector-region combinations ($d_{all,i}$), the cumulated inputs from all sector-region combinations into target-sector-regions, and the total output of target-sector-regions (x_T):

$$e_{T,i} = d_{all,i} \times L_{all-T} \times diag(x^T) \qquad \text{Eq. 2.8}$$

Thereby, the total output is diagonalized (indicated by the function *diag*) to assign the impacts to the target-sector-regions (target perspective). To assess the scope 3 impacts of target-sector-regions ($e_{T,wdc,i}$, a row vector) without double counting (wdc), we replace the total output (x^T) of Equation 2.8 by the direct final demand for target-sector-region outputs (Y_{T-all}) and the final demand for target-sector-region-products embodied in non-target-sector-regions. The latter is the product of direct inputs of target-sector-regions into non-target-sector-regions (A_{T-O}), thus deliberately omitting target-sector-region inputs into other target-sectors, and the cumulated output of non-target sector-regions. The latter is the product of cumulated inputs of non-target-sector-regions into non-target-sector-regions (L'_{O-O}) and the direct final demand for the outputs of all non-target-sector-regions (Y_{O-all}):

$$e_{T,wdc,i} = d_{all,\ i} \times L_{all-T} \times diag\overline{(Y_{T-all} + A_{T-O} \times L'_{O-O} \times Y_{O-all})} \qquad \text{Eq. 2.9}$$

Whereby the term in brackets is summed over the rows (indicated by the bar) and diagonalized to allocate the impacts to the target-sector-regions (target perspective). In Equation 2.9, double counting is prevented because the direct and indirect demand for target-sector-region-outputs (denoted by the terms in brackets) only includes flows from target-sector-regions to the final demand and from target-sector-regions into non-target-sector-regions, but not the flows between target-sector-regions. This term is also called the total output without double counting by Dente et al[36, 37]. Multiplication with L_{all-T} then warrants that the complete supply chain of the double-counted corrected total output is considered. Equation 2.9 can be reproduced by multiplying the black arrows in Figure 2.1. All variables are listed in Table 2.1, whereby the dimensions refer to the MRIO database EXIOBASE3 used for the case of global material production.

2.2.4 Mapping the Global Supply Chain by Multi-Dimensional Matrices Calculation

To assess the scope 3 impacts of target-sector-regions from four different perspectives in the global supply chain and to map the linkages between these perspectives, we decompose the procedure explained in Equation 2.9 into the individual steps by multi-dimensional matrices calculation. This allows us to construct the four-dimensional (4D) impact array $E^{wdc}_{T-4D,\,i}$ for each indicator (*i)*, whose four dimensions represent and connect the four perspectives presented in Figure 2.1:

for n_C *= 1:C*

$$E^{wdc}_{T-4D,\,i}(:,:,1,n_C) = diag(d_{all,\,i}) \times L_{all-T} \times diag(Y_{T-all}(:,n_C)) \qquad \text{Eq. 2.10}$$

for n_O*= 1:O*

$$E^{wdc}_{T-4D,\,i}(:,:,(n_O+1),n_C) = diag\big(d_{all,\,i}\big) \times L_{all-T} \times A_{T-O} \times L'_{O-O} \times diag(Y_{O-all}(n_O,n_C))$$

end Eq. 2.11

end

Whereby C denotes the total number of regions and categories of final demand of the respective MRIO system and O refers to the total number of non-target-sector-regions.

Diagonalizing the impact coefficients of all sector-region-combinations ($d_{all,i}$) allows to resolve the production perspective in the first dimension of $E^{wdc}_{T-4D,\,i}$. This dimension refers to all sector-region-combinations (covered by the respective MRIO system) where the emissions take place and the impacts are caused. In analogy, we diagonalize the direct final demand for the output of target-sector-regions (Y_{T-all}) and the final demand for the outputs of all non-target-sector-regions (Y_{O-all}) to map the target perspective in the second dimension of $E^{wdc}_{T-4D,\,i}$. The elements of the second dimension thus refer to all target-sector-regions. Running the equations as a *for loop* for each of the final-demand combination (n_C, C refers to the total number of regions and categories of final demand) and for each of the non-target-sector-regions (n_O, O refers to the total number of non-target-sector-regions) allows us to map the final supply and the final demand perspective in the third and fourth dimension of $E^{wdc}_{T-4D,\,i}$, respectively. Note that the first element of the third dimension of $E^{wdc}_{T-4D,\,i}$ refers to the direct final demand of target-sector-region outputs (Eq. 2.10), and that the remaining elements of the third dimension of $E^{wdc}_{T-4D,\,i}$ refer to the target-sector-region outputs finally embodied in non-target-sector-regions (Eq. 2.11, e.g. the materials that ends up in other commodities supplied to the final demand). The elements of the 4th dimension of $E^{wdc}_{T-4D,\,i}$ represent the region and category of final demand of the respective MRIO system.

2.2.5 Environmental and Socio-Economic Indicators

The developed calculation method can be applied to any MRIO system. Here we use the EE-MRIO database EXIOBASE3[4, 15] and implement a set of environmental and socio-economic indicators. The indicators *'material footprint'* (in tonnes of cultivated biomass, extracted mineral ore and fossils), *'value added'* (in euros) and *'workforce'* (in number of people working full-time) were directly adopted from the satellite matrix of EXIOBASE3. The indicators *'climate change impacts'*, *'PM health impacts'*, *'water stress'*, and *'land-use related biodiversity loss'* were implemented following the most recent impact assessment methods recommended by UNEP-SETAC[38]. In terms of climate change impacts, each greenhouse gas listed by the satellite matrix of EXIOBASE3 (CO_2, CH_4, N_2O, hydrofluorocarbons and perfluorinated compounds) was weighted with the respective global warming potential to derive the amount of emitted CO_2 equivalents. For the indicator PM health impacts, we multiplied each type of particulate matter emissions listed by the satellite matrix of EXIOBASE3 ($PM_{2.5}$, NO_x, SO_x, and NH_3) with sector-specific impact factors adapted from UNEP-SETAC[38] and Fantke et al[41] to measure human's burden of disease in 'disability adjusted life years' (DALYs). The indicator water stress was derived by weighting the total blue water consumption indicated by the satellite matrix of EXIOBASE3 with sector and region-specific impact factors adapted from Boulay et al[42]. This allowed us to account for regional and temporal differences in water scarcity and crop production patterns based on previous research[23, 43]. The resulting unit (m^3 of H_2O equivalents) refers to the scarcity-equivalent volume of water consumed under global average water scarcity conditions. In terms of land-use related biodiversity loss, we weighted the area of different land-use types provided by the satellite matrix of EXIOBASE3 (different types of crops, forestry, pastures and infrastructure) with region-specific impact factors adapted from UNEP-SETAC[38] and Chaudhary et al[44]. By this, we quantified the global potentially disappeared fraction of species (global PDF years), which indicates the fraction of global species that are committed to extinction due to human land-use. All these indicators were implemented as additional rows in the satellite matrix. This approach ensures that all emissions and resource consumptions are assessed with the characterization factors that match their location. Further details for implementing PM health impacts, water stress and land-use related biodiversity loss is documented in the Appendix A.1.

2.2.6 Application on Global Material Production

The above described methodology and the implemented indicators are provided as a matlab tool and can be applied to any of the 163 industrial sector and 49 regions specified by EXIOBASE3 to asses and track the related scope 3 impacts (link). In this study, we apply the tool to the case of global material production. Out of the 163 industrial sectors distinguished by EXIOBASE3, we define 75 target sectors, that refer to the extraction and processing of the four major material categories suggested by the UNEP and IRP[45]: biomass, metals, non-metal minerals and fossils. Hereby, the system boundaries for the target sectors end at the stage of final material production, e.g. metals, mineral materials (e.g. cement), fuels, food or chemicals. All other sectors were defined as non-target sectors that refer to the remaining economy (in total 88 non-target sectors in our example, see Supporting Information: *Classification.xlsx* of the publication). To assess the impacts of material production on a global scale, we classify all 49 regions as target-regions. This results in 3675 target-sector-regions referring to global material production (T, 75 target-sectors x 49 target-regions regions = 3675 target-sector-regions) and 4312 non-target-sector-regions, which refer to the remaining global economy (O, 7987 sector-region combinations – 3675 target-sector-regions = 4312 non-target-sector-regions). Following the procedure described in Section 2.2.2–2.2.3 allows deriving the 4D-impact array $E_{T-4D,\,i}^{wdc}$ for each indicator (i), which maps the scope 3 impacts of global material production from four perspectives of the global supply chain.

2.2.7 Quantifying the Achievement of Double Counting Correction

To quantify the overestimation of material-related impacts if the correction for double counting is neglected, we applied Equation 2.8 (procedure to assess the scope 3 impacts including double counting) and Equation 2.9 (procedure to assess the scope 3 impacts without double counting) to 41 target-sectors referring to material processing (see Supporting Information: *Classification.xlsx* of the publication) and to all 49 regions (41 target-sectors x 49 target-regions regions = 2009 target-sector-regions). Here, we exclude the 34 sectors that refer to material extraction, because this step is already included in the upstream supply chain of material processing (meaning that this would further increase double counting). In accordance to Dente et al. [36], we derive the double counting factor of material-related impacts ($f_{T,i}$, a column vector) for each target-sector-region and each indicator (i) by the following equation:

$$f_{T,i} = \frac{e_{T,i} - e_{T,\ i}^{wdc}}{e_{T,i}} \qquad \text{Eq. 2.12}$$

Note that $f_{T,i}$ provides the fraction of overestimation of each target-sector-region. The share of double counting is attributed to the target-sector-region in the upstream supply chain of other target sector-regions (and not to the target-sector regions that are either directly consumed or embodied in non-target sectors, because for those the entire scope 3 impacts were considered by both approaches). Thus, the double counting factor indicates for each target-sector-region, how much of its output (and the impacts related to its production) is supplied to other target-sector-regions.

2.3 Results and Discussion

2.3.1 Overestimation of material-related impacts due to double-counting

The results reveal that double-counting leads to an overestimation of global material-related (MR) impacts by about 20–30% (the range refers to the seven indicators covered in this study showed in the Appendix A.2: Figure A.1). Thereby, the overestimation is highest for metals (32–34%) and fossils (30–45%), which can be attributed to the importance of metals and fossils as a supplying material for the production of other materials (e.g. coal and steel used for cement production) and also to circular linkages (e.g. coke used for steel production and vice versa). A closer look at the individual material sectors reveals particularly high double-counting for coke oven products (>65% for all indicators) and nuclear fuels (>50% for all indicators, Appendix A.2: Table A.1). This means that the majority of these materials and the related impacts are used for the production of other materials. Since nuclear fuels are almost exclusively used for electricity production, this means that half of the impacts of global electricity production by nuclear fuels are caused in the upstream supply chain of material production.

The regional distribution reveals that double counting is highest for China's material production (~35% for all indicators, Appendix A.2: Figure A.2). About one third of the impacts related to China's material production are counted several times, because these materials are used for the production of other materials (either in China or in other regions). The major reason for this high fraction is attributed to China's leading role in global minerals and fossils production (particularly iron and steel, petroleum and chemicals which are used for the production of other materials). Double counting is also comparably high for Other Asia (30–35% for climate change and PM health impacts, and land-use related biodiversity), and Russia (~30% for climate change and PM health impacts). This can be attributed to the importance of these regions as producer of fossils and minerals (particularly iron and steel, petroleum, and chemicals) used for other material production either domestic or elsewhere. Africa and Latin America show comparably low double counting (10–25%). The reason is that material-related impacts are dominated by agriculture in these regions. The comparably low double counting for Europe and North America (15%–25%) may be attributed to their importance as importer of raw materials (Appendix A.2: Figure A.2).

Due to the issue of double counting and the intermediate stage of materials in the global supply chain, the number of studies addressing the impacts of materials on a global scale is very limited[2, 6, 9]. A direct comparison is not possible, since previous studies followed a bottom-up approach and used different underlying data (ecoinvent database). For a comparison of the climate change impacts of global metal production calculated with EXIOBASE3 and ecoinvent see the method annex of IRP[40]. Additionally, previous studies only assessed specific material groups and neglected those material groups strongly intertwined with the selected ones to mitigate double counting. Thus, our study may overestimate double counting for those studies, which "manually" corrected the most evident cases of double counting.

In terms of top-down analysis, only Hertwich and Wood[34] have assessed the scope 3 greenhouse gas emissions embodied in the global industry by EXIOBASE3. Thereby, the category 'afolu' (agriculture, forestry, food) is similar to the biomass sector of our study and the category 'materials' is similar to the metals and non-metallic minerals sector of our study. Since the category 'energy' distinguished by Hertwich and Wood[34] includes not only fossils but also electricity and heat, a direct comparison of the results is only possible in terms of biomass and minerals, but not for fossils. In contrast to our study, where biomass and minerals are responsible for 16 Gt CO_2 equivalents emissions in 2011, these two categories are responsible for 20 CO_2 equivalents emissions in the study of Hertwich and Wood[34], indicating that the greenhouse gas emissions of biomass and minerals were overestimated by 20% in the study of Hertwich and Wood[34] (by applying Eq. 2.12). This is in the range of the double counting factor derived in this study for biomass (15%) and metals (30%) in terms of climate change impacts and demonstrates the significance to correct for double counting in future top-down scope 3 impact assessments.

A comparison to the results of Dente et al[36] for climate change impacts related to Japan's material production is presented in the Appendix A.3.

2.3.2 Underestimation of material-related impacts if only direct impacts are considered

Our methodology reveals that the impacts caused by the remaining economy situated in the upstream supply chain of global material production (called *'upstream remaining economy'*) contributes 21% and 26% of the total MR climate change and PM health impacts, respectively (Figure 2.2, production perspective). This means that addressing only the direct impacts would underestimate the climate change and PM health impacts of global material production by this fraction. In contrast, water stress and land-use related biodiversity loss are almost exclusively caused directly during material production (>99%, Figure 2.2, production perspective), meaning that these two impact categories would not have been under-estimated. In terms of socio-economic indicators, a third of the MR value added and a tenth of MR workforce is related to the remaining economy. This means that addressing only direct benefits would significantly underestimate the value added of global material production.

As visualized in Figure 2.2, the climate change and PM health impacts of the remaining economy are caused in the upstream supply chain of all four material groups. Note that this can be reproduced by following the pink flows from the upstream remaining economy (production perspective) to the material groups (target perspective) in Figure 2. Assessing only the direct impacts would thus underestimate the climate change and PM health impacts of each material group. In terms of climate change impacts, metals would underlie strongest underestimation (35%), followed by fossils (22%), non-metallic minerals (21%), and biomass

(13%, note that the percentages indicate the share of the upstream remaining economy in total impacts of the respective material group). For PM health impacts, fossils would underlie strongest underestimation (40%), followed by biomass (25%), non-metallic minerals (20%), and metals (18%). In terms of value added generated by the upstream remaining economy, the majority is generated in the upstream supply chain of fossils (36%) and biomass (33%) production (Figure 2.2). This means that considering only direct value added would underestimate MR benefits particularly for fossils and biomass production.

2.3.3 Sectoral linkages and nexus of various impacts of the global material supply chain

Our methodology allows not only to assess the scope 3 impacts of target-sector regions without double-counting, but further enables to evaluate the linkages between all material sectors and the remaining economy in the upstream and downstream supply chain. Knowledge on the sectoral linkages of the global material supply chain (Figure 2.2) is particularly important to understand how the reduction of the impacts of a supplying material will reduce the impacts of the downstream value chain, or vice versa, how the reduction in the consumption of a material will reduce the supply and thus the impacts of the upstream supply chain. This allows to identify those sectors, which have a high leverage in the downstream value chain (a reduction of their impacts will efficiently reduce the impacts of the downstream products) and those sectors which have a high leverage in the upstream supply chain (a reduction of the consumption of those sector outputs will efficiently reduce the impacts of their upstream supply chain). In the following we discuss the sectoral linkages of the production, target and final supply perspective (Figure 2.2, note that the final demand perspective is not shown in Figure 2.2 since the focus lies here on the sectoral linkages; for a final demand perspective see IRP[40].

Non-metallic minerals are responsible for 44% of global material extraction (Figure 2.2). Most of this is used for the production of non-metallic materials, such as cement for example, but there is also a sizable portion of 17% of the non-metallic minerals used for fossils production (Figure 2.2). This fraction represents more than a third of the fossils-related mass-based material footprint from a target perspective. A closer look at this flow reveals that this is mainly attributed to sand and clay used in the upstream supply chain of chemicals, such as sand and clay used for the production infrastructure (80% of the non-metallic minerals used for fossils, Appendix A.2: Figure A.3). The downstream material value chain reveals that a third of all finished materials is directly consumed, which includes two third of the produced biomass (e.g. as food) and more than a third of produced fossils (e.g. for heating and transport) (Figure 2.2). In contrast, non-metallic minerals are mainly used for construction and a third of metals end up in electrics and electronics (Figure 2.2).

Indicators such as the material footprint are useful for understanding the system, but are not representing the environmental impacts that may occur. This is underlined by the fact that although non-metallic metals share the highest fraction in the global material footprint, the majority of MR climate change impacts is caused by the extraction and processing of biomass and fossils (each 28% of total MR climate change impacts from a production perspective). Furthermore, a large fraction of PM health impacts is due to emissions released during the production of metals (30% of total MR health impacts from a production perspective, Figure 2.2) and a fifth of MR climate change impacts and a quarter of MR PM health impacts occur in the upstream remaining economy of material production (Figure 2.2). A closer look at the individual sectors of the upstream remaining economy reveals that this is mainly attributed to electricity production by coal (60% of the climate change and PM health impacts caused by upstream remaining economy, Appendix A.2: Figure A.4), which underlines the importance for improvements towards cleaner electricity production.

The share of metals in MR climate change and PM health impacts is considerable higher from the target sector perspective (18% and 39% of total MR climate change and PM health impacts, respectively) than from the production perspective, which is attributed to the impacts caused by fossils and the remaining economy in the upstream supply chain of metals production (Figure 2.2). Overall, half of metals-related climate change impacts and a third of metals-related PM health (from target perspective) are attributed to the supply by fossils and the remaining economy in their upstream supply (Figure 2.2). A closer look at the flows between fossils and metals shows that this is mainly attributed to the ironmaking and steel production chain, which demands coal (60% of climate change impacts caused by fossils in the upstream supply chain of metals production) and coke oven products (70% of PM health impacts caused by fossils in the upstream supply chain of metals production, Appendix A.2: Figure A.5). On the one hand, these results indicate the importance to reduce the impacts of coal extraction and coke production, which would have a high leverage on all downstream materials such as the production of iron and steel. On the other hand, these results point to the potential of substituting steel through other materials that cause less impacts in the upstream supply chain (e.g. cross-laminated timber in construction). Targeting the latter question also requires knowledge on the downstream value chain of material production, whose in-depth analysis indicates that a large fraction of steel-related climate change and PM health impacts finally end up in construction (32%), machinery and equipment (17%), motor vehicles and trailers (12%), other electrics and electronics (11%) and other transport equipment (5%, Appendix A.2: Figure A.6).

Global water stress and land-use related biodiversity loss occur almost exclusively during the production of biomass (>95%, Figure 2.2). In terms of water stress, the largest fraction is attributed to the cultivation of wheat (31%), vegetables, fruits and nuts (22%) and paddy rice (17%, Appendix A.2: Figure A.6). For land-use related biodiversity loss, forestry and logging (33%) and cattle farming (22%, Appendix A.2: Figure A.7) are especially important. A closer look at the material supply chain shows a non-negligible flow of water stress and land-use related biodiversity loss from biomass to fossils (Figure 2.2). The majority of these flows is attributed to chemicals (80% of water stress and land-use related biodiversity loss due to fossils), mainly supplied by wheat, paddy rice, and sugar cane in terms of water stress, and by forestry and logging in terms of land-use related biodiversity loss (Appendix A.2: Figure A.8). Our results point to the importance of policy strategies and technology improvements towards less water and land intensive biomass production and a shift to regions with higher water availability and less protected ecosystems (e.g. regions with high water availability but low temperatures may produce food by greenhouses operated by waste heat to substitute food imports from water scarce regions). The fact that the majority of biomass is directly consumed by the final demand (Figure 2.2) points to the responsibility carried by consumers, such as the moderate consumption of animal products and food waste prevention.

Besides environmental impacts, we include the socio-economic indicators value added and workforce. Our results reveal that less than a quarter of global MR value added is generated in the biomass sector, although the majority of people are employed for this purpose (78% from production perspective, Figure 2.2). In contrast, a fifth of MR value added is generated by fossils, but only 3% of MR workforce is employed for the production of fossils. A similar imbalance between work input and economic benefit is observed in the upstream supply chain of material production: almost a third of the MR value added is generated by the remaining economy in the upstream supply chain of material production, while only 10% of MR workforce is employed there (Figure 2.2).

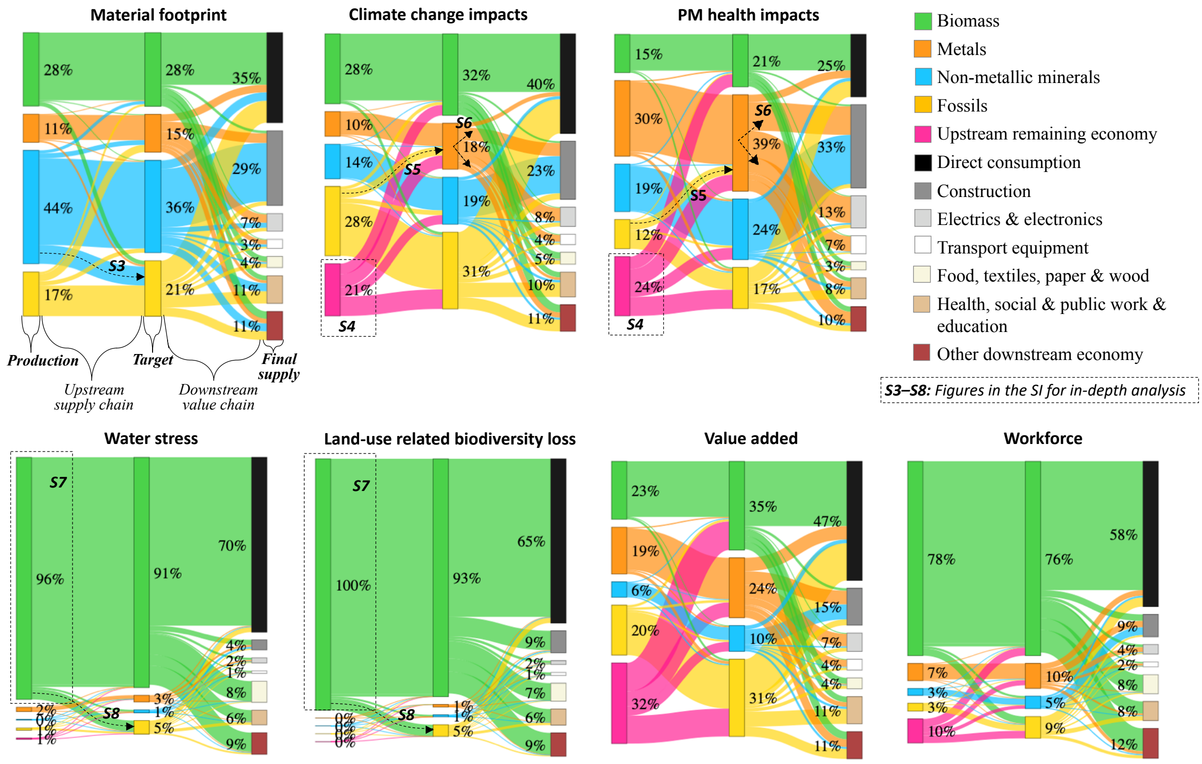


Figure 2.2. Sectoral shares and linkages of the global material supply chain and the related environmental impacts and socio-economic benefits from production, target and final supply perspective (Reference year: 2011). Note that the category *'direct consumption'* refers to materials directly consumed by the final demand and that the remaining categories of the final supply perspective refer to materials used by the remaining economy (i.e. non-target sectors). Further in-depth analysis of the marked sectors and flows are shown in the Appendix A.2 (Figure A.3–A.8).

2.3.4 Global Material-Related Trade

In addition to the sectoral linkages of the global material supply (Figure 2.2), our method allows to investigate where on globe the impacts of materials arise (production perspective), in which regions the final materials are produced (target perspective) and consumed (final demand perspective), and how these regions are connected to each other due to international trade (Figure 2.3, note that the final supply perspective is not shown in Figure 2.3, since the location of final supply equals the location of final demand in most cases). Due to international trade, regions' share in global MR impacts vary along the three steps of the global supply chain (Figure 2.3). Overall, 8–13% of global MR environmental impacts, 17% of value added and 10% of workforce are attributed to international trade among the ten world regions' upstream supply chain in 2011 (Figure 2.3). An even higher fraction of 17%–23% is attributed to international trade among the ten world regions' downstream value chain (Figure 2.3). In sum, a third of global MR climate change impacts, PM health impacts, and value added, and a quarter of MR water stress, land-use related biodiversity loss, and workforce are attributed to international trade among the ten world regions (Figure 2.3).

Detailed insights into global trade patterns are particularly important to understand how material production and consumption of one region influence the domestic impacts of another region. Our evaluation reveals that China is as a net importer in the upstream supply chain of MR impacts (Figure 2.3), but even more so a net exporter of MR impacts in the downstream value chain (except for land-use related biodiversity loss, Figure 2.3). For instance, 3-4% of global MR climate change and PM health impacts are imported by China's upstream material supply chain from other regions, and 6–8% of global MR climate change and PM health impacts are exported by China's downstream material value chain to other regions. China's international importance as material processing and trading country is further reflected by the fact that it occurs in more than half of the top ten international supply chains of MR climate change and PM health impacts (Table 2.2). In particular, China plays a key role in exporting iron and steel to Other Asia, North America, and Europe (Table 2.2).

The Middle East is a large exporter of MR climate change impacts and value added in the upstream material supply chain (3–4% of global) and a large exporter of water stress both in the upstream and downstream material value chain (3 and 7% of global, respectively). In terms of climate change impacts and value added, this is mainly attributed to the export of crude petroleum, which is refined and consumed in Other Asia, North America, China, Europe and India (as reflected in the top ten material supply chains of Table 2.2). The importance of the Middle East as a global water stress exporter is mainly attributed to the export of vegetables, fruits, nuts and wheat preferably consumed in Europe, Russia, and Other Asia (Table 2.2). In contrast, India plays a minor role in exporting water stress (<2% of global MR water stress) despite its global importance in terms of domestic water stress (24% of global water stress, Figure 2.3). This and the fact that India is neither involved in any of the top ten international water stress flows (Table 2.2) indicates that water intensive agricultural goods cultivated in India are mainly consumed by Indian population.

Latin America and Other Asia are the main exporters of land-use related biodiversity loss from both a production and target sector perspective (Figure 2.3). More specifically, major biodiversity impacts come from exports of wood, cattle meat (Latin America) and paddy rice (Other Asia, Table 2.2). Most economic value from exports is added in the Middle East in the crude oil sector, while in Africa and Other Asia many jobs are related to the production of export goods such as vegetables, fruits and nuts (Table 2.2).

Consumption in Europe and North America relies on net imports of all types of impacts, (Figure 2.3). This means that a sizable fraction of the impacts of goods consumed in Europe and North America occur elsewhere (3–4% for North America and 6–8% for Europe). The top ten material-supply chains further reflect the importance of Europe as final destination of internationally traded materials (Table 2.2). These results underline the importance to consider displacement effects through international trade in international policy (e.g. with regard to carbon accounting, which typically only considers domestic greenhouse gas emissions).

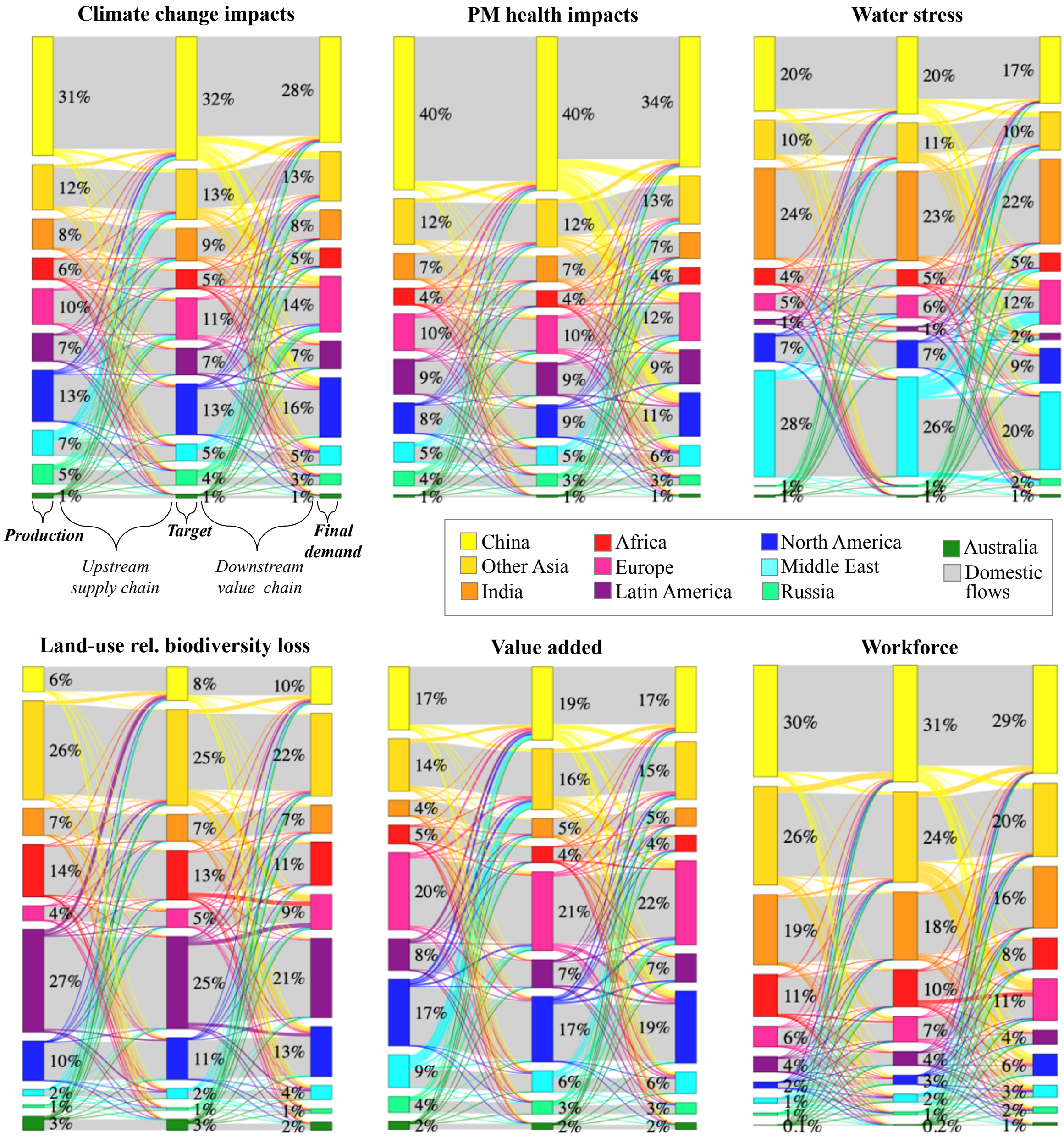


Figure 2.3. Regional shares in global MR impacts from production (left bar), target (middle bar) and final demand perspective (right bar), and regional flows within the upstream (between producing and target region) and downstream value chain (between target region and region of final demand). The colors of the bars reflect the regions and the colors of the flows indicate the exports of the respective region. Grey flows refer to flows within a region.

Table 2.2. Top ten international global supply chains of MR impacts. (Reference year: 2011)

Top 10 internat. trade fluxes		1. Production		2. Target		3. Final supply	4. Final demand
		Sector	Region	Sector	Region	Sector	Region
Material extraction [Mt]	155	Crude petroleum ex.	Middle East	Petroleum ref.	Other Asia	Direct demand	Other Asia
	98	Sand & clay ex.	China	Chemicals	China	Direct demand	Other Asia
	88	Natural gas ex.	Russia	Natural gas ex.	Russia	Direct demand	Europe
	81	Sand & clay ex.	China	Chemicals	China	Direct demand	Europe
	78	Sand & clay ex.	China	Chemicals	China	Direct demand	North America
	75	Crude petroleum ex.	Middle East	Petroleum ref.	North America	Direct demand	North America
	74	Cattle farming	India	Cattle farming	India	Leather products	Europe
	71	Sand & clay ex.	India	Chemicals	Other Asia	Direct demand	Europe
	65	Sand & clay ex.	China	Chemicals	China	Health & social work	Other Asia
	60	Crude petroleum ex.	Russia	Petroleum ref.	Europe	Direct demand	Europe
Climate change impacts [Mt CO_2eq]	78.2	Natural gas ex.	Russia	Natural gas ex.	Russia	Direct demand	Europe
	57.4	Crude petroleum ex.	Middle East	Petroleum ref.	Other Asia	Direct demand	Other Asia
	31.2	Cattle farming	India	Cattle farming	India	Leather products	Europe
	28.0	Crude petroleum ex.	Middle East	Petroleum ref.	North America	Direct demand	North America
	22.5	Crude petroleum ex.	Russia	Petroleum ref.	Europe	Direct demand	Europe
	21.0	Natural gas ex.	Russia	Natural gas ex.	Russia	Furniture manuf.	Europe
	19.5	Crude petroleum ex.	Middle East	Petroleum ref.	Europe	Direct demand	Europe
	16.4	Crude petroleum ex.	Middle East	Petroleum ref.	India	Direct demand	India
	15.0	Natural gas ex.	Other Asia	Natural gas ex.	Other Asia	Direct demand	Europe
	14.7	Crude petroleum ex.	Africa	Petroleum ref.	Europe	Direct demand	Europe
PM health impacts [kilo DALYs]	43.9	Forestry & logging	Other Asia	Forestry & logging	Other Asia	Direct demand	India
	29.3	Iron & steel prod.	China	Iron & steel prod.	China	Machinery eq. nec	Other Asia
	28.8	Iron & steel prod.	China	Iron & steel prod.	China	Construction	Other Asia
	22.8	Iron & steel prod.	China	Iron & steel prod.	China	Machinery eq. nec	North America
	17.8	Iron & steel prod.	China	Iron & steel prod.	China	Radio, TV & commun. eq.	Other Asia
	16.2	Iron & steel prod.	Europe	Iron & steel prod.	Europe	Construction	Middle East
	14.8	Iron & steel prod.	China	Iron & steel prod.	China	Machinery eq. nec	Europe
	13.5	Forestry & logging	Other Asia	Forestry & logging	Other Asia	Direct demand	China
	13.3	Petroleum ref.	Middle East	Petroleum ref.	Middle East	Direct demand	Europe
	12.7	Electricity prod. by coal	China	Chemicals	China	Direct demand	Other Asia
Water stress [Bio m^3 H_2Oeq]	507	Veg., fruits, nuts cult.	Middle East	Veg., fruits, nuts cult.	Middle East	Direct demand	Europe
	309	Veg., fruits, nuts cult.	Middle East	Veg., fruits, nuts cult.	Middle East	Direct demand	Russia
	76	Veg., fruits, nuts cult.	Middle East	Food prod. nec	Europe	Direct demand	Europe
	54	Wheat cult.	China	Wheat cult.	China	Wearing apparel	Europe
	53	Wheat cult.	China	Wheat cult.	China	Wearing apparel	Other Asia
	52	Wheat cult.	Middle East	Wheat cult.	Middle East	Direct demand	Europe
	45	Wheat cult.	China	Wheat cult.	China	Textiles	Other Asia
	44	Veg., fruits, nuts cult.	Middle East	Veg., fruits, nuts cult.	Middle East	Direct demand	Other Asia
	44	Wheat cult.	China	Wheat cult.	China	Wearing apparel	North America
	43	Crops nec cult.	Middle East	Crops nec cult.	Middle East	Direct demand	Europe
Land-use rel. biodiversity loss [global mPDF years]	0.261	Cattle farming	Latin America	Meat cattle prod.	Latin America	Direct demand	Europe
	0.212	Cattle farming	Latin America	Meat cattle prod.	Latin America	Direct demand	Russia
	0.206	Forestry & logging	Latin America	Forestry & logging	Latin America	Direct demand	India
	0.202	Cattle farming	Africa	Meat cattle prod.	Africa	Direct demand	Europe
	0.188	Cattle farming	Australia	Meat cattle prod.	Australia	Direct demand	Other Asia
	0.163	Veg., fruits, nuts cult.	Latin America	Veg., fruits, nuts cult.	Latin America	Direct demand	Europe
	0.145	Cattle farming	Australia	Meat cattle prod.	Other Asia	Direct demand	Other Asia
	0.139	Veg., fruits, nuts cult.	Latin America	Veg., fruits, nuts cult.	Latin America	Direct demand	North America
	0.113	Paddy rice cult.	Other Asia	Paddy rice cult.	Other Asia	Direct demand	Europe
	0.110	Forestry & logging	Other Asia	Forestry & logging	Other Asia	Direct demand	India
Value added [billion euros]	50.3	Crude petroleum ex.	Middle East	Petroleum ref.	Other Asia	Direct demand	Other Asia
	24.5	Crude petroleum ex.	Middle East	Petroleum ref.	North America	Direct demand	North America
	17.1	Crude petroleum ex.	Middle East	Petroleum ref.	Europe	Direct demand	Europe
	14.3	Crude petroleum ex.	Middle East	Petroleum ref.	India	Direct demand	India
	9.3	Chemicals	North America	Chemicals	North America	Direct demand	Europe
	8.0	Veg., fruits, nuts cult.	Africa	Veg., fruits, nuts cult.	Africa	Direct demand	Europe
	8.0	Crude petroleum ex.	Middle East	Petroleum ref.	China	Construction	China
	7.8	Crude petroleum ex.	Middle East	Petroleum ref.	Other Asia	Construction	Other Asia
	6.9	Chemicals	Other Asia	Chemicals	Other Asia	Direct demand	Europe
	5.4	Crude petroleum ex.	Middle East	Petroleum ref.	China	Direct demand	China
Workforce [million people FTE]	10.0	Veg., fruits, nuts cult.	Africa	Veg., fruits, nuts cult.	Africa	Direct demand	Europe
	5.5	Veg., fruits, nuts cult.	Other Asia	Veg., fruits, nuts cult.	Other Asia	Direct demand	Europe
	5.2	Veg., fruits, nuts cult.	Other Asia	Veg., fruits, nuts cult.	Other Asia	Direct demand	China
	3.6	Veg., fruits, nuts cult.	Other Asia	Veg., fruits, nuts cult.	Other Asia	Direct demand	Russia
	3.2	Veg., fruits, nuts cult.	Other Asia	Veg., fruits, nuts cult.	Other Asia	Direct demand	North America
	3.1	Veg., fruits, nuts cult.	Other Asia	Food prod. nec	China	Direct demand	China
	2.6	Meat animals nec	Other Asia	Meat animals nec	Other Asia	Direct demand	Europe
	2.0	Crops nec cult.	Other Asia	Crops nec cult.	Other Asia	Direct demand	Europe
	2.0	Veg., fruits, nuts cult.	China	Food prod. nec	China	Direct demand	Other Asia
	1.9	Meat prod. nec	Other Asia	Meat prod. nec	Other Asia	Direct demand	Europe

2.3.5 Relation between Material-Related Impacts and Human Development

The fact that some regions carry high shares of environmental impacts but comparably low shares in value added (India, Latin America and Other Asia) and vice versa (Europe) suggests an unequal distribution of MR impacts and benefits around the world. This analysis is confirmed when classifying regions' MR impacts according to their HDI (Figure 2.4 and Appendix A.2: Figure A.9 and A.10). Although low-developed regions (HDI ≤0.6) carry 20-40% of the MR environmental impacts and occupy half of MR global workforce, only 14% of the VA is generated in these regions (production perspective, Figure 2.4, and Appendix A.2: Figure A.9). In contrast, high-developed regions (HDI >0.8) carry less than a quarter of MR impacts, occupy only 7% of MR workforce but generate almost half of MR value added.

The evaluation further reveals a clear trend of high-developed regions displacing their impacts to less developed regions, especially in the final demand perspective of MR impacts (Figure 2.4 and Appendix A.2: Figure A.9). Along the entire supply chain, 40–60% of high developed regions' MR impact footprints are displaced to less developed regions. Furthermore, 80% of MR workforce attributed to final demand by high-developed regions was occupied in less developed regions. However, only a quarter of the MR value added consumed by high-developed regions was generated in less developed regions (Figure 2.4 and Appendix A.2: Figure A.9). These results show that impacts and benefits are unequally distributed around the globe and that trade related to raw materials adds to this imbalance.

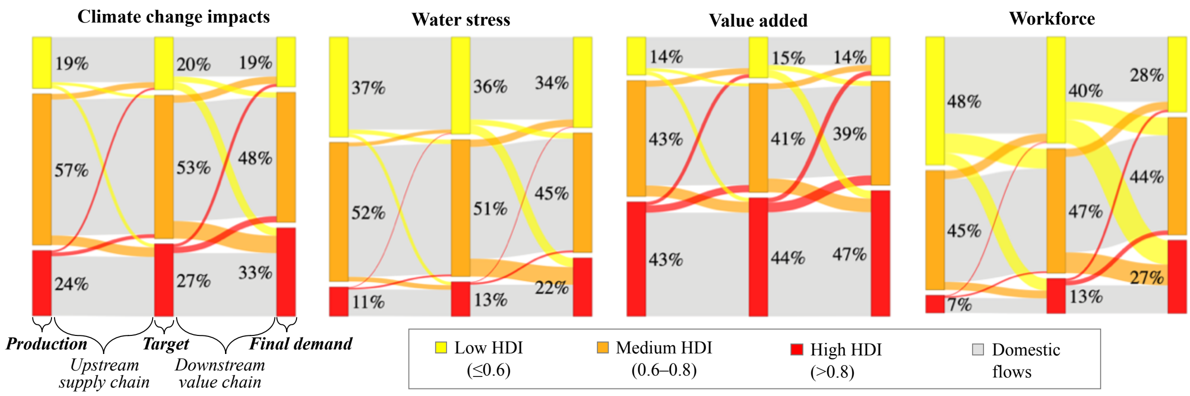


Figure 2.4. Regional shares (split by the HDI) of global MR impacts from production, target and final demand perspective and trade relations within the upstream and downstream value chain. The colors of the bars reflect the regions development stage and the colors of the flows stands for the exports of the respective regions to regions with other development stage. Grey flows refer to flows within the same HDI class. The analog flow charts for the material footprint, PM health impacts and land-use related biodiversity loss are shown in the Appendix A.2 (Figure A.8).

2.3.6 Temporal Development of Material-Related Impact Footprints

Between 1995–2011, global MR climate change impacts, PM health impacts and water stress have increased by 30–50%, while land-use related-biodiversity loss has remained stable (Figure 2.5a). The same trends were reported by Wood et al[4] for total global climate change impacts, global blue water consumption and occupied land area, based on the same EXIOBASE3 data. In contrast, land-use related biodiversity losses were found to increase in many other sources, including the IRP[2], suggesting high uncertainties in the temporal evolution of land-use data and related biodiversity loss in EXIOBASE3.

Per-capita impacts have increased for most regions (Figure 2.5a). Exceptions include climate change impacts in India, PM health impacts in Europe, Russia and North America, (Figure 2.5a). China showed the strongest growth in MR climate change and PM health impacts, both in total and per capita (Figure 2.5a). This is attributed to China's strong economic growth and investments in infrastructure build-up ("gross fixed capital formation"), which has increased almost fivefold over the period in terms of MR climate change impacts (Figure 2.5b). Nevertheless, China's per-capita footprints are still below the global average in terms of water stress and land-use related impacts in 2011 (Appendix A.2: Figure A.11). In contrast, Europe and North America show only minor or even no increase in their MR environmental footprints between 1995–2011, but still cause per-capita impacts above the global average in 2011 (Appendix A.2: Figure A.11). Even higher per-capita impacts are caused by Australia for all indicators (100–600% above the global average). Other regions such as Africa and India demonstrate a considerable increase in MR impacts over the past 20 years (plus 25–100%, except land-use related-biodiversity loss) and even more for value added (plus 300%), but still induce per-capita consumption-related impacts below the global average in 2011 (except water stress in India, Figure 2.5a and Appendix A.2: Figure A.11).

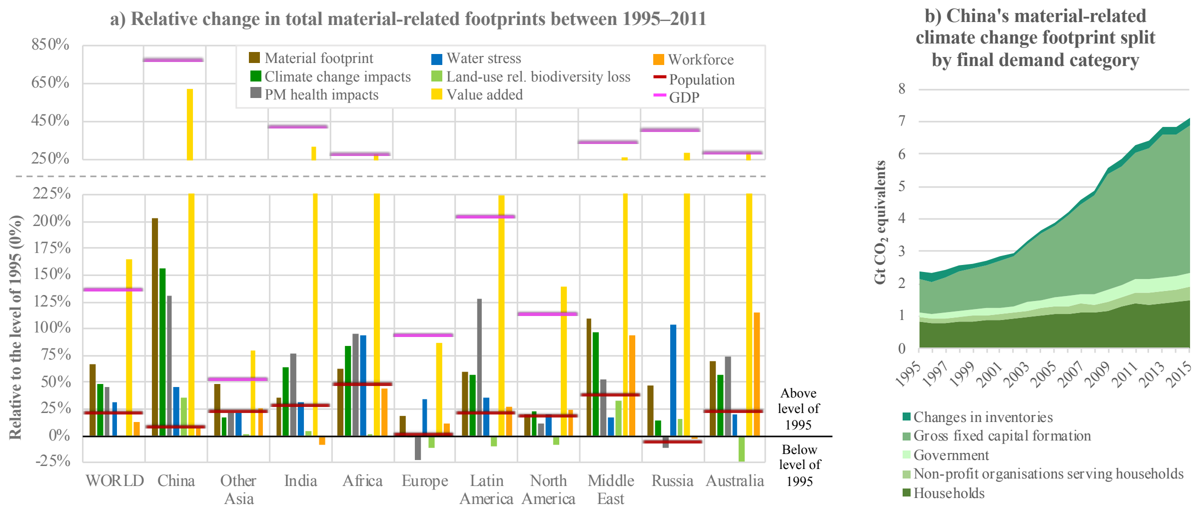


Figure 2.5. (a) Relative change in total MR footprints (shown by bars) compared to growth in population (red line) and GDP (pink line) in the timeframe from 1995–2011 for the entire world and for ten major world regions. The 0% line reflects the level of 1995, meaning that positive values denote an increase and negative values a decrease compared to the year 1995. (b) Temporal Development of China's material-related climate change footprint split by final demand by households, governments, etc. Note that the data provided by EXIOBASE3 for 2012–2015 are now-casted.

2.3.7 Temporal Development of Materials' Share in Total Global Impacts

Between 1995–2011, the share of material production in total global impacts has slightly increased in terms of climate change impacts (from 50% to 53%) and PM health impacts (from 25% to 33%), but remained constant for water stress and land-use-related biodiversity loss (both >90%, mainly biomass extraction, Appendix A.2: Figure A.12). The share of material production in total global value added has slightly increased (from 20% to 23%) and the share of global population employed for material production has slightly decreased from (59% to 53%, Appendix A.2: Figure A.12).

Regarding the temporal development of MR climate change impacts between 1995–2011 from a production perspective, we observe the strongest increase for the upstream remaining economy both in absolute (+2.6 Gt CO_{2eq}) and relative terms (+120%), followed by fossils in absolute terms (+1.7 Gt CO_{2eq}) as shown in Figure 2.6a. A closer look at the individual sectors reveals that this increase is mainly attributed to electricity production by coal (Figure 2.6d, increase by a factor of three during 2011–2015) and the related coal mining activities (Figure 2.6c). The analysis of the regional production patterns reveals that this increase is mostly driven by China, whose climate change impacts have increased by a factor of more than six in terms of electricity production by coal (Figure 2.6h) and by a factor of three in terms of coal mining activities (Figure 2.6g).

From a target perspective, we observe the strongest increase of MR climate change impacts for metals and non-metallic minerals both in absolute (+2.1 Gt CO_{2eq} and +2.5 Gt CO_{2eq}), respectively) and relative terms (+100% and +130%, respectively) as shown in Figure 2.6b). This is mainly driven by the production of iron and steel (70% of metals-related climate change impacts in 2011), and the production of cement, lime and plaster (55% of non-metallic minerals-related climate change impacts in 2011), whose cumulated upstream impacts have increased by a factor of 2.2 and 2.5 during 1995–2011 on a global scale, respectively (Figure 2.6e and 6f). In accordance to coal-related impacts, this increase is mainly attributed to China, whose climate change impacts have increased by a factor of four in terms of iron and steel production (sharing 31% of global iron and steel-related climate change impacts in 2011, Figure 2.6i), and by factor of five in terms of cement, lime and plaster production (sharing 52% of global cement, lime and plaster-related impacts in 2011, Figure 2.6j).

Biomass is the material category with the lowest increase in climate change impacts from both a production (Figure 2.6a) and target perspective (Figure 2.6b). These findings show the results of policy actions aiming at the reduction of climate change impacts of biomass, but they also highlight that more action is needed with regard to minerals (particularly iron, steel, cement), fossils (particularly coal). This could be achieved through material-light design of infrastructure, shift in materials to renewables (e.g. from sustainable forestry) and a shift to cleaner electricity production, particularly in big countries with large growth of infrastructure, such as China and India.

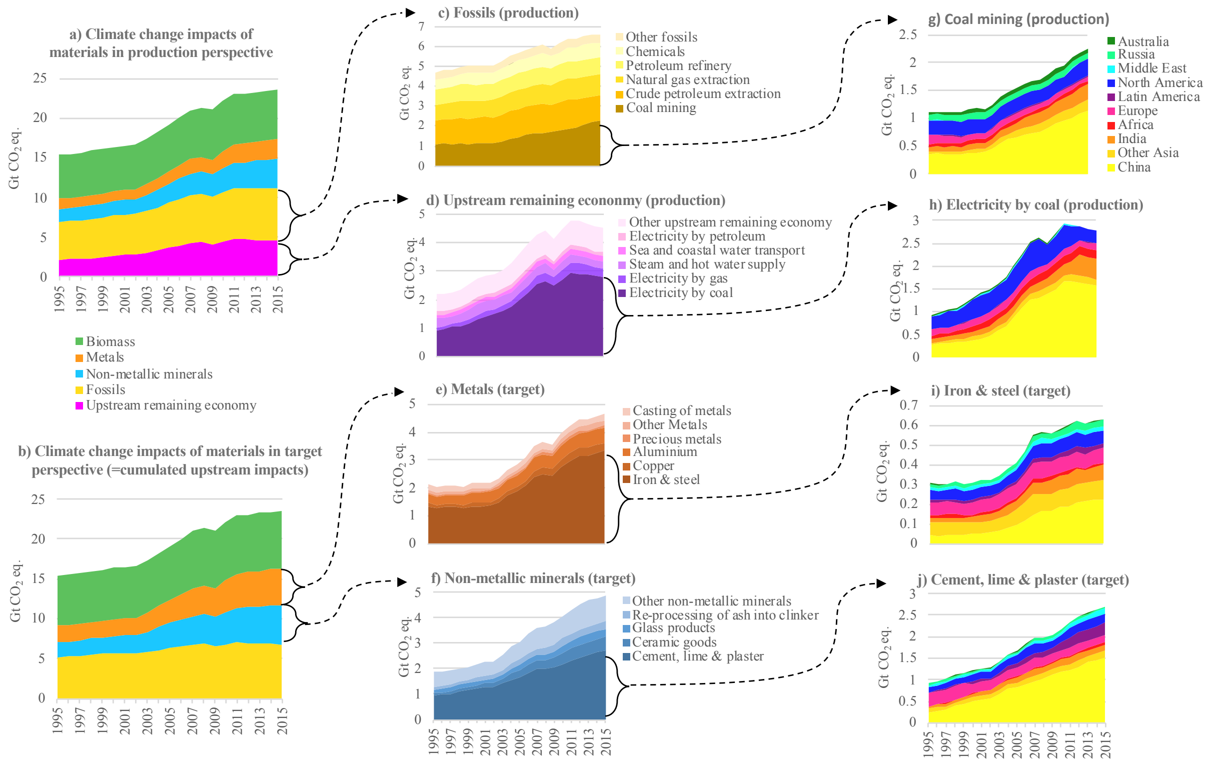


Figure 2.6. Temporal development of (a) material-related climate change impacts from production and (b) target perspective, (c) fossils-related climate change impacts from production perspective, (d) climate change impacts caused by the upstream remaining economy of material production, (e) cumulated climate change impacts of metals and (f) non-metallic minerals from target perspective, (g–j) regional pattern of climate change impacts caused by key industrial sectors. Note that the data provided by EXIOBASE3 for 2012–2015 are now-casted.

2.4. Conclusions and Outlook

The method presented in this study is the first that allowed to assess the scope 3 impacts of global material production (or any other industrial sector output) without double counting for a broad set of environmental and socio-economic indicators. The comparison with previous approaches revealed, that the standard MRIO procedure would overestimate the impacts of global material production by 20–30% due to double counting. In contrast, assessing only the direct impacts would underestimate the impacts of global material production (20–25% in terms of climate change and PM health impacts; a third in terms of value added). These results demonstrate the importance for future studies to correct for double counting when assessing the environmental impacts and socio-economic benefits of industrial sectors.

Previous studies pointed out that double counting is a prerequisite to reflect the reality in a way that several industrial sectors can contribute different measures to mitigate the same impacts[34]. The method presented here avoids double counting, but still allows to derive various measures along the supply chain by adopting different perspectives and by mapping the connection between these perspectives. Since the production perspective reveals all production locations and sectors where emissions are released and impacts are caused it shows improvement potentials for producers. The effect of such measures at the production site can then be tracked in the downstream value chain with the method presented here. The target perspective shows the cumulated upstream impacts of target sector outputs and allows to identify those products with the largest impacts. Improvement measures can then again be assessed in the upstream and downstream chain. In the downstream supply chain, the final supply and final demand perspective allocates all impacts to the final sector and consumer, respectively, to reveal high-impact reduction potentials for consumption. Therefore, our approach allows to derive improvement measures along several steps of the global value chain in a more precise way than previous approaches by excluding double counting.

MR impacts have increased for most regions in total and per capita. With regard to MR climate change and PM health impacts, this increase is driven by minerals and fossils. A shift to cleaner electricity production would only reduce MR climate change impacts by up to 20%, while the majority of emissions are directly released during the production process. This and the limited potential to further increase the efficiency of high impact material production technologies, such as cement and steel production processes[40], point to the importance for policies that reduce the consumption of these materials, e.g. by the substituting them through more sustainable alternatives. This is especially important for emerging and developing countries, where build up infrastructure and a growing urbanization may otherwise boost material consumption, following the same trajectory as shown for China in this study. Thus, it is crucial to establish new ways of construction to delimit material demand and related impact.

Further, our results point to the importance of, on the one hand, sourcing agricultural products from regions with high water availability and resilient ecosystems and, on the other hand, increasing productivity in regions of high water scarcity and valuable ecosystems to mitigate overall impacts in these regions. In the downstream supply chain, consumers and retailers have a high leverage for food-related impacts, e.g. by food waste prevention and reduced consumption and substitution of high-impact products (e.g. those grown in regions with high water scarcity and sensitive ecosystem). Due to the relevance of the location where agricultural products are grown, knowledge on the supply chain and regionalization in the impact assessment is crucial to guide sustainable food consumption. The tool presented in this paper can be used for such assessments.

Our tool (link) covers state-of-the art regionalized impact indicators following the UNEP-SECAC recommendations[38] and adding the socio-economic indicators value added and workforce. Together with the spatial tracking of the value chains, this allows for pinpointing where on the globe emissions, resource consumptions and impacts take place and where socio-economic benefits are generated. Our tool can be used by scientists, policy makers, industries, and non-governmental organizations to study the impacts and benefits of key sectors and regions and to evaluate improvement potentials along several steps in the global supply chain. This may substantially contribute to derive efficient measures for sustainable production and consumption.

The provided tool covers the time span between 1995–2011 and relies on monetary tables (physical tables are provided only for 2011 in EXIOBASE3). Future studies may consider to apply the method presented here also to physical MRIO tables (as done by Dente et al. (2018;

2019) for a Japan IO table) to further validate the results. In addition, future studies may apply the methodology to other MRIO databases (Eora26 and GTAP) to improve the regional resolution (e.g. to provide the results for single countries in Africa and Latin America). Other allocation methods, such as the shared responsibility approach, may be applied to the framework presented here to assess the impacts of sectors and regions, e.g. based on the generated value added[46]. Future work may also consider to apply the method on bottom-up LCA (or to merge it in a hybrid approach) to assess the impacts at a higher product detail and to integrate further impact categories that are currently not covered in MRIO (e.g. human and ecotoxicology).

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Chapter 3

A highly resolved MRIO database for analyzing environmental footprints and Green Economy Progress

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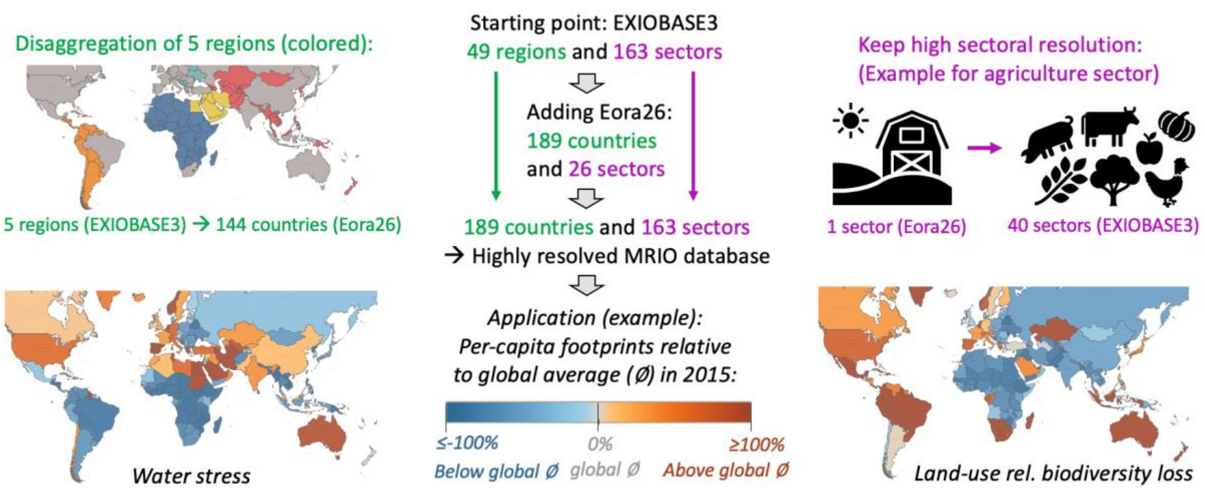
GRAPHICAL ABSTRACT



ABSTRACT

Moving towards a greener economy requires detailed information on the environmental impacts of global value chains. Environmentally-extended multi-regional input-output (MRIO) analysis plays a key role in providing this information, but current databases are limited in their spatial (e.g. EXIOBASE3) or sectoral resolution (e.g. Eora26 and GTAP) as well as their indicator coverage. Here, we present an automated, transparent, and comparably time-efficient approach to improve the resolution, quality, and indicator coverage of an existing MRIO database. Applied on EXIOBASE3, we disaggregate and improve the limited spatial resolution by weighting each element with country and sector specific shares derived from Eora26, FAOSTAT, and previous studies. The resolved database covers 189 countries, 163 sectors, and a cutting-edge set of environmental and socio-economic indicators from the

years 1995 to 2015. The importance of our improvements is highlighted by the EU-27 results, which reveal a significant increase in the EU's water stress and biodiversity loss footprint as a result of the spatial disaggregation and regionalized assessment. In 2015, a third of the EU's water stress and half of its biodiversity loss footprint was caused in the countries aggregated as rest of the world in EXIOBASE3. This was mainly attributed to the EU's food imports, which induce comparably high water stress and biodiversity loss in Egypt and Madagascar, respectively. In a second example, we use our database to add carbon, water stress and biodiversity loss footprints to the Green Economy Progress (GEP) Measurement Framework. Most countries have not achieved their environmental target and many countries, facing strong future population growth, show increasing footprints. Our results demonstrate that far more action is needed to move towards a greener economy globally, especially through supply chain management. The attached database provides detailed information on the environmental impacts of global value chains to plan efficient strategies for a greener economy.

3.1 Introduction

Effective environmental policies require reliable, relevant, and up-to-date indicators to measure environmental protection efforts[1]. The Green Economy Progress (GEP) Measurement Framework of the UNEP aims to provide such indicators to facilitate cross-country comparisons of national efforts towards greener economies[2, 3]. Until now, the GEP and many other indicator frameworks measured these efforts according to territorial (or production-based accounting) principles, under which countries are responsible for environmental pressures generated within their borders. However, a large share of today's products and services are no longer produced within a single country but rely on global value chains[4-6]. This means that countries import intermediate goods and raw materials, add one or more layers of value, and sell the resulting product either for final consumption or to another producer, who adds the next value layer[7]. At each of these steps, environmental pressure is generated in the form of natural resource use, emissions, or waste. In order to capture the impacts of global value chains, consumption-based accounting has been suggested to complement traditional production-based accounting[8]. It allows assessing the cumulative environmental impacts of a nation's consumption, including the impacts caused abroad due to imports, but excluding domestic impacts due to exports. Thus, consumption-based impacts, which are also called "footprints", address the importance of supply chain management.

Environmentally-extended multi-region input-output (MRIO) analysis has emerged as an appropriate methodological framework for consumption-based accounting[9, 10]. This concept aggregates the global economy into a specific number of regions and sectors to record its transactional flows and environmental accounts for a specific year or time frame. Applying simple mathematical calculations allows to evaluate the linkages between economic consumption activities and environmental impacts. Thus, MRIO analysis has been applied to calculate a wide range of environmental and socio-economic footprints and to track them along different steps in the global value chain[1, 11]. Recently, UNEP's International Resource Panel (IRP) published a report on carbon, water stress and biodiversity loss footprints of global material production, revealing the importance of material production and international trade for these footprints[12]. The report further highlights the importance for footprint analysis of high-income countries such as the EU, which increasingly outsource their resource-related environmental footprints to lower-income regions.

These studies have become possible only recently as MRIO databases suitable for calculating environmental and socio-economic footprints became available. Dietzenbacher et al[13] emphasize that a useful MRIO database for analyzing environmental and socio-economic footprints should respect three aspects: (i) be global, (ii) include a set of environmental and socio-economic indicators, (iii) and cover time series. Further, the ideal MRIO database should be as detailed as possible in terms of sectors and products and discern as many countries and regions as possible[7]. While there is consensus for the ideal system, limitations in data quality, consistency, and availability have led to the development of several MRIO databases with different strengths and weaknesses[14]. These include EXIOBASE3[15], Eora and Eora26[16, 17]; GTAP[18], WIOD[19], OECD-ICIO[20] and GRAM[21, 22]. Currently, EXIOBASE3 and Eora26 are the only publicly available databases with harmonized country and sector resolution, covering a large set of environmental pressures with time series from 1995 to 2015 (Appendix B.1: Table B.3.1 for a comparison of the databases).

For many major economies, the necessary input-output data to construct a MRIO database are regularly published by the national statistical agencies. Countries for which national input-output tables are unavailable or that are outside the focus of the specific database still need to be represented in the MRIO table to ensure that global supply chains are fully covered[23]. Usually, this is achieved by aggregating those countries not explicitly covered in the database into one or several "rest of the world" (RoW) region(s). Consequently, there is a considerable number of countries with minimal information. This leads to higher uncertainties in the results, both for these countries and all the other countries which are connected to them by trade. This raises three issues: (i) a low level of regional detail limits the comparison of environmental indicators between countries; (ii) a limited country coverage might lead to spatial aggregation errors; (iii) the relevance of different countries varies depending on the environmental indicator. For instance, many of the least developed countries heavily contributed to biodiversity loss impacts[24], but these countries are not individually covered in the EXIOBASE3 and WIOD databases[25].

The size and importance of spatial and sectoral aggregation errors have been studied previously. De Koenig et al[26] found that material footprints calculated with different spatial and product aggregations deviate in the order of only a few percent with outliers in the order of a 25% difference. For carbon footprints, Wood et al[27] found significant errors for the aggregated model, while other studies showed that additional regional detail yields little numerical difference[23, 25, 28]. Also, footprints of occupied workforce and the related compensation were found rather independent of the chosen aggregation options[23]. In contrast, the effects of different aggregation options led to a considerable underestimation in the water scarcity footprints of many countries[28]. A detailed study comparing MRIO with bottom-up trade data came to the same to conclusion for water stress footprints (up to a 48% differences for nations and even more for sector analyses)[29]. For land-use accounting, footprints were found to vary significantly[23] and Bjelle et al[30] concluded that particularly regions in Asia and Africa should be represented in more detail in order to avoid aggregation errors.

Overall, these studies show that a lower level of spatial or sectoral detail may be acceptable for global environmental stressors such as greenhouse gas emissions, which are caused by all industries and all countries. However, when calculating water and land footprints, a high level of spatial and sectoral disaggregation is essential, especially for agricultural, forestry, mining and related processing sectors[31]. EXIOBASE3 was built with a strong environmental focus and hence provides detailed information for sectors such as agriculture, energy, mining, and transport, where impact intensities can differ considerably[7]. However, while EXIOBASE3 stands out with its high sectoral resolution (163 sectors), it is limited in the regional resolution (44 countries and five RoW regions, Appendix B.1: Table B.1 and Figure B.1). Eora26 has the benefit of a higher country resolution (189 countries), but is limited in its sectoral resolution (26 sectors). This implies that at the current state, none of the existing MRIO databases (Appendix B.1: Table B.1) are suitable to perform a detailed and comprehensive analysis for a broad range of environmental indicators.

Due to its strong environmental focus and high sectoral coverage, several studies have been built on EXIOBASE to improve its country resolution. Two studies[32, 33] enhanced the water footprint assessments in EXIOBASE2 by using detailed crop production and water scarcity impact assessment at a high spatial resolution. However, both studies did not analyze time series and Lutter et al[32] did not enhance the resolution for trade data. Weinzettel and Pfister[33] additionally enhanced the trade data of agricultural sectors by using FAO trade balances, but did not improve the trade data of the other sectors. Bruckner et al[34] have linked EXIOBASE3 to the global physical biomass trade model LANDFLOW and improved the country and product detail with regard to cropland use. Bruckner et al[35] further improved this work by setting up the Food and Agriculture Biomass Input-Output model FABIO, which covers 130 agriculture, food, and forestry products for 190 countries. Since FABIO is limited in the sector detail of the remaining economy, Bjelle et al[30] addressed this issue by disaggregating the five RoW regions of EXIOBASE3 into 214 single countries, while keeping the high detail of 163 industrial sectors. All of these studies[30, 34, 35] focused exclusively on land-use, but did not address other environmental and socio-economic indicators that are important to assess trade-offs among them and a broader environmental progress.

In this study, we combine EXIOBASE3 and Eora26 to provide a resolved MRIO (R-MRIO) database with high country and sector detail, covering a broad set of partially regionalized environmental and socio-economic indicators, namely material footprint, climate change impacts, health impacts due to particulate matter (PM) emissions, water stress, land-use related biodiversity loss, value added, and workforce (Section 3.2). The database is available as time series from 1995 to 2015. As a first application example, we use it to assess the environmental and socio-economic footprints of the EU-27 (including Croatia and without the United Kingdom). This allows us to find hotspots in the EU's supply chain with regard to the impacts displaced to the individual RoW countries (Section 3.3.1). Due to its differences compared to previous MRIO databases, we call our database a "resolved" MRIO (R-MRIO) database and discuss its benefits and limitations in Section 3.3.2. In a second application example, we use the resolved database to add carbon, water stress and biodiversity loss footprints to the Green Economy Progress (GEP) Measurement Framework of the UNEP[2, 3]. For each country, we compare these footprints against specific per-capita targets to measure its progress towards a greener economy from a consumption perspective (Section 3.3.3).

3.2 Methods

3.2.1 Terminology

Each environmentally-extended MRIO database is composed of a transaction matrix (T), a final demand matrix (Y), and the satellite matrices of the economy (Q_T) and the final demand (Q_Y), all of which refer to a specific time frame. The transaction matrix is a square matrix, which records the transactional flows between all sector-region-combinations of the respective time frame. The final demand matrix indicates the transactional flows from each sector-region to each final demand combination. The satellite matrices indicate the environmental and socio-economic accounts for each sector-region combination (Q_T) and each final demand combination (Q_Y) of the MRIO system.

The R-MRIO database of this study distinguishes 163 sectors, 189 countries, six final demand categories, and nine satellite accounts. The resulting transaction matrix (30'807 rows and 30'807 columns), final demand matrix (30'807 rows and 1104 columns), and the satellite matrices of the economy (9 rows and 30'807 columns) and the final demand (9 rows and 1104 columns) are provided as time series from 1995 to 2015 (database from 1995–2005 and 2006–2015). In the following, matrices and vectors are displayed in uppercase (e.g. T, Y, Q_T and Q_Y) and the respective elements are displayed in lowercase (e.g. t, y, q_t, and q_y).

3.2.2 Overview

To derive the matrices of the R-MRIO database, we primarily used EXIOBASE3 (version 3.4) and merged its sector-specific data with the country-specific data of Eora26 to disaggregate the five rest of the world regions of EXIOBASE3 into 145 countries with 163 industrial sectors, respectively, for each year from 1995 to 2015. EXIOBASE3 was chosen as a starting point because the economically most important countries have a high sector resolution, and those countries aggregated by EXIOBASE3 into RoW regions have inadequate sectoral resolution in Eora26. Additionally, many environmental extensions are more reliably and transparently reported in EXIOBASE3[15] (Appendix B.2: Paragraph B.1, Figure B.2 and B.3). The merging process of EXIOBASE3 and Eora26 is described in Section 3.2.3. The implementation of the environmental indicators is reported in Section 3.2.4. We further improved the data quality for all agricultural, food, and forestry sectors by integrating production data from FAOSTAT and regionalized data on water stress and land-use related biodiversity loss (Section 3.2.5). The implementation of the workforce indicator and the balancing of the R-MRIO database is explained in Section 3.2.6 and 3.2.7, respectively. The calculation with the R-MRIO database for the EU's footprint analysis and to assess Green Economy Process is described in Section 3.2.8. The entire procedure to resolve the database, implement the indicators, and improve the data quality is attached as MATLAB code (link).

3.2.3 Merging EXIOBASE3 and Eora26

The match between regions and sectors of EXIOBASE3 and Eora26 is included in the Supporting Information of the publication (*SI_Exio_Eora_match.xlsx*). For the 44 countries individually covered by EXIOBASE3, the elements of the resolved transaction and final demand matrix ($T^{Exio-Eora}$ and $Y^{Exio-Eora}$) equal those of the original transaction and final demand matrix of EXIOBASE3 (T^{Exio} and Y^{Exio}, Figure 3.1). The five RoW regions of EXIOBASE3 were disaggregated into 145 single countries by weighting each sector-specific element from EXIOBASE3 with the corresponding regional share of the country-specific element from Eora26:

$$t^{Exio-Eora}_{c_j s_j,\, c_k s_k} = t^{Exio}_{\Sigma c_j s_j,\, \Sigma c_k s_k} * \frac{t^{Eora}_{c_j \Sigma s_j,\, c_k \Sigma s_k}}{\sum_{c_j c_k} t^{Eora}_{c_j \Sigma s_j,\, c_k \Sigma s_k}} \qquad \text{Eq. 3.1}$$

Where c represents the resolved country derived from Eora26 (e.g. Egypt), Σc stands for the corresponding RoW region in EXIOBASE3 (e.g. RoW Middle East), s stands for the resolved sector derived from EXIOBASE3 (e.g. cultivation of cereal grains), and Σs represents the matching sector group in Eora26 (e.g. agriculture). The index j and k refer to the selling sector and country (rows of T) and the buying sector and country (columns of T), respectively.

As an example, to resolve the input of Iran's cultivation of cereal grains into Egypt's cattle farming ($t^{Exio-Eora}_{5,4}$, Figure 3.1), we used the fact that Egypt and Iran are part of the RoW Middle East in EXIOBASE3, in combination with the fact that the cultivation of cereal grains and cattle farming sectors are part of the agriculture sector in Eora26. In the R-MRIO database, the RoW Middle East is composed of 16 countries, and the agriculture sector distinguishes 15 sectors, including different types of crops, animal farming and forestry. It was assumed that the agriculture sector in Eora26 also includes forestry, since the environmental extension on timber extraction is almost exclusively allocated to the agriculture sector in Eora26, and since a description on the coverage of the sectors in Eora26 was not available. In the simplified example of Figure 3.1, the RoW Middle East only includes Egypt and Iran and the agriculture sector of Eora26 only distinguishes cultivation of cereal grains and cattle farming. Accordingly, we multiplied the input of RoW Middle East's cultivation of cereal grains into RoW Middle East's cattle farming from EXIOBASE3 ($t^{Exio}_{3,4}$, Figure 3.1) by the regional share of the input of Iran's agriculture sector into Egypt's agriculture sector ($t^{Eora}_{3,2}$, Figure 3.1) in the total input of RoW Middle East's agriculture sector into RoW Middle East's agriculture sector in Eora26. The total input of RoW Middle East's agriculture sector into RoW Middle East's agriculture sector in Eora26 equals the input of Egypt's agriculture sector into Egypt's ($t_{2,2}^{Eora}$) and Iran's agriculture sector ($t_{2,3}^{Eora}$), plus the input of Iran's agriculture sector into Egypt's ($t_{3,2}^{Eora}$) and Iran's agriculture sector ($t_{3,3}^{Eora}$):

$$t_{5,4}^{Exio-Eora} = t_{3,4}^{Exio} * \frac{t_{3,2}^{Eora}}{t_{2,2}^{Eora} + t_{2,3}^{Eora} + t_{3,2}^{Eora} + t_{3,3}^{Eora}} \qquad \text{Eq. 3.2}$$

With this procedure, we only added country-specific information from Eora26 to the EXIOBASE3 database to provide a better estimate on the regional resolution, but the total sum of the merged transaction matrix ($T^{Exio-Eora}$) remains the same as for the original EXIOBASE3 database (T^{Exio}).

In accordance to the resolved transaction matrix ($T^{Exio-Eora}$), we derived each element of the resolved final demand matrix ($Y^{Exio-Eora}$):

$$y_{c_j s_j, c_k f_k}^{Exio-Eora} = y_{\Sigma c_j s_j, \Sigma c_k f_k}^{Exio} * \frac{y_{c_j \Sigma s_j, c_k f_k}^{Eora}}{\sum_{c_j c_k} y_{c_j \Sigma s_j, c_k f_k}^{Eora}} \qquad \text{Eq. 3.3}$$

whereby f stands for the category of final demand (e.g. households, capital formation). The final demand categories are the same for EXIOBASE3 and Eora26.

The total output vector of the R-MRIO database ($X^{Exio-Eora}$) was calculated as the row sum of the merged transaction ($T^{Exio-Eora}$) and final demand matrix ($Y^{Exio-Eora}$).

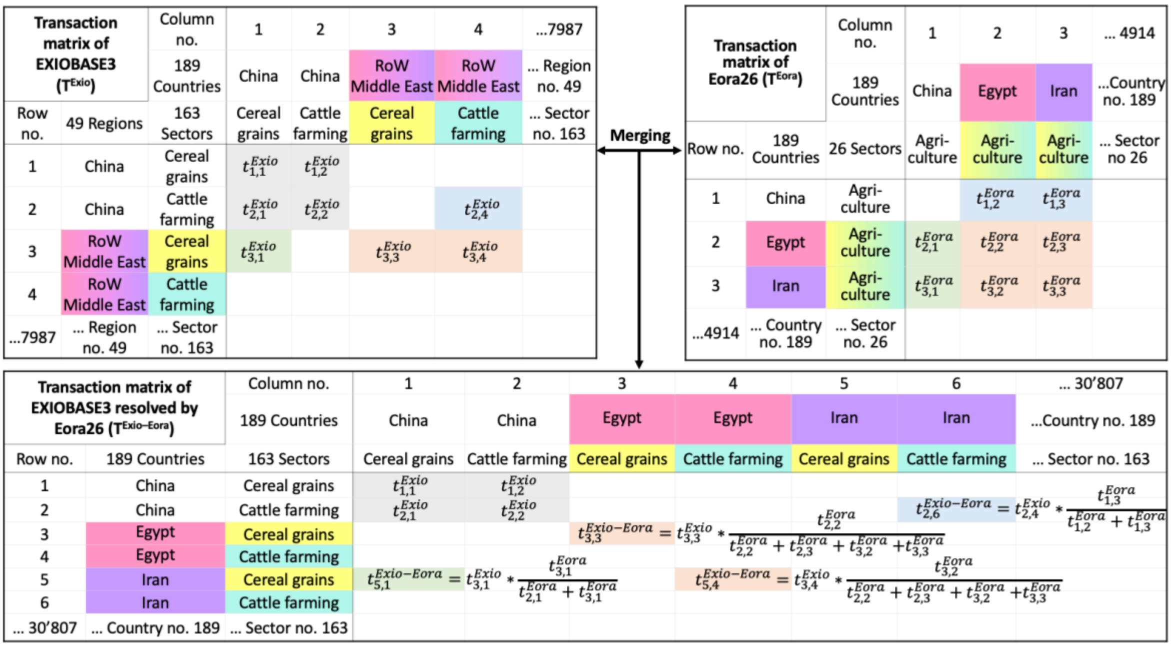


Figure 3.1: Derivation of the resolved transaction matrix ($T^{Exio-Eora}$) by merging EXIOBASE3 and Eora26. In this simplified example the RoW Middle East of EXIOBASE3 is only composed of Egypt and Iran, and the agriculture sector of Eora26 only includes the cultivation of cereal grains and cattle farming. In the R-MRIO database, the RoW Middle East is composed of 16 countries derived from Eora26, and the agriculture sector equals 15 different crops, farming and forestry sectors derived from EXIOBASE3.

3.2.4 Implementation of the environmental impact categories

For the 44 countries individually covered by EXIOBOASE3, we used the impact coefficients, built on EXIOBASE3, of Cabernard et al[11]. The general procedure for the remaining 145 countries was to implement each impact category into Eora26 (Section 3.2.4a) and to scale the impacts reported by Cabernard et al[11] to country-sector resolution by following the same approach as for the transaction and final demand matrices (Section 3.2.4b). The implementation of the indicators into Eora26 is also attached as MATLAB code (Exiobase_resolved.m).

3.2.4a) Implementation of impact assessments for Eora26

The indicators material extraction and blue water consumption were directly adopted from the satellite matrix of Eora26. For land use, we used the data on crops and pastures indicated by the satellite matrix from Eora26. Since reliable data on forestry and infrastructure land is not available in Eora26, this type of data was compiled from FAOSTAT[36] and OECD[37], respectively.

For climate change impacts, PM health impacts, water stress, and land-use related biodiversity loss, we applied the most recent impact assessment methods recommended by the UNEP-SETAC[38] and followed the same general procedure described in Cabernard et al[11]. For climate change impacts, we weighted each greenhouse gas listed in the satellite matrix of Eora26 (CO_2, CH_4, N_2O, hydrofluorocarbons and perfluorinated compounds) with the respective global warming potential to derive the amount of emitted CO_2 equivalents (Appendix B.2: Paragraph B.1, Figure B.2 and B.3). For PM health impacts, we multiplied each type of emissions listed by the satellite matrix of Eora26 leading to PM health impacts ($PM_{2.5}$, NO_x, SO_x, and NH_3) with sector-specific characterization factors (CFs) derived from UNEP-SETAC[38] and Fantke et al[39]. This allowed us to measure humanity's burden of disease in 'disability adjusted life years'[40].

The water stress indicator was implemented into Eora26 by weighting total blue water consumption indicated by the Eora26 satellite matrix with country-specific water stress factors adapted from Boulay et al[41] for agricultural and non-agricultural sectors. The resulting unit (volume of H_2O equivalents) indicates the scarcity-equivalent of water consumed under global average water scarcity conditions.

In terms of land-use related biodiversity loss, we weighted the area of cropland and pastures given by the Eora26 satellite matrix with country-specific CFs adapted from UNEP-SETAC[38] as reported by Chaudhary et al[42] and summarized by Verones et al[43]. These CFs are based on species loss methods developed for selected animal taxa[44] and plants[45]. For forestry and infrastructure, we weighted the respective land use area compiled from FAOSTAT[36] and OECD[37] with the country-specific CFs from UNEP-SETAC[38]. This allowed us to quantify the global potentially disappeared fraction of species (global PDF years), which indicates the fraction of global species that are committed to extinction due to anthropogenic land use.

3.2.4b) Derivation of the resolved satellite matrices

Following the same approach as for the resolved transaction and final demand matrices (Section 3.2.3), we derived the satellite matrix ($Q\_T^{Exio-Eora}$), whose rows refer to the respective indicator (i) and indicate the total impact (e.g. in volume of H_2O equivalents for water stress) for each of the 30'807 country (c)-sector (s) combinations in the columns (k) of the satellite extension. Consequently, we spatially resolved the sector-specific impact of Cabernard et al[11], which was built on EXIOBASE3 (Q_T^{Exio}), with the country-specific impact of Eora (Q_T^{Eora}):

$$q\_t_{i,c_k s_k}^{Exio-Eora} = q\_t_{i,\Sigma c_k s_k}^{Exio} * \frac{q\_t_{i,c_k \Sigma s_k}^{Eora}}{\Sigma_{c_k} q\_t_{i,c_k \Sigma s_k}^{Eora}} \quad \text{Eq. 3.4}$$

As an example, to resolve the water stress (WS) caused by Egypt's cattle farming ($q\_t_{WS,Egypt:\,cattle}^{Exio-Eora}$), we multiplied the water stress caused by the RoW Middle East's cattle farming from Cabernard et al[11] ($q\_t_{WS,M.East:\,cattle}^{Exio}$) with the relative share of the water stress of Egypt's agriculture ($q\_t_{WS,Egypt:\,agri}^{Eora}$) in the water stress of the RoW Middle East's agriculture indicated by Eora26. The later equals the sum of the water stress in the agriculture sector of all countries in Eora26 classified as RoW Middle East:

$$q\_t_{WS,Egypt:\,cattle}^{Exio-Eora} = q\_t_{WS,M.East:\,cattle}^{Exio} * \frac{q\_t_{WS,Egypt:\,agri}^{Eora}}{q\_t_{WS,Egypt:\,agri}^{Eora} + q\_t_{WS,Iran:\,agri}^{Eora} + q\_t_{WS,Iraq:\,agri}^{Eora} + \cdots} \quad \text{Eq. 3.5}$$

The same principle was applied to derive the resolved satellite extensions of the final demand ($Q\_Y^{Exio-Eora}$), whose rows indicate the total impact of the respective indicator (i) for each of the 1134 final demand combinations (c and f) in the columns (k):

$$q\_y_{i,c_k f_k}^{Exio-Eora} = q\_y_{i,\Sigma c_k f_k}^{Exio} * \frac{q\_y_{i,c_k f_k}^{Eora}}{\Sigma_{c_k} q\_y_{i,c_k f_k}^{Eora}} \quad \text{Eq. 3.6}$$

3.2.5 Improvement for agricultural, food and, forestry sectors

EXIOBASE3 distinguishes 30 agriculture, food and forestry sectors, which are aggregated in the sectors "agriculture" and "food and beverages" in Eora26. To improve the data quality of these sectors for the 145 resolved countries, we integrated production data from FAOSTAT[36] and adjusted the respective outputs in the transaction and final demand matrices (Section 3.2.5a). Additionally, we integrated data on water stress caused by each crop sector from Pfister and Bayer[46] (Section 3.2.5b), and data on biodiversity loss caused by each crop sector, pasture, and forestry from Chaudhary et al[42] (Section 3.2.5c).

3.2.5a) Integration of FAOSTAT data

We compiled the production amounts of all crops, food, and wood products, and the live stocks for all animals from FAOSTAT[36] from 1995 to 2015, and classified them into the 30 agriculture, food and forestry sectors (biomass sectors) distinguished by EXIOBASE3. Analogous to the procedure in Section 3.2.3, we weighed the total output indicated by EXIOBASE3 (X^{Exio}) for the corresponding RoW region (Σc), with the share of the country's biomass sector in the total biomass sector of the respective RoW region compiled from FAOSTAT (X^{FAO}) to derive the total output ($X^{Exio-FAO}$) for each biomass sector (s) of each resolved country (c):

$$x_{c_j s_j}^{Exio-FAO} = x_{\Sigma c_j s_j}^{Exio} * \frac{x_{c_j s_j}^{FAO}}{\Sigma_{c_j} x_{c_j s_j}^{FAO}} \qquad \text{Eq. 3.7}$$

By dividing $X^{Exio-FAO}$ through the corresponding total output of the merged database from Section 3.2.3 ($X^{Exio-Eora}$), we derived a correction factor to scale the outputs of the biomass sectors (s) of the merged transaction and final demand matrices from Section 3.2.3 ($Y^{Exio-Eora}$ and $Y^{Exio-Eora}$):

$$t_{c_j s_j, c_k s_k}^{Exio-final} = \frac{x_{c_j s_j}^{Exio-FAO}}{x_{c_j s_j}^{Exio-Eora}} * t_{c_j s_j, c_k s_k}^{Exio-Eora} \qquad \text{Eq. 3.8}$$

$$y_{c_j s_j, c_k f_k}^{Exio-final} = \frac{x_{c_j s_j}^{Exio-FAO}}{x_{c_j s_j}^{Exio-Eora}} * y_{c_j s_j, c_k f_k}^{Exio-Eora} \qquad \text{Eq. 3.9}$$

The final total output vector of the R-MRIO database ($X^{Exio-final}$) was calculated as the row sum of the scaled transaction ($T^{Exio-final}$) and final demand matrices ($Y^{Exio-final}$).

3.2.5b) Water stress of crops

In order to account for higher spatial and temporal detail of specific crop growth patterns, we compiled blue water consumption and water stress data for all crops from Pfister and Bayer[46] and Pfister and Lutter[47] and classified them into the eight crops sectors distinguished by EXIOBASE3 as was done for EXIOBASE2 by Lutter et al[32]. To derive the water stress (WS) for each crop sector (s) of each resolved country (c) of the final satellite matrix ($Q\_T^{Exio-final}$), we weighted the crop-specific water stress indicated by Cabernard et al[11] (Q_T^{Exio}) for the aggregated region (Σc), with crop-specific country shares derived from Pfister and Lutter[47] (Q_T^{water}):

$$q\_t_{WS, c_k s_k}^{Exio-final} = q\_t_{WS, \Sigma c_k s_k}^{Exio} * \frac{q\_t_{WS, c_k s_k}^{water}}{\Sigma_{c_k} q\_t_{WS, c_k s_k}^{water}} \qquad \text{Eq. 3.10}$$

The same procedure (Eq. 3.10) was applied to improve the data on blue water consumption (BWC) for each crop sector of each resolved country.

3.2.5c) Land-use related biodiversity loss of crops, pastures, and forestry

Land resources are mainly used through land occupation and corresponding activities. Depending on the vulnerability and species richness of the occupied ecosystem, this can lead to severe biodiversity losses. Since EXIOBASE3 and Eora26 are limited in their spatial and sectoral resolution, we used more detailed and well documented data on land use and biodiversity impacts due to land occupation. To quantify global potential species loss due to land occupation for crops, we used the characterization factors (CFs) of the biodiversity impact assessment recommended by the UNEP-SETAC[38], which are available on an ecoregion level (~800 units globally)[42]. For assessing the land use of pasture, intensive forestry, and extensive forestry, we applied the respective country average CFs[42].

For crops, production data for 160 crops with approximately 10 km x 10 km spatial resolution, representing the year 2000, were compiled from Pfister et al[48]. These data were multiplied with respective CFs for land use on an ecoregion level based on Chaudhary et al[42]. Classification into permanent and annual cropland for each crop type is based on the FAO classification[49], since it is required to apply the different CFs. In a second step, the total species loss per crop and location were aggregated on the sectoral level of EXIOBASE3, following the approach of Lutter et al[32]. The resulting total species loss was divided by the respective land use of the sector to derive production weighted CFs for each crop sector and country of the R-MRIO database. This allowed us to account for the spatial distribution and production volume of different crops for each country of the R-MRIO database. These CFs were applied to the land use time series from FAOSTAT[36], which account for yield increases and production changes for each crop and country. This allowed us to derive the biodiversity loss caused by each crop and country of the R-MRIO database (Q_T^{Land}) for each year from 1995 to 2015.

For pasture and forestry, we used the CFs from Chaudhary et al[42] and respective land use areas reported by FAOSTAT[36]. Pastures are reported as “Pastures (temporary and cultivated only)” and “Permanent meadows and pastures” by FAOSTAT[36]. We used both entries for the year 2000 and 2010, and applied the pasture CFs from Chaudhary et al[42] to derive Q_T^{Land} for pastures. For forestry, FAOSTAT[36] reports data on FAO Global Forest Resource Assessments (FRA) for forest sub-category items “Planted forest”, “Primary forest” and “Other naturally regenerated forest,” for 1990, 2000, 2005, 2010 and 2015. We used the data for the year 2000 and 2010, and applied intensive forest CFs for “planted forests” and extensive forest CFs for “Other naturally regenerated forest”. According to Chaudhary et al[42], each forestry area was multiplied with the UNEP-SETAC[38] recommended CFs for land use on country resolution to derive Q^{Land} for forestry. For pasture and forestry, we interpolated and extrapolated the values for 2000 and 2010 to derive time series from 1995 to 2015.

Finally, we weighted the land-use related biodiversity loss indicated by Cabernard et al[11] (Q_T^{Exio}) for the aggregated region (Σc), with the sector-specific country shares of Q_T^{Land}. This allowed us to derive better biodiversity loss (BD) estimates for each crop, pasture and forestry sector (s) for each country (c) of the R-MRIO database ($Q\_T^{Exio-final}$):

$$q\_t_{BD\text{ - }c_k,s_k}^{Exio-final} = q\_t_{BD\text{ - }\Sigma c_k,s_k}^{Exio} * \frac{q\_t_{BD\text{ - }c_k,s_k}^{Land}}{\Sigma_{c_k}\, q\_t_{BD\text{ - }c_k,s_k}^{Land}} \qquad \text{Eq. 3.11}$$

The same procedure (Eq. 3.11) was applied to improve data on land use area for each crop, pasture, and forestry sector of each resolved country from 1995 to 2015.

3.2.6 Workforce

Since no workforce accounts are reported by Eora26, the workforce coefficients were directly adopted from EXIOBASE3. To derive the entries in the satellite matrix ($Q\_T^{Exio-final}$) for the workforce (WF) employed in each sector (s) of each of the 145 resolved countries (c), we used the sector-specific workforce coefficients (D^{Exio}) of the corresponding RoW region (Σc) from

EXIOBASE3 and multiplied it with the total output of the respective country and sector of the merged database ($X^{Exio-final}$):

$$q\_t^{Exio-final}_{WF\,,c_k s_k} = d^{Exio}_{WF\,,\Sigma c_k s_k} * x^{Exio-final}_{c_j s_j} \qquad \text{Eq. 3.12}$$

As an example, it was assumed that the number of people employed to generate one unit of output in the cultivation of cereal grains sector was the same for Egypt as for the RoW Middle East ($d^{Exio}_{WF\,,M.East:\,cereals}$). This value was multiplied with the total output of Egypt's cereal grains sector of the R-MRIO database ($x^{Exio-final}_{Egypt:\,cereals}$) to derive the number of people occupied in Egypt's cereal grains sector ($q\_t^{Exio-final}_{WF\,,Egypt:\,cereals}$):

$$q\_t^{Exio-final}_{WF\,,Egypt:\,cereals} = d^{Exio}_{WF\,,M.East:\,cereals} * x^{Exio-final}_{Egypt:\,cereals} \qquad \text{Eq. 3.13}$$

3.2.7 Balancing by value added

In a balanced MRIO database, the total output of each sector-country combination needs to equal its total input[50]. As done for the GRAM database[21, 22] and discussed by Wiebe and Lenzen[51], we calculated the value added of the resolved satellite matrix of the economy ($Q\_T^{Exio-final}$) as the difference of the total output ($X^{Exio-final}$) and the column sum of the transaction matrix ($T^{Exio-final}$) to ensure that the total input equals the total output of the R-MRIO database:

$$q\_t^{Exio-final}_{VA-c_k,s_k} = x^{Exio-final}_{c_j,s_j} - \textstyle\sum_{c_j s_j} t^{Exio-final}_{c_j s_j\,,c_k s_k} \qquad \text{Eq. 3.14}$$

Since we calculated the value added as a residual, the R-MRIO database is not suitable for analyzing footprints of value added, as discussed in Section 3.3.2.

3.2.8 Calculation with the R-MRIO database

3.2.8a) Footprint and supply chain analysis for the EU–27

In a first application example, we used the R-MRIO database to assess the environmental and socio-economic footprints of the EU-27 (including Croatia and without the United Kingdom). We derived the footprint of the EU-27 (F_{EU}) from the matrix multiplication of the impact coefficients (D, matrix with 9 rows representing each indicator and 30'807 columns), the Leontief inverse (L, matrix with 30'807 rows and columns), and the final demand of the EU (Y_{EU}, matrix with 30'807 rows and 27 columns representing the 27 EU member states), and by adding the direct impacts of the final demand of the EU (Q_Y_{EU}, matrix with 9 rows and 27 columns).

$$F_{EU} = D \times L \times Y_{EU} + \; Q\_Y_{EU} \qquad \text{Eq. 3.15}$$

The impact coefficient matrix (D) was derived from the element-wise division of the total impact indicated by the resolved satellite matrix (Q_T) through the total output of the respective country and sector (X).

While the direct impacts of the final demand (Q_Y_{EU}) are usually caused locally, the impacts of the economy ($D\_T \times L \times Y_{EU}$) are frequently caused in another country due to the EU's reliance on imports. By diagonalizing the impact coefficient vector (D_i) of the respective indicator (i), we calculated a footprint map for the impacts caused by the economy ($Fmap_{i,EU}^{economy}$):

$$Fmap_{i,EU}^{economy} = diag(D_i) \times L \times Y_{EU} \quad \text{Eq. 3.16}$$

The footprint map involves 30'807 rows and 27 columns. The rows indicate the country and sector where the EU's footprint is caused, while the columns attribute these impacts to the consumption by each EU member state. This allowed us to estimate the EU's footprint caused in RoW countries ($Fmap_{i,RoW,EU}^{economy}$).

In a final step, we investigated the importance of food imports with regard to the EU's water stress and biodiversity loss footprint caused in RoW countries ($F_{i,RoW,EU}^{food}$). For this purpose, we applied the method of Cabernard et al[11] based on Dente et al[52, 53], which allows to assess and track the cumulated upstream impacts of intermediate sectors (like food production) without double counting along the global value chain. Following the procedure described in Cabernard et al[11], we defined global food production as target (T) and the remaining global economy (global non-food production) as non-target (O) to calculate the total impacts caused in RoW countries due to EU's food consumption ($F_{i,RoW,EU}^{food}$):

$$F_{i,RoW,EU}^{food} = diag(D_{i,RoW} \times L_{RoW-T}) \times (Y_{T-EU} + A_{T-O} \times L'_{O-O} \times Y_{O-EU}) \quad \text{Eq. 3.17}$$

Thereby, $D_{i,RoW}$ refers to the impact coefficients of the RoW countries, L_{RoW-T} indicates the cumulated inputs of all sectors of the RoW countries into global food production , and Y_{T-EU} equals the EU's direct final demand for food products. The last term ($A_{T-O} \times L'_{O-O} \times Y_{O-EU}$) refers to the EU's indirect final demand for food products (e.g. food consumed via other sectors such as restaurants and other service sectors) and is calculated by the matrix product of the direct inputs of global food production into global-non-food production (A_{T-O}), the cumulated input of global non-food production into global non-food production (L'_{O-O}) and the direct final demand of the EU for global non-food products and services (Y_{O-EU}). Diagonalizing the cumulated impacts coefficients of global food production in RoW countries ($diag(d_{i,RoW} \times L_{RoW-T})$) allows to allocate the impacts to the food sectors (T). A detailed description of the procedure and derivation of all terms is described in Cabernard et al[11] by the example of global material production instead of food.

The remaining impacts caused in RoW countries due to EU's consumption of commodities other than food ($F_{i,RoW,EU}^{nonfood}$) were derived by applying the method of Dente et al[52, 53] to the R-MRIO database in accordance to Cabernard et al[11]:

$$F_{i,RoW,EU}^{nonfood} = diag(D_{i,RoW} \times L_{RoW-O}) \times Y_{O-EU} \quad \text{Eq. 3.18}$$

Thereby, L_{RoW-O} refers to the cumulated inputs of all sectors of the RoW countries into global non-food production and Y_{O-EU} refers to the EU's direct final demand for non-food sectors. The sum of the EU's footprint caused in RoW countries due to food consumption ($F_{i,RoW,EU}^{food}$), and nonfood consumption ($F_{i,RoW,EU}^{nonfood}$) equals the EU's total footprint caused in RoW countries

($F_{i,RoW,EU}^{economy}$). The split into food and non-food production (Eq. 3.17 and 3.18) allows to reallocate the impacts of the EU's food consumption to the food sector themselves instead of splitting them among different end-sectors as it is the case with the general Leontief model. This allowed us to evaluate the importance of food imports with regard of EU's water stress and biodiversity loss footprint caused in RoW countries.

3.2.8b) Adding carbon, water stress, and biodiversity loss footprints to the GEP Framework

In a second application example, we used our database to add carbon, water stress, and land-use related biodiversity loss footprints to the Green Economy Progress (GEP) Measurement Framework of the UNEP[2, 3]. The GEP dashboard includes "good" and "bad" indicators, where bad indicators refer to negative environmental impacts. The three considered footprint indicators, carbon, water stress, and land-use related biodiversity loss, represent "bad" indicators and are supposed to be added to the GEP dashboard according to the methodology report on GEP[2], which was the basis for our calculations below.

We calculated the carbon, water stress and land-use related biodiversity loss footprint (F) of all 189 countries by the matrix multiplication of the impact coefficient matrix (D) with the Leontief Inverse (L) and the final demand of each country (Y, 30807 rows and 189 columns) and by adding the impacts caused by the countries' final demand (Q_Y, row vector with 189 columns):

$$F = D \times L \times Y + Q\_Y \qquad \text{Eq. 3.19}$$

We used the data for carbon, water stress, and biodiversity loss footprints to derive the average per-capita values from 2001 to 2005 ($\mathbf{y^0}$) and from 2011 to 2015 ($\mathbf{y^1}$). The target $\mathbf{y^*}$ was determined for each country individually by using the lowest number of either:

(1) the ratio of $\mathbf{y^1_p/y^0_p}$ of the 10 percent most improving countries for a relevant comparison group (**p**) multiplied with $\mathbf{y^0}$ of the respective country. We used the Human Development Index (HDI) of each country for the year 2015 to classify the countries in comparison groups.

(2) a general threshold **t,** which was set at the 75th percentile of the per-capita impact distribution from 2001 to 2005 based on PAGE[2]. This means the countries should never exceed the value achieved by the bottom 75 percent of all countries.

(3) If both values of **(1)** and **(2)** were higher than $\mathbf{y^0}$, we used the minimum target of 0.99 * $\mathbf{y^0}$. This is because the target should be smaller than $\mathbf{y^0}$ based on PAGE[2].

The progress indicator (P) was then calculated as:

$$P = \frac{y^0 - y^1}{y^0 - y^*} \qquad \text{Eq. 3.20}$$

If P is positive, this means per-capita footprints have decreased and progress has happened. If P is 1 or higher, the target was reached, while positive P values below 1 mean that the target was not achieved although per-capita footprints have decreased. Negative values indicate increasing per-capita footprints.

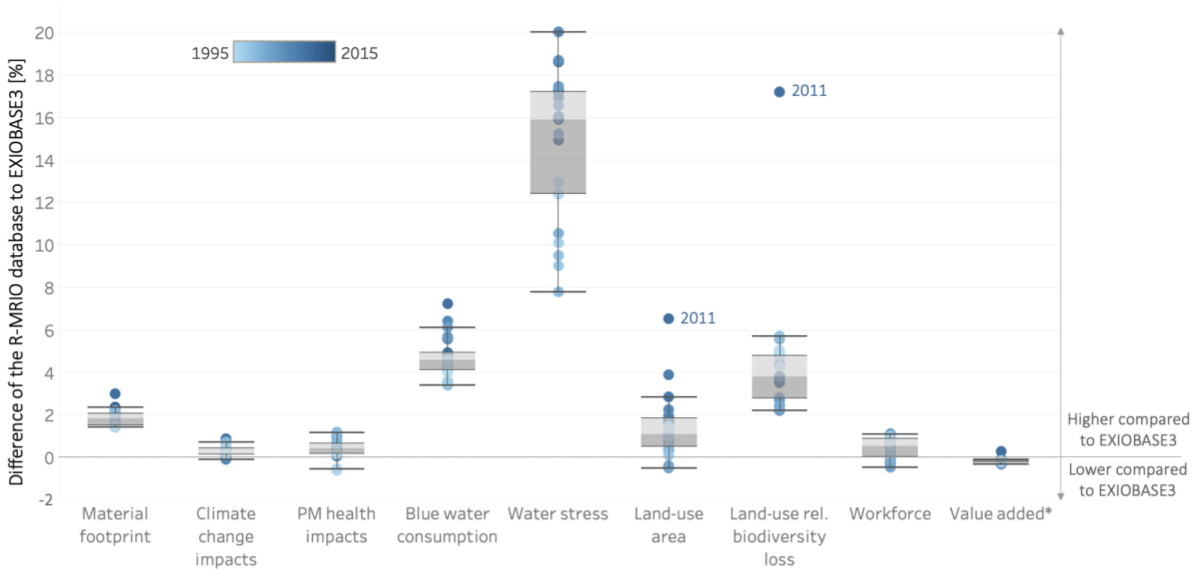
3.3. Results and Discussion

3.3.1 EU’s footprints and the role of food imports from RoW countries

3.3.1a) The effect of spatial disaggregation on EU’s footprint

Figure 3.2 shows the EU’s footprint calculated with the R-MRIO database as it compares to the footprint calculated with the tool developed by Cabernard et al[11] (based on EXIOBASE3) for all indicators from 1995 to 2015. For the indicators carbon, PM health impacts and workforce, the spatial disaggregation has almost no effect on the EU’s footprint (±2%, Figure 3.2). However, for water and land use, the spatial disaggregation of the RoW regions leads to a significant difference in the EU’s footprints (Figure 3.2). This is in accordance with previous studies, which showed that a high spatial and sectoral resolution is particularly relevant for water and land use indicators, which largely occur in RoW regions[23, 28-31].

The effect of spatial disaggregation on the EU's footprint is even stronger for water and land if regional conditions on water scarcity and ecosystem value are taken into account (Figure 3.2). It increases the EU's water stress footprint by up to 20% compared to ≤8% for blue water consumption (Figure 3.2). Likewise, the spatial disaggregation has a stronger effect on the EU's land-use related biodiversity loss than land use area footprint (Figure 3.2). In accordance to previous studies, this highlights not only the importance for spatial disaggregation when assessing water and land, but also to take regional conditions on water scarcity and ecosystem value into account[24, 29].



**In contrast to the other indicators, the value added was calculated as a residual to balance the R-MRIO database and is thus meant to remain the same as in EXIOBASE3. This is because in a balanced MRIO database, the consumption-based value added equals the final demand, which was kept the same as in EXIOBASE3. The difference is shown here as a means of verification and implies that our approach leads to less than 0.3% imbalances for the EU’s consumption-based value added.*

Figure 3.2: Difference of the EU’s environmental and socio-economic footprint calculated with the R-MRIO database of this study compared to the same footprints calculated by the tool developed by Cabernard et al[11] based on EXIOBASE3 from 1995 to 2015. Boxplots are reported in addition to individual data points from 1995 to 2015.

The effect of spatial disaggregation on the EU's water and land footprint is attributed to the EU's strong reliance on water and land intensive imports from RoW regions. In contrast to the EU's material, carbon, and PM health impact footprint, where less than 20% were induced in RoW regions, 42% of the EU's water use and 27% of the EU's land use footprint were created in RoW regions according to the R-MRIO database in 2015. With regard to environmental impacts, the fractions outsourced to RoW regions increase further as a consequence of the spatial disaggregation: in 2015, half of the EU's water stress footprint and a third of the EU's biodiversity loss footprint was induced in RoW regions. For water stress, this is almost exclusively attributed to the spatial disaggregation of water scarce countries in the RoW Middle East (Appendix B.3: Figure B.4). These countries are highly diverse and include e.g. Egypt, which is a major food and cotton exporter to the EU (with a trade agreement) and Iran, which is a major crop producer that was affected by trade restrictions in the past decades [54]. For land-use related biodiversity loss, the EU's higher footprint calculated with the R-MRIO database is mainly driven by the spatial disaggregation of countries with high ecosystem value in RoW Africa (Appendix B.3: Figure B.4).

For most indicators, the effect of the spatial disaggregation increases during the investigated timespan (Figure 3.2). This is because over the past two decades the EU's water and land intensive food and wood imports from RoW countries have increased, meaning the environmental burden displaced to RoW regions has also increased. For the EU's land-use related biodiversity loss footprint, the effect of spatial disaggregation was particularly high in 2011 (+17% higher in the R-MRIO database compared to Cabernard et al[11], Figure 3.2). This was attributed to increased wood imports from countries in RoW Latin America with high ecosystem value (Appendix B.3: Figure B.5). Conclusively, these results indicate that the EU sources water and land-intensive commodities from RoW countries with comparably higher water scarcity and ecosystem value. Analyzing the EU's supply chain allows us to identify those countries and sectors where most of the impacts are caused (Section 3.3.1b).

3.3.1b) RoW hotspots in the EU's water stress and biodiversity footprint supply chain

The R-MRIO database allows to track the supply chain of the EU's footprint back to each country and sector where the impacts are caused. All countries affected by the EU's water stress and land-use related biodiversity loss footprints are shown in Figure 3.3. Figure 3.4 illustrates the supply chain of the fractions of the EU's water stress and biodiversity loss footprint caused in RoW regions (50% and 33%, respectively), both of which have significantly increased due to the improved resolution. This reveals that the effect of the spatial disaggregation on the EU's water stress footprint is almost exclusively attributed to food imports from Egypt (Figure 3.3A and 3.4A). In 2015, 28% of the EU's total water stress footprint was caused in Egypt (Figure 3.3A). This was mainly attributed to vegetables, fruits, nuts, wheat and other crops (e.g. cotton) cultivated for the EU's food supply (Figure 3.4A). Germany, France, Italy, the Netherlands and Spain were responsible for the majority (80%) of the EU's water stress footprint induced in Egypt (Figure 3.4A). The Netherlands in particular had an especially high reliance on Egypt's agriculture, given that more than half of their total water stress footprint was generated in Egypt in 2015.

In addition to Egypt, hotspots include Iran, Pakistan, Morocco, and Syria (Figure 3.3A and 3.4A). Similar to Egypt, the EU's water stress footprint caused in Iran was mainly due to the cultivation of vegetables, fruits and nuts. In Pakistan, most water stress related to the EU's food consumption was attributed to paddy rice and wheat cultivation (Figure 3.4A). The EU's water stress footprint displaced to Morocco was mainly due to food imports by France and Spain (Figure 3.4A).

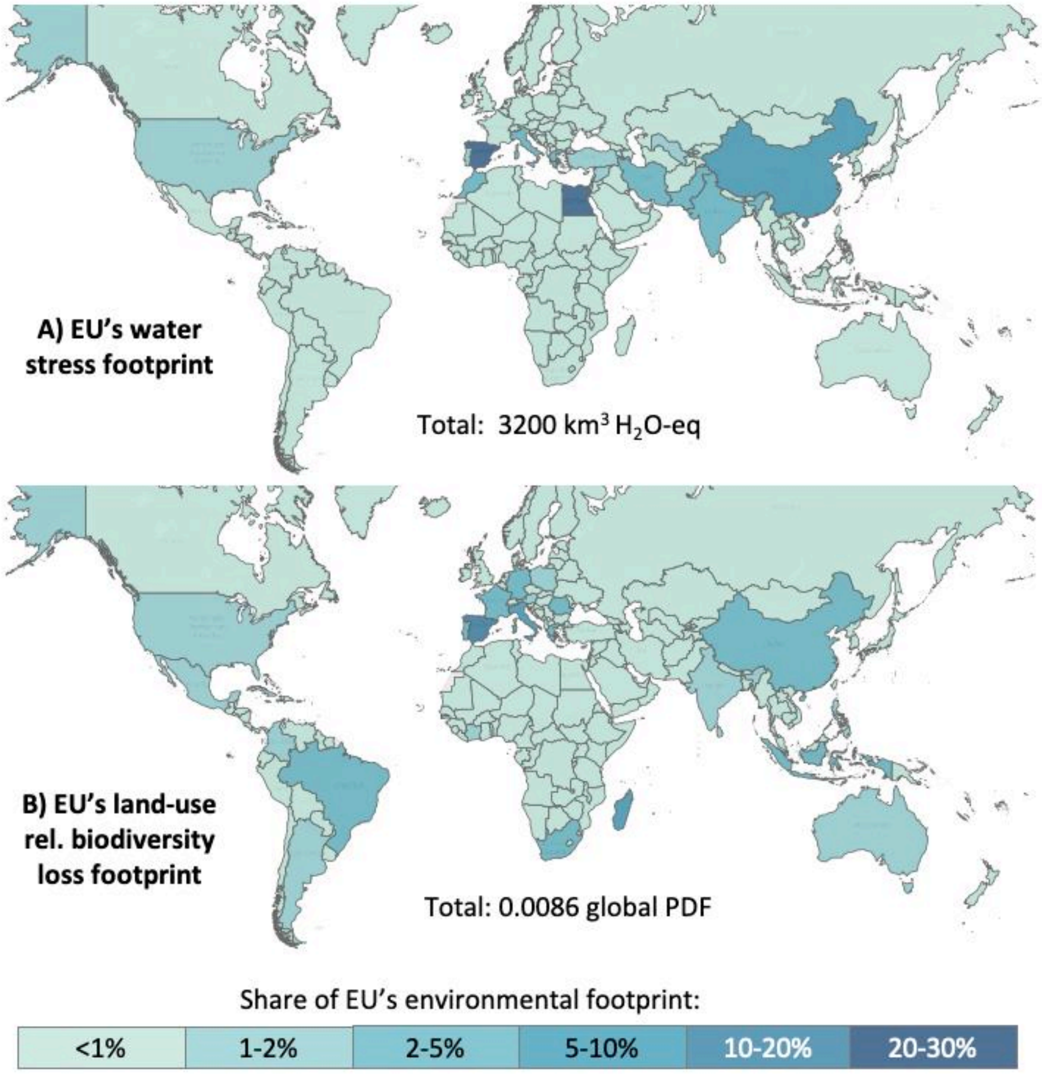


Figure 3.3: Map of the EU's total A) water stress and B) land-use related biodiversity loss footprint calculated with the R-MRIO database of this study in 2015.

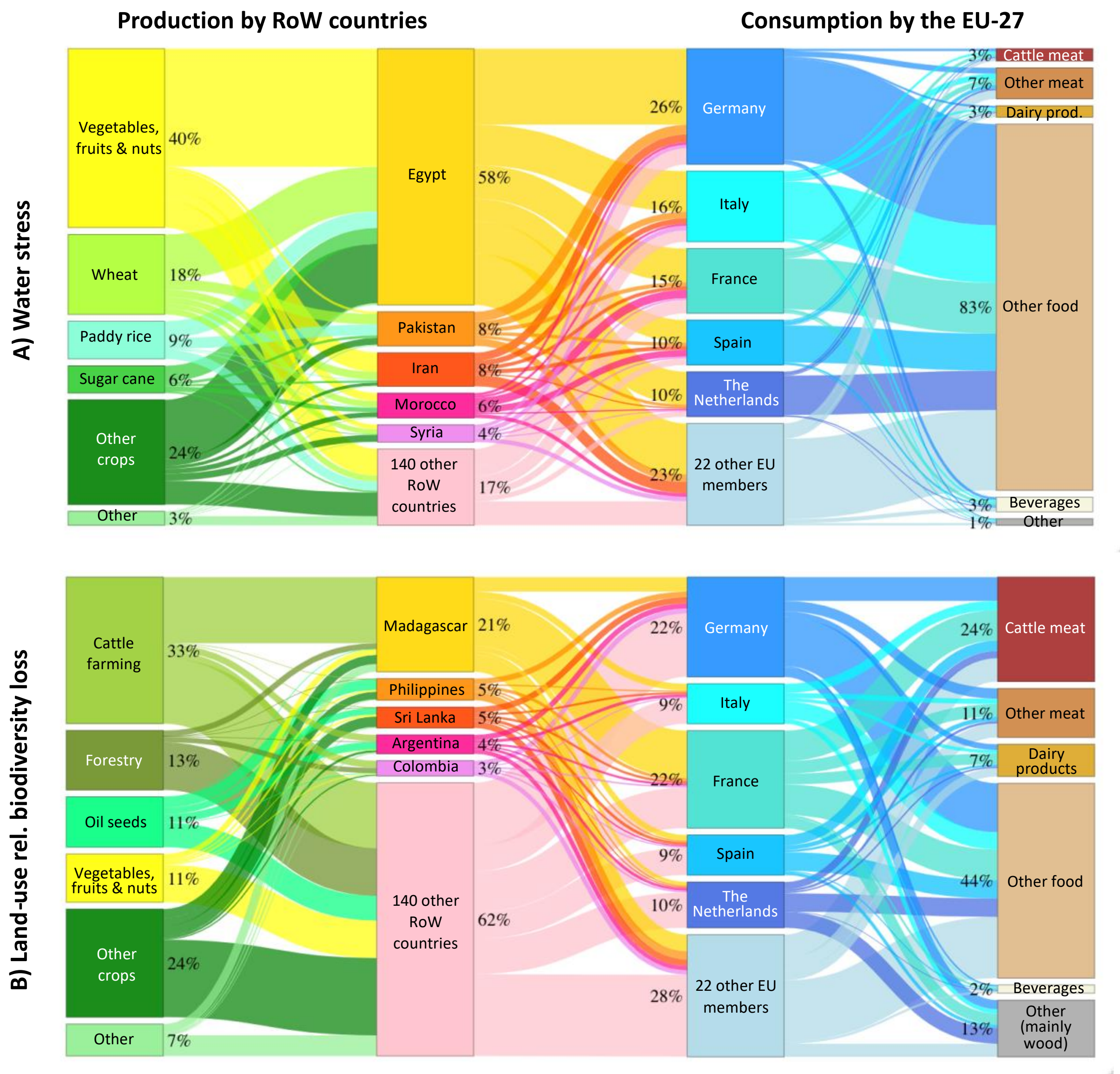


Figure 3.4: Supply chain of the EU's A) water stress and B) land-use related biodiversity loss footprint (consumption perspective) displaced to RoW countries (production perspective) in 2015. The supply chain was analyzed with the R-MRIO database. Each bar sums up to 100%, and these 100% refer to the fraction of the EU's footprint caused in RoW countries (50% for water stress and 33% for land-use related biodiversity loss of the total respective footprints of the EU).

In contrast to the EU's water stress footprint, which is mainly concentrated in a few countries (Figure 3.3A and 3.4A), the EU's biodiversity loss footprint is spread across many RoW countries (Figure 3.3B and 3.4B). Madagascar drives the effect of spatial disaggregation on the EU's increased biodiversity loss footprint for all years except 2011 (Appendix B.3: Figure B.4). In 2015, 8% of the EU's footprint (Figure 3.3B) occurred in Madagascar, and the majority was due to cattle farming (Figure 3.4B). This involves a high fraction of global species loss due to the extreme endemism of species in Madagascar. Most of the EU's biodiversity loss footprint caused in Madagascar was attributed to France's food consumption (Figure 3.4B). In 2015, a fifth of France's total land-use related biodiversity loss was caused in Madagascar, whereby the vast majority was attributed to meat (mainly cattle) and dairy products.

The supply chain analysis of the EU's footprints caused in RoW countries highlights the importance of food imports for both water stress (99%, Figure 3.4A) and land-use related biodiversity loss (87%, Figure 3.4B). While animal-based products play a minor role for water stress, they contributed to 43% of the EU's biodiversity loss footprint caused in RoW countries in 2015 (mainly cattle meat). This includes also the impacts attributed to imported feed for the EU's livestock farming. Besides food, wood imports used for construction and furniture further contributed to the EU's land-use related biodiversity loss footprint caused in RoW countries (~13%, Figure 3.4B). Increased wood imports from Peru, Colombia, Venezuela and Bolivia were the major driver of the EU's particularly high biodiversity loss in 2011 (Appendix B.3: Figure B.5).

3.3.2 Comparison to previous studies, limitations, and future improvements

The EU's water stress footprint induced in Egypt (28%, Figure 3.3A) is considerably higher when compared to Pfister and Lutter[47], where only 11% of the EU's water stress footprint was caused in the Nile watershed in Egypt. Pfister and Lutter[47] combined EXIOBASE2 with water stress estimates on a watershed level, but could not differentiate trade patterns within the RoW countries. They assumed a proportional share of impacts for the crop production of each country in the RoW Middle East. However, in fact there is a higher share of trade with Egypt (and thus water from the Nile) than e.g. with Iran, which was accounted for in this study by adding this information from Eora26[54]. While this result highlights the importance of spatial disaggregation when assessing water stress, the relevance of RoW countries points to the need for future work to further improve the spatial and sectoral resolution in MRIO databases.

Similar to this study, Bjelle et al[30] expanded the regional resolution in EXIOBASE3 to 214 countries while keeping the high and harmonized sector detail to investigate land embodied in trade. In contrast to our work, Bjelle et al[30] further changed the regional distribution of the land use accounts, with differences of >50% compared to EXIOBASE3 (Appendix B.3: Table B.2). For a comparison of the two databases, we calculated the land use footprints for all countries (Appendix B.3: Figure B.6). The average global per-capita land use footprint is similar for the two databases (6% higher in the R-MRIO database). On the country level, land use footprints are mostly comparable (Appendix B.3: Figure B.6). For the RoW countries, per capita footprints are highest for Mongolia, Kazakhstan, Botswana, Namibia, and Bolivia in both databases (Appendix B.3: Figure B.6). In contrast, land use footprints are about five times higher for Gabon, Congo, the Central African Republic, and Papua New Guinea in Bjelle et al[30] compared to this study (Appendix B.3: Figure B.6). For those 44 countries individually covered by EXIOBASE3, land use footprints are broadly comparable for all countries except Mexico and Taiwan, where they are five times higher in Bjelle et al[30] compared to our work and EXIOBASE3. This is surprising, because Mexico's domestic accounts are almost identical in both databases (Appendix B.3: Table B.2). This implies that according to Bjelle et al[30], Mexico is a very strong net importer of land use, which is in contrast to previous MRIO databases (EXIOBASE3, Eora26).

While hotspots on land use footprints are mostly similar for the two databases, they strongly differ within the R-MRIO database of this study if local conditions on ecosystem value are taken into account (Appendix B.3: Figure B.6). For example, within the EU-27, Finland stands out as having the highest per-capita land use footprint, while concurrently having a comparably low biodiversity loss footprint. Spain, however, has the opposite pattern, with a high biodiversity loss in combination with a comparably low land use footprint on a per-capita level (Appendix B.3: Figure B.6). This underlines again the importance of regionalization for land use to assess biodiversity loss as addressed in this study.

Compared to this study, the MRIO database of Bjelle et al[30] has a higher spatial resolution (214 countries compared to 189 countries), but the additionally covered countries include almost exclusively islands with very low population numbers and high data uncertainty (since data rely on average estimates). Due to the large size of the database and the resulting computational requirements, Bjelle et al[30] did not calculate results using the entire MRIO system as was done in this study. Instead, Bjelle et al[30] used the emissions embodied in bilateral trade (EEBT) approach to estimate land use footprints. The main limitation of the EEBT approach is that it does not account for the intermediate demand of imports that is required to produce exports by a country. Thus, it is suitable to assess total footprints, but not applicable to assess the total impacts of intermediate sectors (e.g. food) nor to analyze the supply chain of a region's footprint as illustrated by the EU's water stress and biodiversity loss footprints in this study (Figure 3.3 and 3.4). The slightly lower resolution of this study's database allows for a detailed footprint and supply chain analysis of both countries and intermediate sectors using the entire MRIO system.

In contrast to our work, Bjelle et al[30] expanded the regional resolution of EXIOBASE3 by constructing the monetary supply and use tables of 170 RoW countries. Since supply and use tables were not available for RoW countries, Bjelle et al[30] used proxy data in the form of generic estimates on the coefficients for the supply and use matrices to construct the database. The main challenge for the practical implementation of such a concept is the computational requirements due to the enormous size of the database [30]. The procedure applied in this study represents an automated, transparent, and comparably time-efficient approach to merge the sector and country resolution of two MRIO databases (Section 3.2.3 and 2.4), and to further improve the quality by integrating other data sources (Section 3.2.5). This allowed us to extend not only land use data, but also to implement a set of other environmental and socio-economic indicators.

For the entire assessment, we weighted the values of EXIOBASE3 with country and sector-specific relative shares derived from Eora26, FAOSTAT[36] and previous work[42, 46-48]. Thus, the total output and the domestic impacts match with EXIOBASE3 (and Cabernard et al[11] for the environmental impact categories) when aggregated back to the 49 regions (Appendix B.3: Paragraph B.2). Solely the resolution and the contributions of the disaggregated RoW countries and sectors change according to the relative shares of the integrated data. As shown by Lenzen [55], even a small amount of proxy information on additional geographical detail improves the reliability of an MRIO database. Since we added the information of 145 individual countries, our developments involve an essential improvement of the EXIOBASE3 database. The same procedure can be applied to add country and sector-specific data from other MRIO databases (e.g. from GTAP) to further improve the country and sector resolution in an automated and time-efficient way.

In this study, we focused in particular on water and land use, and the related impacts. Thus, we integrated additional data on agriculture and forestry from FAOSTAT[36] and previous work[42, 46-48]. These improvements are essential, since agriculture and forestry are responsible for more than 90% of global water stress (almost exclusively due to crops) and land-use related biodiversity loss (agriculture and forestry)[12]. More than a third of these impacts were caused in the 145 countries aggregated as RoW regions in EXIOBASE3 (calculated with the tool developed by Cabernard et al[11]). The approach applied here for biomass sectors should be extended to material and energy sectors, which are more relevant for climate change and PM health impacts[12]. Also, trade-specific improvements, such as scaling the imports and exports by integrating country and sector specific trade data are further steps to improve the quality of the R-MRIO database.

For a balanced MRIO database, the total input of each sector and region should equal its total output[50]. In contrast to Bjelle et al[30] and official MRIO databases (EXIOBASE3, Eora26, GTAP), we did not apply matrix balancing calculations (e.g. RAS), but balanced the total input by calculating the residual value added as done for the GRAM database[21, 22]. When comparing these two approaches, Wiebe and Lenzen[51] found differences in the results, but it was not clear which approach leads to superior results. The simpler solution applied here has the benefit that it alters the data as little as possible and keeps the calculation traceable[21, 22, 51]. It was further concluded that the level of detail and the reliability of the underlying raw data have a higher influence on the results than the balancing approach[51, 56]. This highlights the need for caution when analyzing the results of RoW countries with high data uncertainty as well as the importance of improving data quality in these countries[16, 57].

While our approach allows for analyzing environmental and social footprints such as workforce (with caution for RoW countries with high data uncertainty), it is not suitable for analyzing footprints of value added. This is reflected by stronger inconsistencies between the modelled domestic value added and the GDP from official statistics for several RoW countries when comparing the R-MRIO database to Eora26 (particularly for Paraguay, Belarus, Zimbabwe, and Lesotho, Appendix B.3: Figure B.7). Additionally, our approach leads to negative value added, which makes sense if a sector is subsidized, but which occurs more often in the R-MRIO database compared to EXIOBASE3 and Eora26 as a consequence of the merging process (Appendix B.3: Figure B.8–B.9). It mostly affects RoW countries and islands with small population number as well as a few RoW countries with higher population number but low income, which underly high data uncertainty (e.g. Bangladesh and Tanzania, Figure B.9). Within these countries, it mainly affects sectors that contribute to a minor fraction of the domestic GDP (Appendix B.3: Figure B.10). Overall, all sector-country combinations with negative value added contribute to less than 1% of global GDP (Appendix B.3: Figure B.9). This suggests that our approach is appropriate for calculating environmental and social footprints such as workforce (but not value added), which is the focus of this study. However, for RoW countries with low population number or income, caution is needed when analyzing the results of MRIO results due to the high data uncertainty[16, 57].

Further work is needed to model value added, as well as its components, such as taxes and compensation of workforce, on a high spatial and sectoral resolution. This is also important to extend the database for social LCA. The workforce indicator included here, indicating the full-time equivalents of employed people, addresses one aspect in social LCA. However, the workforce accounts were derived only from EXIOBASE3, since no workforce accounts are indicated by Eora26. Thus, the uncertainty is high for RoW countries. The integration of country and sector specific data on workforce (e.g. from the social hotspot database) is an important step to improve the workforce accounts, and to add other social aspects, such as the risks to which workforce is exposed[12, 58].

3.3.3 Green Economy Progress (GEP)

In a second example, we use the R-MRIO database to add the new indicators for carbon, water stress, and land-use related biodiversity loss footprints to the GEP dashboard. These indicators are presented in Figure 3.5 and in the Supporting Information of the publication (*SI_GEP_results.xlsx*) with a table on the intermediate results needed to calculate the indicator. It shows that most countries did not achieve the target improvement (i.e. $P \geq 1$) for any of the three footprints. Overall, only Zimbabwe, Albania, North Macedonia, and North Korea have reached their target for all three footprints. It is necessary to note, however, that these countries have low robustness in the database, since they are economically of small importance and not separately covered in EXIOBASE3.

In total 40, 11, and 17 countries reached the target for carbon, water stress, and biodiversity loss progress, respectively. The relatively large number of countries reaching the target for the carbon footprint is mainly driven by the medium HDI countries. This is because the target was set to only $0.99*\mathbf{y^0}$, since the overall threshold and reference progress would have allowed for an increase of the footprint for most of the medium HDI countries. This means that the target for these countries envisages an unambitious reduction (e.g. for India and South Africa) of only 1% from the average level of 2000 to 2005. Thus, future work should reassess and reset the target for these countries in a reasonably ambitious way.

For 48, 69, and 117 countries, the targets for carbon, water stress and biodiversity loss, respectively, were not met despite decreasing per-capita footprints (i.e. $0 < P < 1$). In total, 100, 108, and 54 countries had a negative result (i.e. $P < 0$) for carbon, water stress, and biodiversity loss, respectively, meaning per-capita footprints have increased. Since increasing footprints means not meeting the GEP target, this implies that the target setting was less important for these countries with regard to carbon and water [3]. In contrast, biodiversity loss footprints have decreased for most countries, indicating that the target setting was more important for biodiversity loss and thus potential absolute thresholds should be reassessed in future research. However, the decrease in biodiversity loss must be considered critically, since these data underly a high uncertainty. In EXIOBASE3, global impacts have increased over the past decades for carbon and water, but decreased for land after 2011 (since data from 2012–2015 were now-casted in EXIOBASE3)[11, 59]. These trends are in accordance with previous studies for carbon and water, but differ for land, where other studies also showed an increasing trend[60]. This suggests high uncertainty in the results on temporal trends for land use and related biodiversity losses, and points to the necessity of future work that improves the data quality for land use time series.

Although many high-income countries show decreasing environmental per-capita footprints, the reductions were below the target for most countries. In contrast, many less economically developed countries show increasing environmental footprints. To some degree, these trends are in line with the Environmental Kuznets Curve hypothesis[61]. The Environmental Kuznets Curve posits that as countries develop, their environmental pressures increase to a certain point after which environmental degradation starts to decrease again due to technical improvements. For instance, in China, emissions have increased dramatically over the last few decades due to rapid economic growth, but may peak within the next few years[62]. However, increasing environmental pressures are anticipated particularly for India, other developing Asian countries, and sub-Saharan-Africa. Together with the strong population growth anticipated for these regions, environmental impacts will heavily increase and planetary boundaries will be far exceeded. Thus, improved environmental policies and an overall change in the consumption behavior are crucial for all countries[63].

In this study, we added environmental footprint indicators to the GEP framework, which was previously limited to production-based accounting. The importance of this extension is highlighted by the results presented for the EU, which showed that a significant fraction of the EU's environmental footprints is induced abroad (Section 3.3.1). Although the GEP framework now allows to measure environmental progress in comparison to country-specific target footprints, it lacks information regarding environmental justice. For example, the GEP indicator paints a broad picture of progressing higher-income countries and regressing lower-income countries, but conceals the fact that higher-income countries continue to have several times higher per-capita footprints when compared to lower-income regions. In addition, the GEP framework does not provide any information on the driving forces behind green economy progress, such as knowledge of global value chains. This is also important in the context of environmental justice, since many high-income countries displace a considerable fraction of their footprint to lower-income regions, as shown here for the EU (Section 3.3.1). This highlights the importance for improved supply chain management, especially for high-income regions. Information on the environmental impacts of global value chains are crucial to develop efficient strategies for improved supply chain management and is to some extent available through the database provided here.

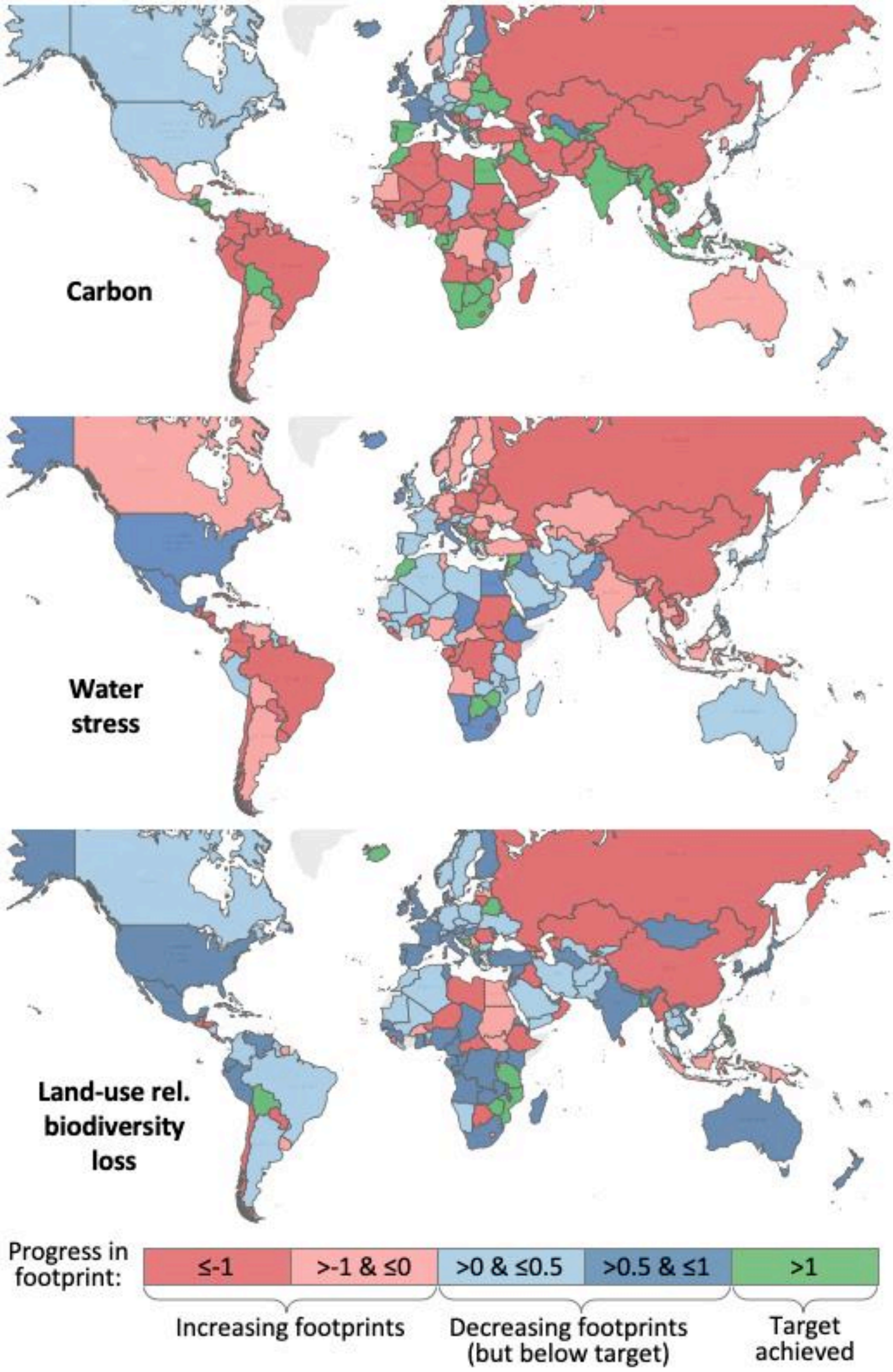


Figure 3.5: Progress indicator for each country of carbon, water stress and land-use related biodiversity loss footprints. Green countries achieved their target (progress >1).

3.4 Conclusions and Outlook

This work provides an as of yet unavailable highly resolved MRIO database with harmonized sector and country resolution, and a set of environmental and socio-economic extensions, over a time series from 1995 and 2015. We improved the resolution of those sectors that are most relevant regarding water and land use. For the first time, this allows to assess water stress and land-use related biodiversity footprints in high spatial and sectoral detail. The importance of these improvements is highlighted by the presented results, which showed a significant increase in the EU's water stress and biodiversity loss footprint induced in RoW countries as a consequence of the spatial disaggregation and implemented regionalized assessment.

The method applied here represents an automated, transparent, and comparably time-efficient approach to add information on an existing MRIO database. It can be easily extended to add information from other MRIO databases (e.g. GTAP) and other data sources to further improve the data quality and indicator coverage. This is particularly important to improve the data quality for RoW countries and the temporal trends of land-use related biodiversity loss. The development of detailed bottom-up MRIO databases should be considered to further improve the spatial and sectoral resolution. Future work is also needed to extend the database for social LCA, such as by modelling value added appropriately and adding further socio-economic indicators.

The database of this study for the first time allows to address different aspects of sustainability on a high country and sector resolution. This provides the necessary data to apply environmental footprints to the GEP framework. The GEP analysis showed that, although sometimes going into the right direction, most countries did not achieve their environmental target. In addition, many countries that anticipate strong future population growth show increasing environmental footprints. This distinctly highlights that more action is needed to move towards a greener economy from a global perspective. Moving towards this direction requires knowledge not only on the progress of a country as indicated by the GEP dashboard, but also on the drivers behind it. The database attached to this study provides detailed information on the environmental impacts of global value chains, which can help to identify these drivers, and thus to plan strategies for a greener economy.

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Chapter 4

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

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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.

4.1 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.

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 (Appendix C.1: Paragraph C.1)[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 (Appendix C.2: Paragraph C.2).[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 4.3.1)?

RQ 2) Which material value chains drive the G20's rising GHG emissions (Section 4.3.2)?

RQ 3) How does the G20's trade in materials affect key aspects of sustainability (Section 4.3.3)?

4.2 Methods and Data

4.2.1 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 4.6). 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 C.3 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] (Appendix C.2: Paragraph C.3). Furthermore, it adds the socioeconomic indicators workforce and value added.

4.2.2 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 (Appendix C.2: Paragraph C.4). Second, we split the production and consumption-based impacts into scope 3 impacts of material production (including upstream 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] (Appendix C.2: Paragraph C.5). 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 (Appendix C.2: Paragraph C.6). 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 (Appendix C.2: Paragraph C.7). 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).

4.3 Results and Discussion

In the following, Section 4.3.1 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 4.3.2 identifies key drivers of the G20's rising GHG emissions (RQ 2). Finally, Section 4.3.3 shows the degree of the G20's displacement of impacts to other G20 members and the rest of the world (RQ 3).

4.3.1 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 4.1a vs 4.1d). 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 4.1b vs 4.1d). 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 4.1c vs 4.1d). 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 4.1e–f, where scope 3 emissions are the same as in Figure 4.1d (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 4.1e). 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 4.1f). 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 Appendix C.3 by the example of Japan's material value chain (Figure C.2 and C.3, Paragraph C.8).

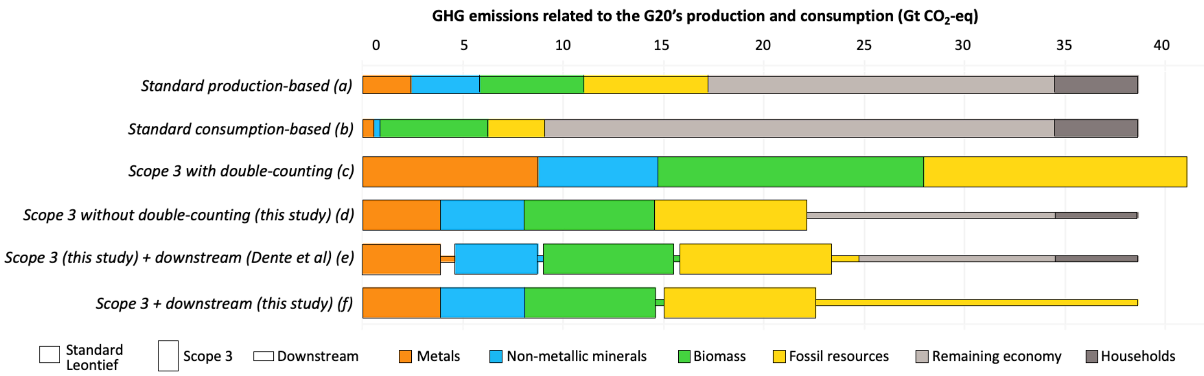

Figure 4.1. Greenhouse gas (GHG) emissions related to the G20's production and consumption of materials calculated with the standard Leontief model (a and b) [20, 30-33, 36-40, 58, 79], scope 3 accounting with double-counting (c)[20, 58, 59] and without double-counting (d–f, based on Cabernard et al[10]) 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 4.2.

The carbon flow analysis of the G20's material value chain is shown in Figure 4.2. 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 4.2a–b and 4.2f) by showing the intermediate steps in the G20's material value chain (Figure 4.2b–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 4.2b–c). Moreover, it extends the method of Cabernard et al[10] by including not only upstream and midstream emissions (scope 3: Figure 4.2d1–d2), but also downstream emissions (Figure 4.2d3) and the link to the emission source (Figure 4.2d–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 4.2c–d). The link to the emission sources shows that upstream emissions were mainly released by coal electricity (Figure 4.2d–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 4.2c–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 4.2b–d), but also in the upstream and midstream chain of material production (Figure 4.2d–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 4.2b–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%).

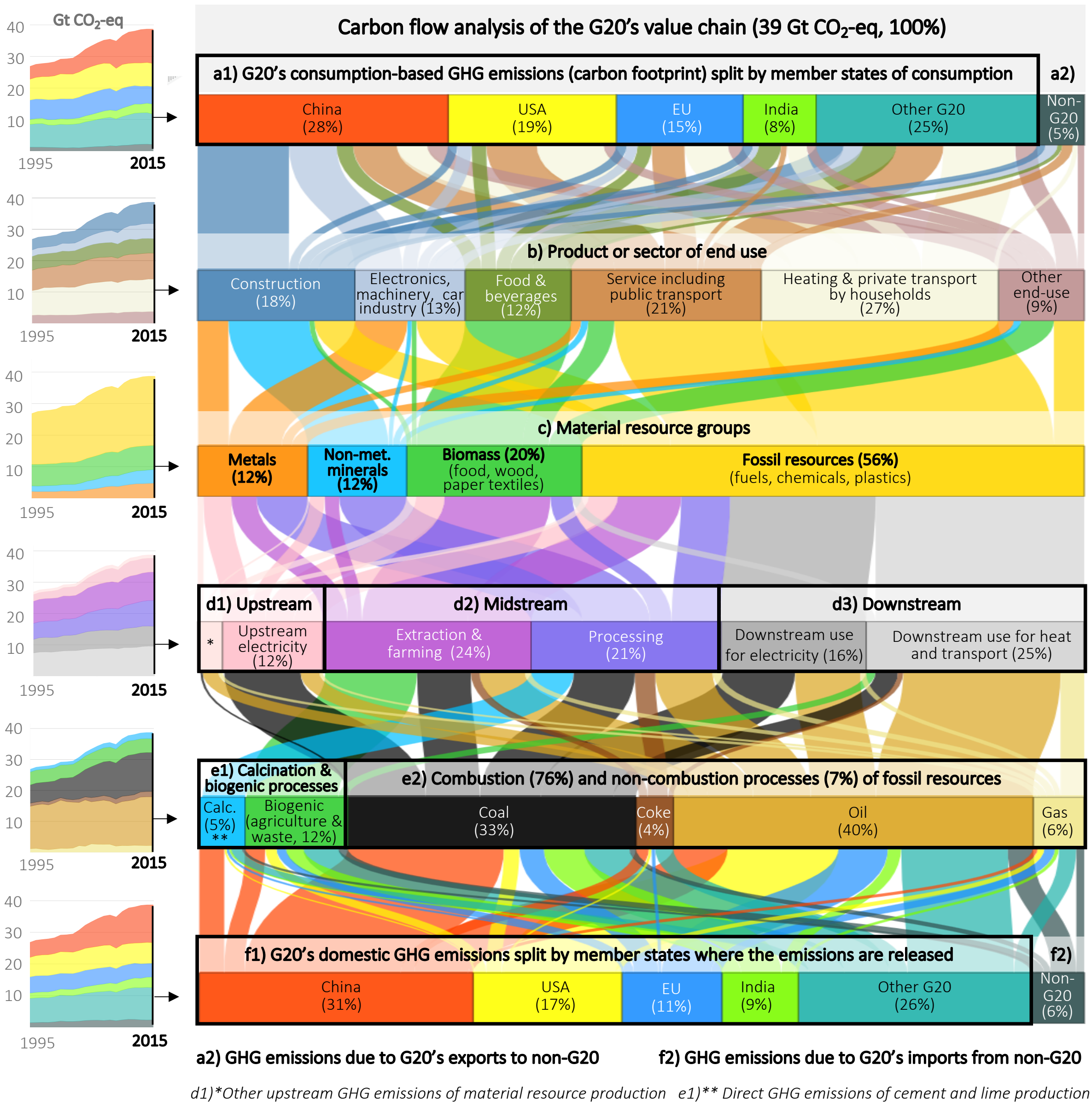

Figure 4.2. Carbon flow analysis of the G20's material value chain, including their consumption (a1, carbon footprint) and production for exports to non-G20 members (a2) in 2015 (totally 39 Gt CO_2-equivalents, 100%). Each bar sums up to 100% and shows the G20's GHG emissions from different perspectives 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.

4.3.2 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 4.2). 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 4.2e). 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 4.2d–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 4.2c). 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 4.2a–c).

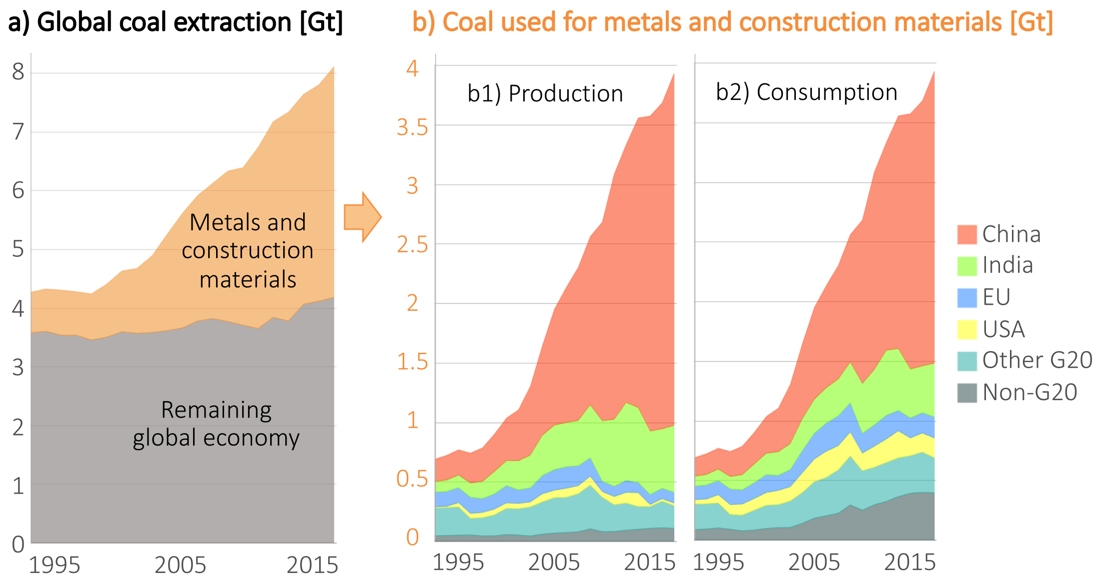

Figure 4.3. a) Global coal extraction split by its use for minerals production and the remaining economy (everything else than minerals production), and b) region where coal is used for minerals production (b1) and where minerals are finally consumed (b2).

In the following, we focus on the use of coal for the extraction and processing of metals and construction materials, as Figure 4.2 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 4.3). 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 4.3b, Appendix D.3: Figure D.4). 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.

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 4.4. 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 4.4b). 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 4.4a–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 4.4c–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 4.5).

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 4.4c–e). Still, one third of the GHG emissions released by China's and India's metals production were attributed to exports (Figure 4.4c–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 4.5). 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.

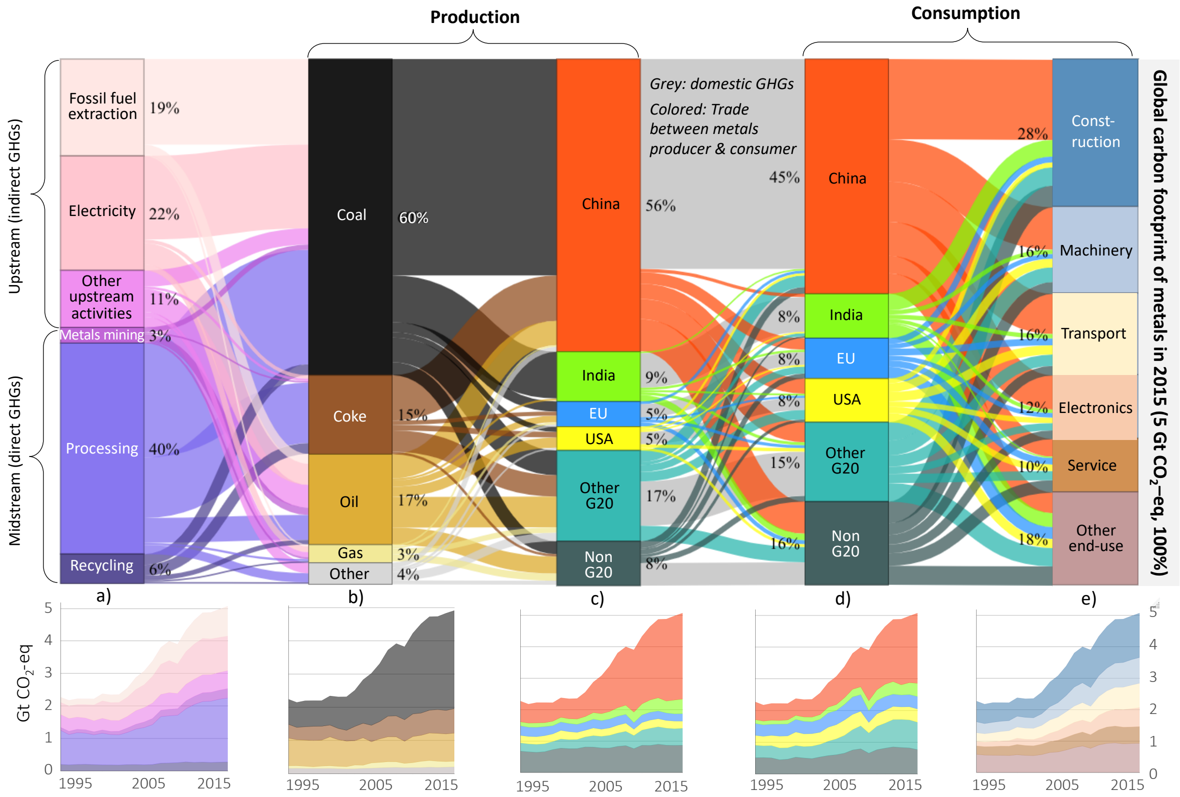

Figure 4.4. Carbon flow analysis of the metals value chain in 2015 (5 Gt CO2-eq, 100%, flow chart) and temporal evolution from 1995 to 2015 (small graphs at the bottom) shown from different perspectives: a) the sector where GHG emissions related to metals production are released, b) the fossil fuel type 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.

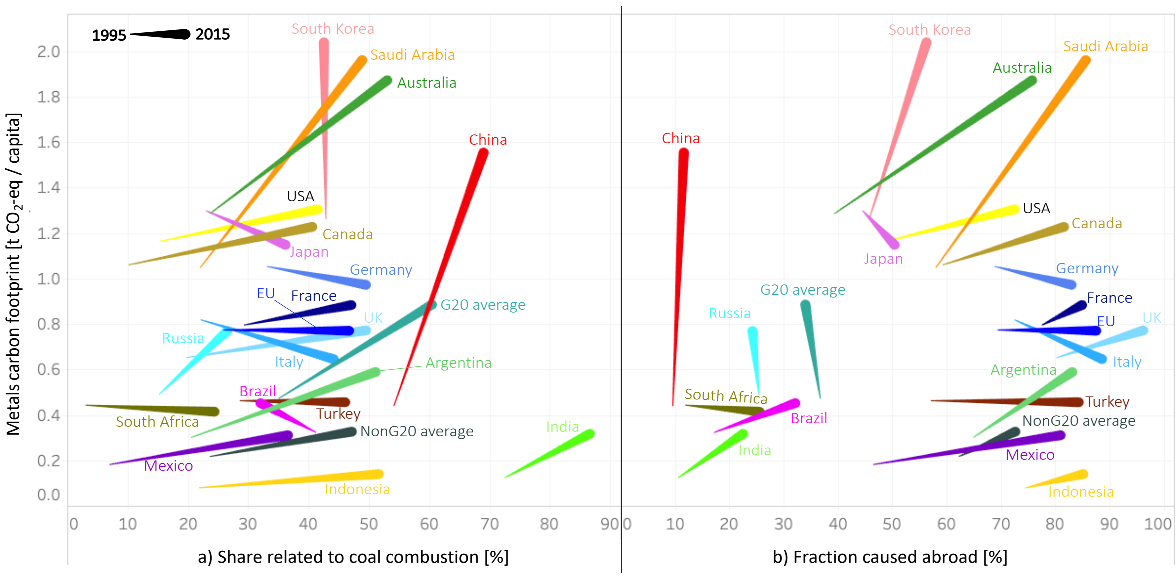

Figure 4.5. Change in the G20's metals-related GHG emissions from a consumption perspective (metals carbon footprint) on a per-capita level plotted against a) the share of coal-based emissions in total GHG emissions and b) the fraction of the metals carbon footprint caused abroad (due to metals imports, 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).

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

As Section 4.3.2 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 4.6 and 4.7, see Appendix C.3: Paragraph C.9–C.11 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 4.6a). 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 4.6b). 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 4.6 and 4.7, Appendix C.3: Figure C.8–C.12). 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 4.7). 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 (Appendix C.3: Figure C.13 and C.14). 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 (Appendix C.3: Figure C.10e, Figure C.15). Consequently, the number of workers required for the EU's consumption was two times higher than the EU's domestic workforce (Figure 4.7f). Nevertheless, the vast majority of the value added created to supply the EU's material demand was generated within the EU (Figure 4.7g, Appendix C.3: Figure C.10g).

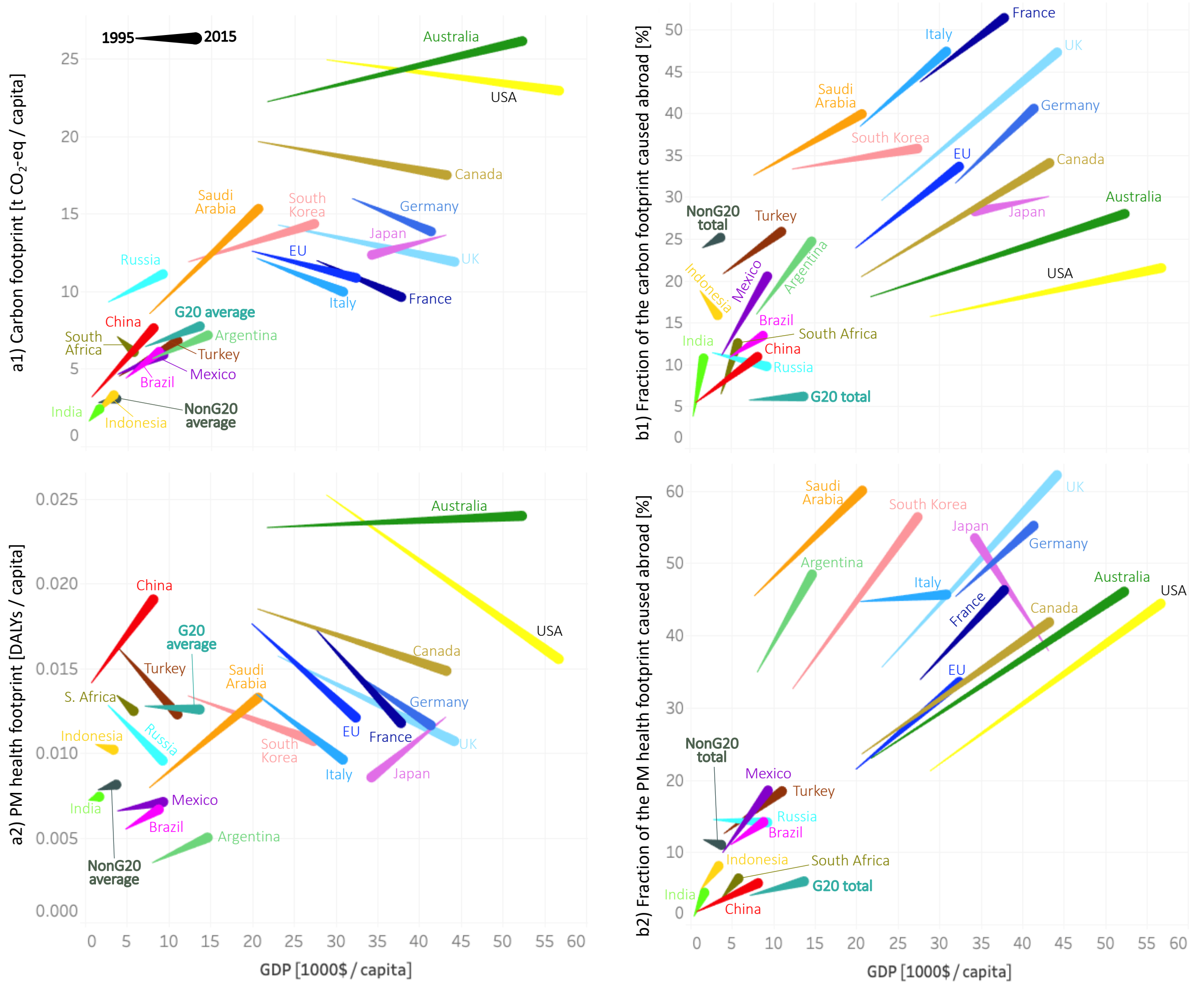

Figure 4.6. Change in a) the G20's GHG emissions and PM health impacts from a consumption perspective (carbon footprint) on a per-capita level and b) share of the G20's carbon and PM health footprint caused abroad, mainly due to material imports (Appendix C.3: Figure C.6a–b) in 1995 and 2015 (as single 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 4.7, Appendix C.3: Figure C.8–C.12). 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 4.7). 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 (Appendix C.3: Figure C.17). 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.

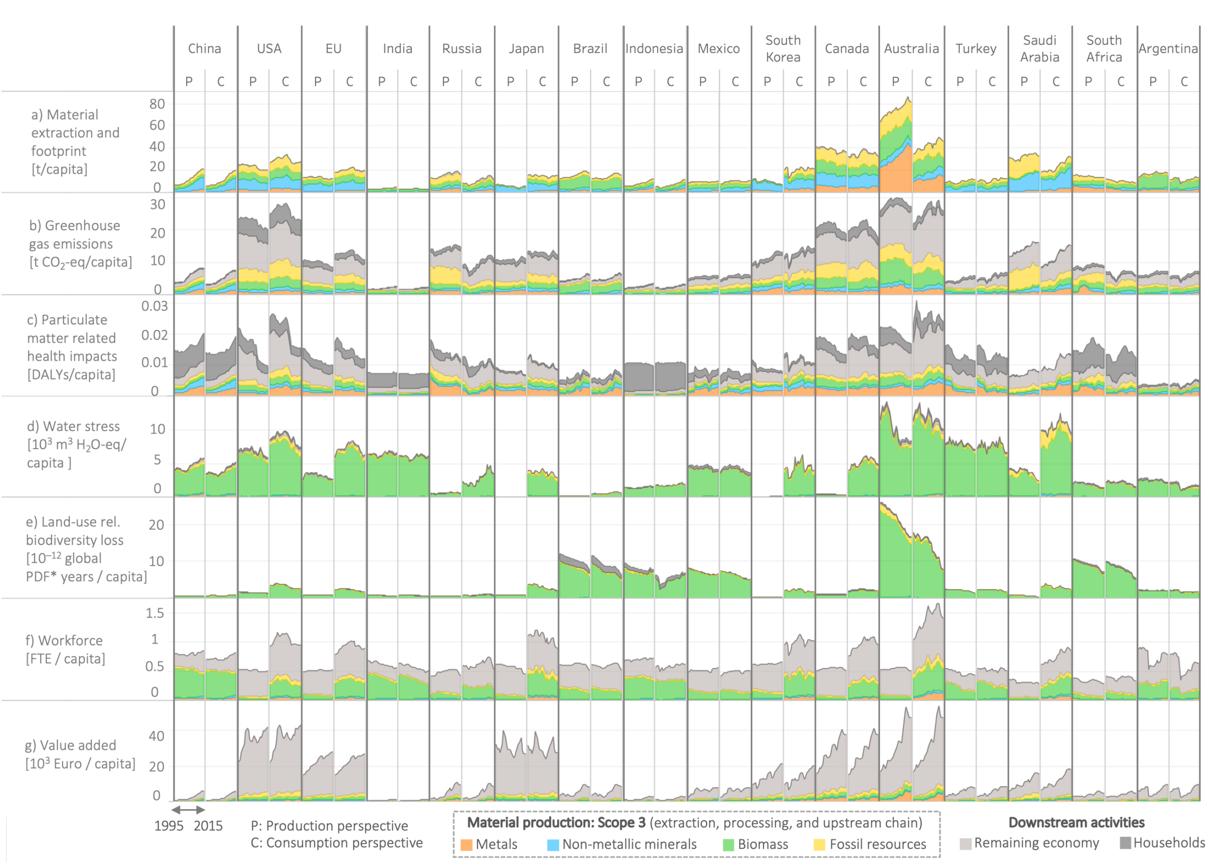

Figure 4.7. Temporal development of the environmental and socioeconomic impacts of the G20 members on a per-capita level split by scope 3 impacts of material production (metals, non-metallic minerals, biomass, fossil resources) and the remaining downstream economy and by households (mainly fossil fuels for GHG emissions, see Figure 4.2c) 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].

4.4 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 Appendix C.4: Paragraph C.12 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 4.2e), 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.

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Chapter 5

Growing environmental footprint of plastics driven by coal combustion

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ABSTRACT

Research on the environmental impacts from the global value chain of plastics has typically focused on the disposal phase, considered most harmful to the environment and human health. However, the production of plastics is also responsible for substantial environmental, health and socioeconomic impacts. We show that the carbon and particulate-matter-related health footprint of plastics has doubled since 1995, due mainly to growth in plastics production in coal-based economies. Coal-based emissions have quadrupled since 1995, causing almost half of the plastics-related carbon and particulate-matter-related health footprint in 2015. Plastics-related carbon footprints of China's transportation, Indonesia's electronics industry and India's construction sector have increased more than 50-fold since 1995. In 2015, plastics caused 4.5% of global greenhouse gas emissions. Moreover, 6% of global coal electricity is used for plastics production. The European Union and the United States have increasingly consumed plastics produced in coal-based economies. In 2015, 85% of the workforce required for plastics consumed by the European Union and the United States was employed abroad, but 80% of the related value added was generated domestically. As high-income regions have outsourced the energy-intensive steps of plastics production to coal-based economies, renewable energy investments throughout the plastics value chain are critical for sustainable production and consumption of plastics.

5.1 Introduction

The global demand for plastics has quadrupled over the past four decades[1] and is projected to further increase in the future, intensifying the impacts on the environment and human health[2-5]. Strategies for the sustainable production and consumption of plastics require information on the value chain of plastics[6-9], such as fossil resource extraction and processing, resin production, manufacturing into plastics products, plastics use, and end-of-life treatments. Many studies have addressed the environmental impacts of (micro)plastics pollution[2, 4-6, 8, 10-14] and plastics incineration[7, 15, 16]. Less attention has been paid to plastics production, which also has significant environmental impacts, such as those caused by the release of greenhouse gas (GHG)[17-20] emissions. Furthermore, plastics production induces health impacts, such as through the release of particulate-matter (PM) emissions, and socioeconomic impacts, such as by employing a workforce and creating value added.

Since the value chain of plastics spans the entire globe, plastics are often produced in a different country than they are ultimately consumed[21]. Therefore, the environmental, health, and socioeconomic impacts resulting from one country's plastics consumption can occur elsewhere around the globe. Multi-regional input-output (MRIO) analysis allows these impacts to be assessed along the global value chain[22-28]. However, the accuracy of results from standard MRIO analysis has been limited when analyzing the cumulative impacts of materials such as plastics due to double counting[29-32]. For example, when assessing cumulative GHG emissions (including upstream emissions) of primary plastics production and plastics recycling, double counting occurs because some primary plastics are ultimately recycled. In standard MRIO analysis[32], the emissions of these primary plastics are counted again as upstream emissions in plastics recycling (a detailed explanation is provided here[31]).

Here, we apply an enhanced method based on MRIO analysis that prevents double counting[29-31, 33] to assess the environmental impacts of global plastics production from 1995 to 2030, and extend this method to evaluate the role of coal combustion (see Methods). We assess GHG emissions that occur in the global plastics value chain, called the carbon footprint of plastics. In this context, the study highlights the importance of plastics production, including resin production, manufacturing into plastics products, and related upstream activities. Moreover, we analyze fossil resources used as a fuel and feedstock for plastics production, called here the fossil resource footprint of plastics. To evaluate the role of trade, the link between plastics producing and consuming regions is mapped. Further, we analyze the future evolution of the global carbon footprint of plastics assuming that the world follows the International Energy Agency's (IEA) projection for a 2-degree and 6-degree scenario[34, 35]. Finally, this study analyzes the PM health impacts, the workforce employed and value added created in the global plastics production chain so as to provide an overview of the health and socioeconomic impacts (see Methods).

5.2 Results

5.2.1 Global carbon footprint of plastics and value chain analysis

Since 1995 the carbon footprint of plastics has doubled, reaching 2.0 Gt CO_2-equivalents in 2015, accounting for 4.5% of global GHG emissions (Appendix D.2: Figure D.1). The major driver of the rising carbon footprint of plastics has been the increased combustion of coal for plastics production, including resin production, manufacturing into plastics products, and related upstream activities (Figure 5.1a–b). As coal-based emissions for plastics production have quadrupled since 1995, plastics production accounted for the vast majority (96%) of the carbon footprint of plastics, while the end-of-life stages, including recycling, incineration and landfills, induced a minor fraction (6%, Year 2015, Appendix D.2: Figure D.1). Consequently, coal-based emissions caused almost half of the carbon footprint of global plastics production in 2015, mainly due to electricity and heat supply from coal for resin production and manufacturing into plastics products (Figure 5.1a–b). In total, 6% of global coal electricity was used for plastics production in 2015.

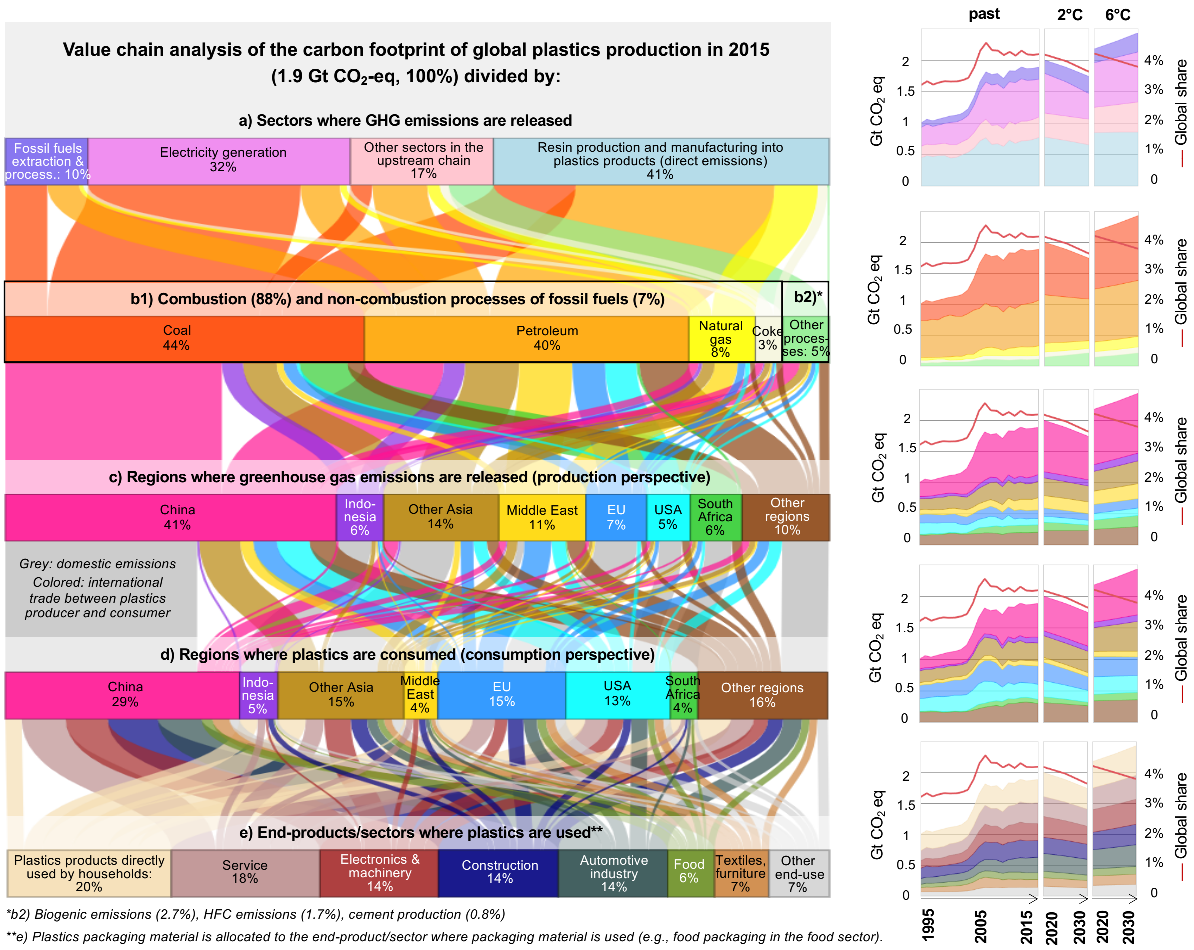

Figure 5.1. The flow chart on the left shows the global value chain analysis of the carbon footprint (GHG emissions) of global plastics production in 2015. The end-of-life stages of plastics (recycling, incineration, and landfills) contributed another 120 Mt CO_2-equivalents in 2015, not illustrated in this figure. The sum of each horizontal bar (a–e) of the flow chart refers to the carbon footprint of global plastics production in 2015 (1.9 Gt CO_2-equivalents, 100%) and allocates it to the different perspectives in the global value chain, such as a) the sectors where GHG emissions are released, b) the processes which release GHG emissions, c) the regions where GHG emissions are released (production perspective), d) the regions where plastics are finally used (consumption perspective) and e) the end-product or sector where plastics are finally used. Plastics packaging material is allocated to the respective end-sectors where it is used (e.g., food packaging in the food sector). The flows show the linkages between the perspectives. Linkages contributing to less than 0.1% of the plastics-related carbon footprint are not shown to enhance clarity. The small graphs on the right show the temporal evolution of the carbon footprint of global plastics production for each perspective (a–e) over the past two decades (1995–2015) and in the future (2020–2030) if the world follows the IEA's projections for a 2-degree and 6-degree scenario[34, 35] (but not accounting for the decrease in global GHG emissions in 2020 due to the Corona pandemic, as in Liu et al[36]). The colors of the graphs on the right correspond to the bars of the flow chart. A detailed value chain analysis of the carbon footprint of global plastics recycling is shown in the Appendix D.2: Figure D.3.

Due to the increased reliance on coal, the fossil resource footprint of plastics, including fossil resources used as fuel and feedstock for plastics production, has tripled since 1995 (Figure 5.2a). Fossil fuels combusted for global plastics production released a total of 1.7 Gt CO_2-equivalents in 2015 (Figure 5.1b1, 88%). The carbon contained in fossil resources used as feedstock for plastics production accounted for another 890 Mt CO_2-equivalents (meaning that this amount would be released if all plastics produced in 2015 were combusted without credits from energy recovery). Thus, twice as much fossil carbon is combusted as fuel for plastics production (1.7 Gt CO_2-eq) than contained as feedstock in plastics (890 Mt CO_2-eq). Our results further indicate that if all plastics produced in 2015 were incinerated, this would increase the annual carbon footprint of plastics by 19% (350 Mt CO_2-equivalents, subtracting credits from energy recovery[37]). While the GHG emissions of plastics incineration are commonly known[7, 8, 15], our results show that even in a worst-case scenario in which all plastics were combusted, the major share of GHG emissions would still occur in the production phase.

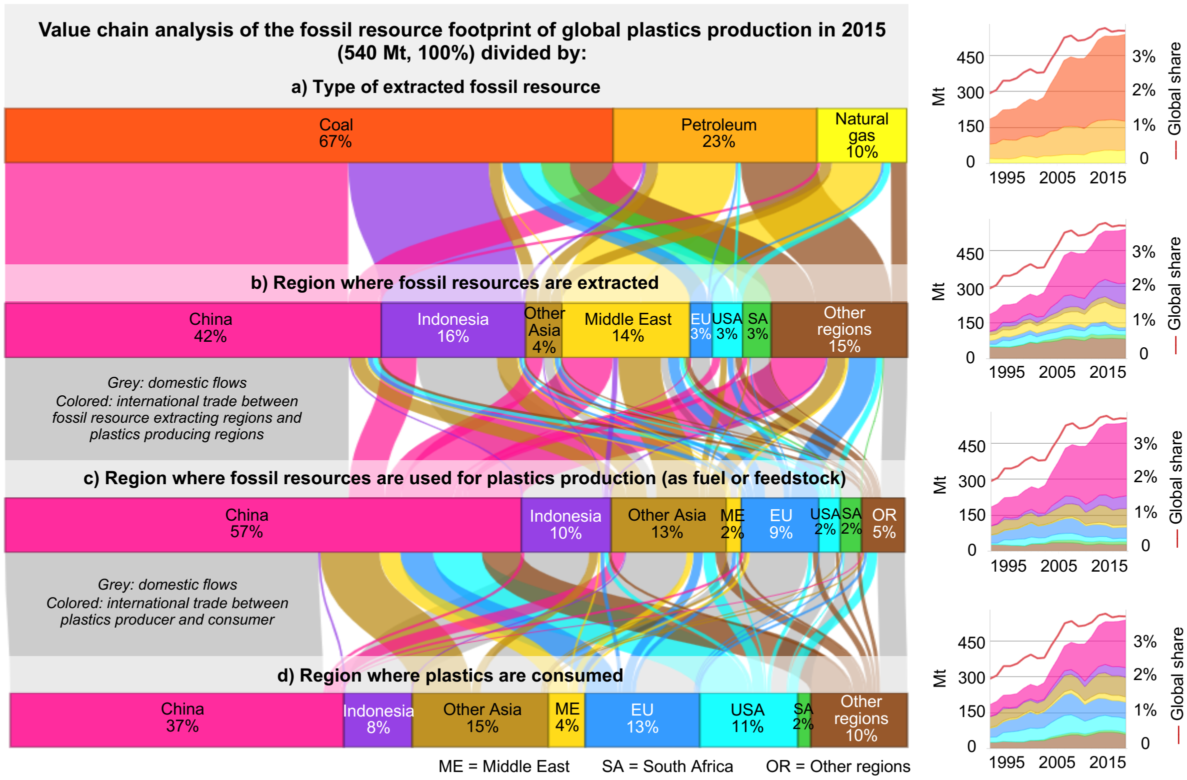

Figure 5.2. The flow chart on the left shows the value chain analysis of the fossil resource footprint of global plastics production, including the extraction of fossil resources used as a fuel and feedstock for plastics production. The sum of each horizontal bar of the flow chart on the left refers to the fossil resource footprint of global plastics production in 2015 (540 Mt in 2015, 100%) and allocates it to the different perspectives in the global value chain (a–d). The small graphs on the right show the temporal evolution of the fossil fuel footprint of global plastics production for each perspective (a–d) over the past two decades. The colors of the graphs on the right correspond to the bars of the flow chart.

Growth in plastics production in coal-based emerging economies, such as China, Indonesia, and South Africa, was the major driver of the increasing carbon footprint of plastics (Figure 5.1). Since 1995, China's plastics-related carbon footprint has more than tripled both from a production and consumption perspective (Figure 5.1b–d). In 2015, 40% of the global plastics-related carbon footprint and more than 60% of the related coal-based emissions were caused in China. In Indonesia, coal mining for plastics production has increased by a factor of 300 since 1995 (Figure 5.2b). In 2015, 15% of Indonesia's totally mined coal was used for plastics production, either domestically or abroad. More than 10% of Indonesia's total domestic GHG emissions were attributed to plastics production in 2015. South Africa's plastics-related carbon footprint has increased tenfold since 1995, and 95% of it was caused by domestic coal consumption in 2015. This is because South Africa uses coal not only to supply electricity and heat but also as a feedstock for plastics production[38]. Almost half of the plastics produced in China and South Africa were exported, such as to the EU and to the USA (Figure 5.1c–d).

High-income regions, such as the EU and the USA, contributed substantially to the increasing global carbon footprint of plastics by their rising demand for plastics produced in lower-income regions, particularly in coal-based economies such as China (Figures 5.1 and 5.3, Appendix D.2: Figure D.4). Due to the outsourcing of plastics production to lower-income regions, the EU's plastics-related carbon footprint increased, although their domestic plastics-related GHG emissions decreased (Appendix D.2: Figure D.5). In 2015, two-thirds of the EU's plastics-related carbon footprint were emitted abroad, mainly in lower-income regions with less stringent environmental policies. The fraction of the plastics-related carbon footprint caused abroad was even higher for Australia, Canada, and the USA (>80% in 2015, Figure 5.3b). Since 1995, the USA's plastics-related carbon footprint generated abroad quadrupled, while their plastics-related domestic GHG emissions decreased (Appendix D.2: Figure D.6). Consequently, the fraction of the USA's plastics-related carbon footprint induced abroad increased from 39% in 1995 to 78% in 2015. One-third of the USA's plastics-related carbon footprint in 2015 occurred in China (Figure 5.1c–d, see Appendix D.2: Results D.1 for further results on the Middle East, and Results D.2 and Figure D.7 for results on the carbon intensity of plastics resin production per region).

In addition to increased plastics exports, emerging economies contributed to the rising global carbon footprint of plastics by their growing plastics demand, mainly due to their growing infrastructures, transportation systems, and digitalization. Since 1995, the plastics-related carbon footprint of China's transportation system, Indonesia's electronics industry, and India's construction sector has increased more than 50-fold. In 2015, 15% of the global carbon footprint of plastics was attributed to plastics used for construction, and almost half of these emissions were attributed to China's construction (Figure 5.1d–e). In addition, plastics are responsible for 15% of the carbon footprint of the global automotive industry, and more than one-third of these GHG emissions were attributed to China's automotive industry. While China also manufactured the majority of the plastics embodied in electronics (65%), a smaller portion (42%) was used by China itself, and the majority (58%) was exported to other regions.

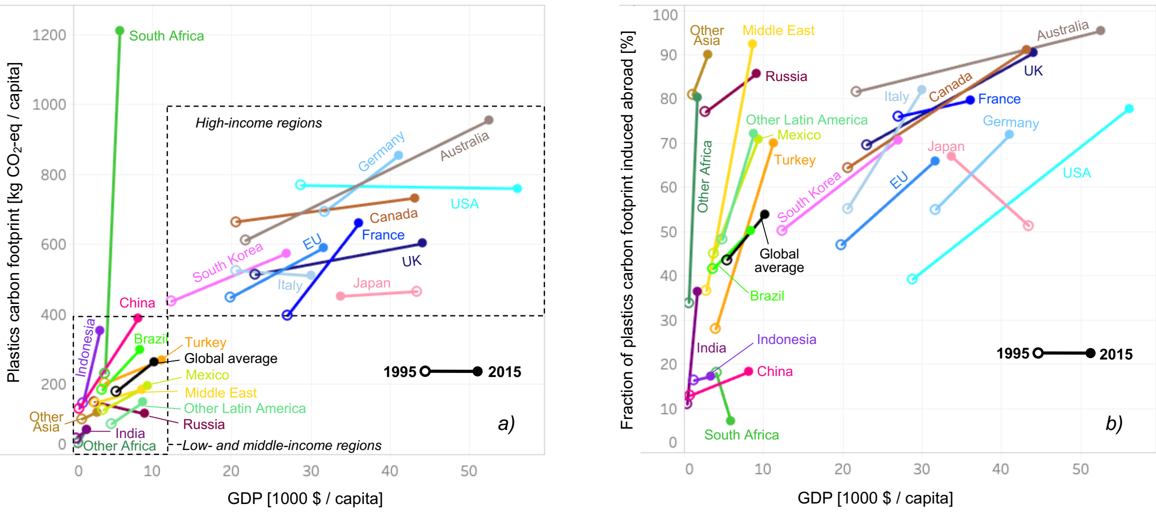

Figure 5.3: Change in a) the per-capita carbon footprints of plastics from a consumption perspective and b) the fraction of the carbon footprint of plastics induced abroad due to imports plotted against the GDP and grouped by income[39] from 1995 to 2015 (as single data points for these two years). The carbon footprints of plastics shown in this figure allocate the GHG emissions to the region where the plastics were finally used (consumption perspective). Net traded GHG emissions of plastics (production-based minus consumption-based emissions) are shown in the Appendix D.2: Figure D.4.

5.2.2 Climate change scenarios

If the world follows the IEA's projection for a 6-degree scenario[34, 35], the global carbon footprint of plastics would grow by 31% from 2015 to 2030, and thus almost at the same speed as projected plastics production (+40%, Figure 5.1, see Appendix D.2: Figure D.8 for per-capita projections). The strongest increase is expected for coal-based economies, such as China, India and South Africa, while the largest international customers of plastics produced in these coal-based economies continue to be the EU and the USA. Following the IEA's projection for a 2-degree scenario[34, 35] would reduce the global carbon footprint of plastics by 10% from 2015 to 2030, while plastics production would increase by 40%. This would be attributed to investment in renewable energy production, mainly clean electricity, and improved energy efficiency in resin production. However, coal combustion would still contribute more than a third of the carbon footprint of plastics in 2030 if the world followed the IEA's projection for a 2-degree scenario[34, 35]. This highlights the potential of a rapid phase-out of coal to further reduce the carbon footprint of plastics in the future, as keeping global warming below 1.5 degrees is critical for preventing major climate-related hazards[40].

Despite the growing demand for plastics in emerging economies, the carbon footprints of plastics remain distinctly higher in high-income regions on a per-capita level (Figure 5.3a), and this imbalance is projected to persist into the future (Appendix D.2: Figure D.8). Taking into account the projected reduction in plastics-related carbon footprints per region if the IEA's measures for a 2-degree scenario[34, 35] were implemented, high-income regions in particular would have a high saving potential at the per-capita level, which would also reduce income-related differences in the carbon footprints of plastics.

5.2.3 Health and socioeconomic impacts of plastics production.

Since 1995 the global PM health footprint of plastics has increased by 70%, causing the loss of 2.2 million disability-adjusted life years (DALYs) and representing 2.8% of global PM health impacts in 2015 (based on EXIOBASE3[22] and Cabernard et al[31], Appendix D.2: Figure D.9 and D.10). Similar to GHG emissions, plastics production accounted for the vast majority (96%) of the plastics-related PM health footprint, half of which was attributed to coal combustion (Year 2015, Figure 5.4a–b). Moreover, the majority (75%) of PM health impacts were caused in China, India, Indonesia, and Other Asia, while high-income regions increasingly consumed plastics produced in these regions (Figure 5.4c–d). In 2015, the vast majority of the EU's (80%) and the USA's (91%) plastics-related PM health footprint was caused abroad, mainly in Asia. Thus, only 8% of the global plastics-related PM health footprint effectively occurred in high-income regions (Appendix D.2: Figure D.11c), although one-third of global plastics was consumed in high-income regions.

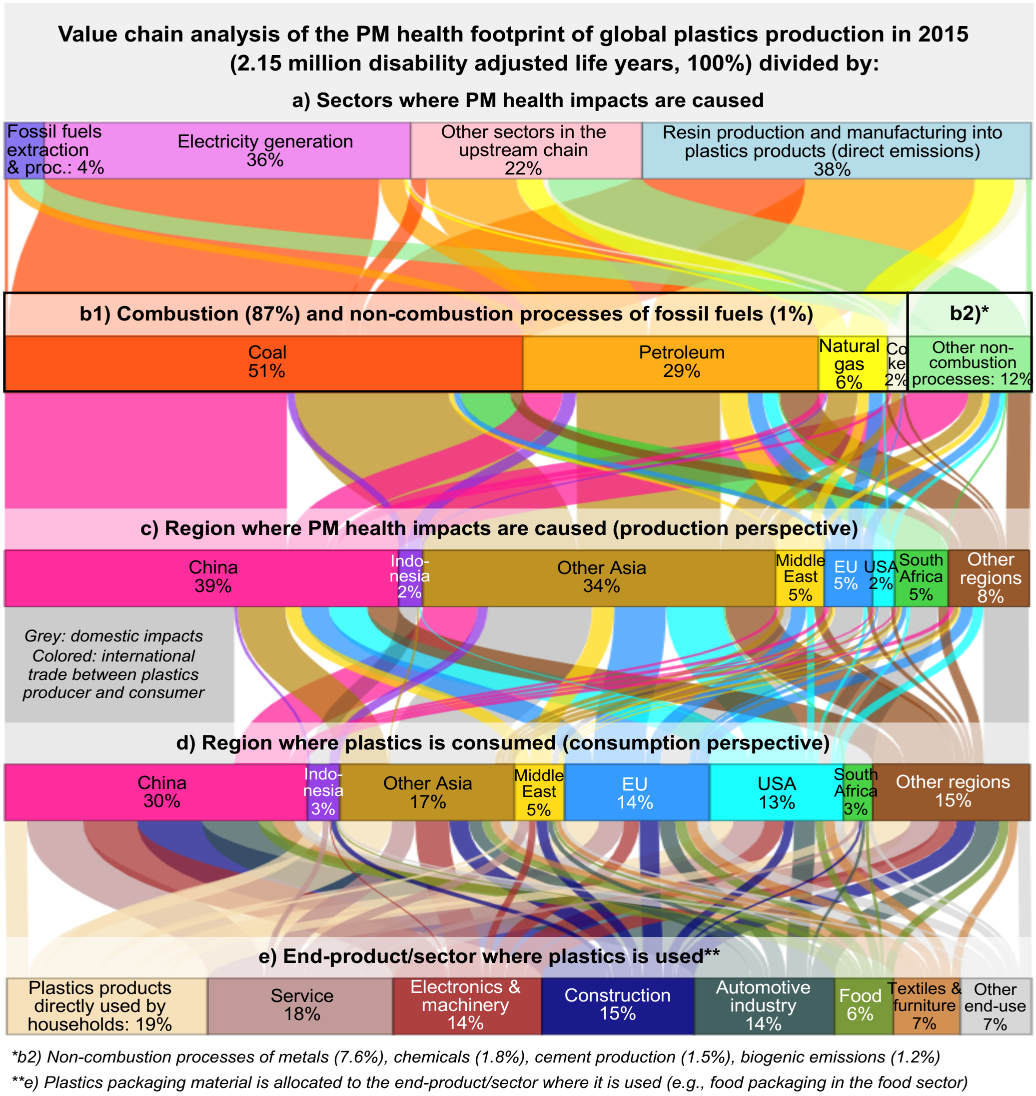

Figure 5.4. Global value chain analysis of the PM health footprint of global plastics production in 2015. The format is the same as in Figure 5.1. The total PM health footprint of global plastics was 2.15 million disability-adjusted life years (DALYs)[31, 41] in 2015, with the end-of-life stages of plastics (recycling, incineration, and landfills) contributing another 910 thousand DALYs, not illustrated in this figure.

The number of employed workers for global plastics production has increased by 54% since 1995. At the same time the value added created by global plastics production, including workforce compensation (48%), operating surplus (40%), and taxes (12%), has more than doubled. In 2015, 106 million workers (in full-time equivalents; 2.3% of the global workforce) were employed in plastics production, while the associated value added reached 1.56 trillion Euros (2.6% of global GDP). The number of the workforce and the created value added are unevenly distributed around the globe: Although more than 90% of the plastics-related workforce was employed in low- and middle-income regions, more than half of the plastics-related value added was generated in high-income regions (Appendix D.2: Figure D.11d–e). China and Other Asia made up the majority of the plastics-related workforce (Figure 5.5a), while the EU generated most of the plastics-related value added (Figure 5.5b). In 2015, 70% of the workforce required for the EU's plastics consumption was employed abroad, but 80% of the related value added was generated domestically. The reliance on the low-paid foreign workforce was even higher for the USA's plastics consumption, where 90% of the workforce was occupied abroad. This means that high-income regions, such as the EU and USA, outsource the low-paid steps in the plastics production value chain to lower-income regions, and focus on the valuable steps of manufacturing plastics into finished products.

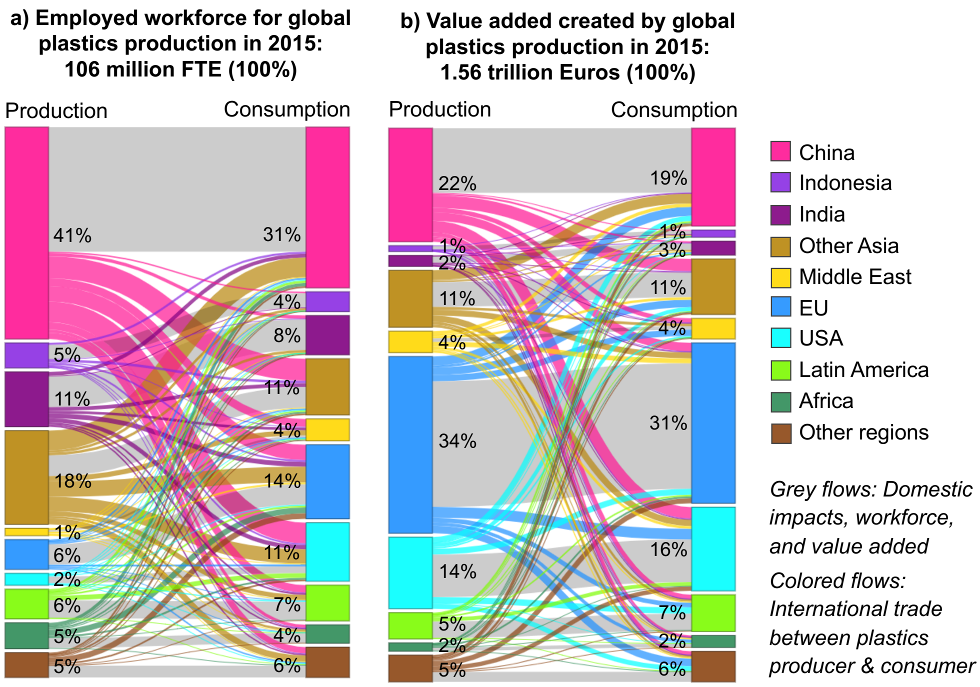

Figure 5.5: The sum of the vertical bars refers to the total a) employed workforce (106 million full-time equivalents (FTE), 100%) and b) created value added (1.56 trillion Euros, 100%) of global plastics production (including resin production, manufacturing into plastics products, and related upstream activities) shown from a production and consumption perspective in 2015. The production perspective indicates the region where the plastics-related workforce is employed and the value added is created. The consumption perspective allocates the plastics-related workforce and value added to the region where plastics were finally consumed. Colored flows refer to plastics consumed in another region than produced due to international trade. The value added of global plastics production includes workforce compensation (48%), operating surplus (40%), and taxes (12%).

5.3 Discussion

5.3.1 Comparison with literature.

Other than previous estimates[42-44], which indicated equal amounts of oil used as fossil fuel and feedstock for plastics production, this study showed that twice as much fossil carbon is combusted as fuel for plastics production than contained as feedstock in plastics. The reason for this difference is that our approach accounts not only for the amount of oil, but for GHG emissions released by combusting all types of fossil fuels along the plastics production chain as well, taking the increased reliance on coal into consideration. In this context, coal also contributes to the carbon footprint of plastics due to its increasing use as a feedstock for plastics production, such as in China[45] and South Africa[38].

The carbon footprint of plastics obtained in this study is higher (+16%) compared to Zheng and Suh[17], who used bottom-up life-cycle analysis to assess the global carbon footprint of plastics in 2015, but did not account for double-counting (see Appendix D.2: Figure D.12 for a comparison of the results). In our study, double-counting would have overestimated the carbon footprint of plastics by 29%, but was avoided by means of the method applied[31]. The reason why the carbon footprint of plastics obtained here is still higher compared to Zheng and Suh[17] is because we considered the regionalized fuel-specific energy mix, such as the increased reliance on coal, while Zheng and Suh[17] calculated with the average global energy mix.

The importance of considering the energy mix is also reflected in the results of the scenarios: In contrast to previous estimates[8, 15], the plastics' share in total global GHG emissions is projected to decrease in the scenarios used here (Figure 5.1). One reason for this is the assumption of increased future investment in renewable energy technologies and improved energy efficiency in the plastics production value chain, which can together exercise substantial leverage for reducing the global carbon footprint of plastics. Another reason could be that the growth in plastics production may be underestimated in the scenarios of this study. This highlights the importance of improved scenarios which take both changes in the energy mix and plastics production into consideration.

5.3.2 Policy implications

In addition to commonly known issues about (micro) plastics pollution[2-6, 8, 10-14] and plastics incineration[7, 15, 16], this study highlights the need for improved policy measures to reduce the increasing carbon footprint of plastics production, which bears the major share of the plastics-related GHG emissions (even in a worst-case scenario where all plastics would be incinerated). On the one hand, our results underscore the importance of ongoing initiatives to reduce primary plastics production by avoiding, reusing, and recycling plastics as discussed in the context of circular economy[8, 9, 42, 46]. However, a general ban on plastics is counterproductive as alternative materials often have higher environmental impacts[47]. On the other hand, this study highlights the particularly strong leverage in the plastics production chain itself to reduce the carbon footprint of plastics. Efficient measures include phasing out coal, transitioning to renewables, and improving the energy efficiency in the plastics production process. As shown here for the past and future, decreasing the emissions in high-income regions as specified in the Paris Agreement is not sufficient. Such an approach even fosters a shift of plastics production to emerging regions with less stringent environmental policies and limited economic power to implement state-of-the-art low-carbon technology. Thus, it is important that high-income regions invest in clean energy production throughout the supply chain.

Since renewable energy investments are currently hampered by the lack of economic incentives[48-50], a key measure required is for the government to implement a carbon price, such as carbon taxes, cap-and-trade emissions schemes, and renewable energy subsidies. Once a reasonable carbon price is in place on a producer and consumer level, the economic opportunities to decarbonize (plastics-related) supply chain emissions will be particularly attractive for consumer-facing companies in high-income regions[48]. One reason for this is that consumer-facing companies can often reduce many more GHG emissions by decarbonizing their (plastics-related) supply chain than by focusing exclusively on their direct emissions. Another reason is that decarbonization of the (plastics-related) supply chain is less costly for consumer-facing companies in high-income regions, than for plastics producing companies in emerging markets[48]. This is because plastics represent only a small portion of end-use prices and consumer-facing companies usually generate higher value per emissions produced (as shown in this study for high-income regions; Figure 5.1c–d and Figure 5.5).

In addition to carbon pricing, creating transparency with regard to (plastic-related) supply chain emissions is another key measure required to incentivize consumer-facing companies to reduce their supply chain emissions[48] since it would allow companies to benefit from increased consumer demand for green products. In this study, transparency with regard to plastics-related supply chain emissions has been improved on a global and country level. Thus, future research is crucial to provide company-level data and to thereby close research information gaps.

One incentive for emerging economies to implement a carbon price to foster renewable energy investments is that such a measure can also reduce PM health impacts and thus local health costs[51] (because unlike the global climate impact of GHG emissions, health impacts depend on the location where they occur). This might be of particular interest to China, which bears the burden of most plastic-related PM health impacts but has limited emission reduction potential from further flue gas treatment improvements[52]. In contrast, the installation of advanced flue gas treatment could significantly reduce plastic-related PM health impacts in India, Indonesia, and other Asian countries[52]. Another incentive for emerging economies to implement a carbon price are the technical and economic opportunities that decarbonization presents in the long term, such as the future competitive advantage to be gained in view of the energy transition and the growth of new industries and services[49, 50, 53]. Consequently, decarbonization efforts might also mitigate the income-related regional imbalance between plastics-related PM health impacts, workforce, and value added shown in this study.

5.4 Methods

5.4.1 Background

Our methodology is based on multi-regional input-output (MRIO) analysis. In MRIO analysis, the world economy is aggregated into a given number of regions and industrial sectors, whose transactional, environmental, and socioeconomic accounts are captured for a given time period[22, 54, 55]. This allows the environmental and socioeconomic impacts of these regions and sectors to be assessed along the global value chain[23-26, 56]. Standard MRIO analysis is accurate for assessing the impacts of plastics end-products such as tableware directly purchased by households[25-28, 57, 58]. However, most plastics are not directly used by households but intermediately by the industry, such as plastics for food packaging, construction materials, or in electronic products. The impacts of these intermediately used plastics could not previously be properly addressed by standard MRIO methodology[25-28, 57, 58] due to double counting[29-32, 59]. This methodical issue of double counting existed not only for plastics but for any materials, such as minerals, fossil resources, and biomass, when assessing their cumulative impacts, including cumulative upstream and direct impacts. For example, when assessing cumulative GHG emissions of steel and coke production, double counting occurs because some coke is used for steel production. This means that the emissions related to coke production are counted again as upstream emissions in steel production. Similarly, when assessing cumulative GHG emissions of primary plastics production and plastics recycling, double counting occurs because some primary plastics are ultimately recycled. In standard MRIO analysis[32], the emissions of these primary plastics are counted again as upstream emissions in plastics recycling (a detailed explanation is provided here[31]).

Recently, a method was developed that prevents double counting[29, 30]. It was extended to MRIO analysis[31] to assess the cumulative impacts of any sector or regions and to track them upstream and downstream the global value chain (without double counting). It was applied to assess GHG emissions[31, 33], particulate-matter related (PM) health impacts[31] and other environmental and socioeconomic impacts of global material production[31]. An explanation of how double counting is prevented and how this affects the environmental footprint of global material production is provided in Cabernard et al[31].

5.4.2 Overview and scope

We used this method[31] to assess fossil resource extraction, GHG emissions (carbon footprint), PM health impacts, and socioeconomic impacts (value added and workforce) along the global plastics value chain. We extended this method to assess the processes of GHG and PM emissions release and the type of fossil fuels used at the different life-cycle stages in the plastics value chain. Further, we compared the amount of fossil resources used as fuels and feedstock for plastics production. To project how the global carbon footprint of plastics will evolve until 2030, we applied our method on a forward-looking MRIO database[35], covering the 2-degree and 6-degree scenarios of the International Energy Agency (IEA)[34]. This study includes cumulative upstream and direct impacts of resin production, further manufacturing, recycling, incineration, and landfills of all types of plastics and rubber, called footprint of plastics in what follows. Impacts related to plastics waste in the environment, such as microplastics pollution, were not addressed.

5.4.3 Database and terminology

We used the global MRIO database EXIOBASE3 (Version 3.7)[22], which aggregates the global economy into 163 industrial sectors for 44 countries and five rest of the world regions (49 regions). This results in 7987 sector-region combinations, whose economic flows are recorded in the coefficient matrix A and the final demand matrix Y for each year from 1995 to 2015 in constant prices[22]. The coefficient matrix A indicates the monetary input of each sector-region combination per monetary output of each sector-region combination (7987 rows x 7987 columns, in Euro / Euro). The final demand matrix Y indicates the final demand of each region for each sector-region combination (7987 rows x 49 columns, in Euro). For each sector-region combination and year, the EXIOBASE3 database provides a set of environmental and socioeconomic accounts (i), which was extended to GHG emissions and PM health impacts[31], and which is called the impact coefficient matrix (D, i rows x 7987 columns, impact / Euro). In this context, each type of GHG emissions listed by the impact coefficient matrix of EXIOBASE3 (CO_2, CH_4, N_2O, hydrofluorocarbons and perfluorinated compounds) was multiplied with the respective global warming potential to estimate the amount of emitted CO_2 equivalents. To calculate PM health impacts, each type of particulate matter emissions listed by the impact coefficient matrix of EXIOBASE3 ($PM_{2.5}$, NO_x, SO_x, and NH_3) was multiplied with sector-specific characterization factors (CFs) to measure the human burden of disease in 'disability adjusted life years' (DALYs), as done in Cabernard et al[31]. These CFs were derived from UNEP-SETAC[60], who provided CFs for $PM_{2.5}$, NO_x, SO_x, and NH_3 emitted to different compartments (outdoor urban, outdoor rural, indoor urban and indoor rural) and CFs for $PM_{2.5}$ emitted at different heights (ground level, low stack, high stack, very high stack). Since we cannot distinguish emission locations by population density in EXIOBASE3, we assumed rural outdoor emissions (with ground-level emissions for $PM_{2.5}$) for all extracting sectors, we averaged rural and urban outdoor emissions for the manufacturing sectors, and we assumed the average of urban outdoor emissions for the rest of the economy, as done in Cabernard et al[31]. The indicators "fossil resource extraction" (in tons of extracted fossil resources), "value added" (in Euros) and "workforce" (in number of people working full-time) were directly adopted from the impact coefficient matrix of EXIOBASE3[22].

5.4.4 Environmental and socioeconomic footprints of plastics

The method from Cabernard et al[31] can be applied to any industrial sector(s) and region(s) of any MRIO system. The first step is to define the sectors and regions of interest, called target-sectors and target-regions. Out of the 163 sectors covered by EXIOBASE3, we defined five sectors as target-sectors, including "*plastics resin production*", "*manufacturing of plastics and rubber products*", "*plastics recycling*", "*incineration of plastics*" and "*landfills of plastics*". Since we analyzed the global plastics value chain, we defined all 49 regions as target-regions. This resulted in 245 target-sector-regions (T, 5 target-sectors x 49 target-regions) referring to the global plastics economy, and 7742 non-target-sector regions (O) referring to the global non-plastics economy. Both target-sector-regions and non-target-sector-regions represent the global economy (all, 7987 sector-regions). Following the method from Cabernard et al[31], we calculated the footprints (FP) of the entire plastics value chain for the indicators (i) fossil resource extraction, GHG emissions, PM health impacts, value added, and workforce:

$$FP_{i,all}^{plastics} = diag(D_{i-all}) \times L_{all-T} \times (Y_{T-all} + A_{T-O} \times L'_{O-O} \times Y_{O-all}) \qquad \text{Eq. 5.1}$$

Eq. 5.1 describes the cumulative upstream and direct impacts of resin production, further manufacturing, recycling, incineration, and landfills of all types of plastics and rubber (called footprint of plastics in this study), but excludes the impacts related to the use phase of plastics as well as the impacts of plastics disposed to the environment. In Eq. 5.1, D_{i-all} refers to the impact coefficients of the respective indicator (i) of the entire economy (all), indicating the impact (e.g., GHG emissions) per Euro of output for each of the 7987 sector-region combinations. L_{all-T} is the Leontief inverse referring to the cumulated inputs of the entire economy (all) into the plastics economy (T). The term in brackets refers to the total output of the global plastics economy. It equals the sum of the direct final demand for plastics products by the global end-consumption (Y_{T-all}) and the intermediate demand for plastics by the global economy ($A_{T-O} \times L'_{O-O} \times Y_{O-all}$). The intermediate demand for plastics by the global economy is composed of the direct input of the plastics economy into the non-plastics economy (A_{T-O}), the cumulated input of the non-plastics economy into the non-plastics economy (L'_{O-O}), and the direct final demand for the outputs of the non-plastics economy (Y_{O-all}). This includes, for example, plastics used for electronics consumed by households. Diagonalizing the impact coefficients ($diag(D_{i-all})$) allocates the global plastics footprints to the sector and region where the fossil resources are extracted, the emissions are released, the impacts are caused, the value added is generated, and the workforce is employed. A detailed explanation of Eq. 5.1 and a list of all terms is described in Cabernard et al[31] by way of the example of global material production.

5.4.5 Division by plastics sectors

To divide the environmental footprints of plastics between the plastics sectors "plastics resin production", "manufacturing of plastics and rubber products", "plastics recycling", "incineration of plastics" and "landfills of plastics", we divided Eq. 5.1 into two terms referring to direct and cumulative indirect impacts, respectively:

$$\begin{aligned} FP_{i,T}^{plastics} &= diag(D_{i-T}) \times L_{T-T} \times (Y_{T-all} + A_{T-O} \times L'_{O-O} \times Y_{O-all}) \\ &+ diag(D_{i-O} \times L_{O-T}) \times (Y_{T-all} + A_{T-O} \times L'_{O-O} \times Y_{O-all}) \qquad \text{Eq. 5.2} \end{aligned}$$

The first term refers to the direct impacts of the plastics sectors, where $\mathrm{D_{i-T}}$ equals the impact coefficients of the plastics sectors (T) and $\mathrm{L_{T-T}}$ is an excerpt of the Leontief Inverse, which indicates the cumulated inputs of the plastics economy into the plastics economy. The second term indicates the cumulative indirect impacts of the plastics sectors caused in the upstream chain by the non-plastics economy: $\mathrm{D_{i-O}}$ equals the impact coefficients of the non-plastics economy (O) and $\mathrm{L_{O-T}}$ is an excerpt of the Leontief Inverse referring to the cumulated inputs of the non-plastics economy (O) into the plastics economy (T). The term $\mathrm{Y_{T-all}} + \mathrm{A_{T-O}} \times \mathrm{L'_{O-O}} \times \mathrm{Y_{O-all}}$ indicates the total output of the plastics economy without double counting. In sum, Eq. 5.2 is the same as Eq. 5.1, but diagonalizing the cumulative upstream impact coefficients ($\mathrm{diag}(\mathrm{D_{i-O}} \times \mathrm{L_{O-T}})$) allocates the cumulative indirect impacts (caused in the upstream chain by the non-plastics economy) to the plastics sector (while Eq. 5.1 allocates the cumulative indirect impacts to the sector in the upstream chain). To track the footprints along the global value chain, we diagonalized the different terms of Eq. 5.1 and 5.2, as explained in Cabernard et al[31].

5.4.6 Distinguishing different processes of GHG and PM emissions

The impact coefficient matrix of EXIOBASE3 indicates the GHG and PM emissions per Euro of output for each sector-region combination and for different processes. These processes include combustion of fossil fuels, non-combustion processes of fossil resources, minerals extraction and processing, and biogenic GHG emissions due to agriculture for bio-based plastics. To allocate the carbon and PM health footprint of global plastics production to each of these processes, we applied the process-specific impact coefficients ($D_{i_{process}}$) to Eq. 5.1 and 5.2.

5.4.7 Type of fossil fuels causing combustion-related emissions

For the carbon and PM health footprint related to fossil fuel combustion, we further investigated which type of fossil fuels, such as coal, petroleum, natural gas, and coke, are combusted in the global plastics value chain. Since this is not indicated by EXIOBASE3, we weighted the combustion-related carbon and PM health footprint of global plastics production with fuel-specific contribution matrices ($C^{GHG}_{fuel-all}$ and $C^{PM}_{fuel-all}$, 4 rows x 7987 columns):

$$FP^{plastics}_{GHG,fuel-all} = C^{GHG}_{fuel-all} \times diag(D_{GHG_{comb}-all}) \times L_{all-T} \times (Y_{T-all} + A_{T-O} \times L'_{O-O} \times Y_{O-all}) \qquad \text{Eq. 5.3}$$

$$FP^{plastics}_{PM,fuel-all} = C^{PM}_{fuel-all} \times diag(D_{PM_{comb}-all}) \times L_{all-T} \times (Y_{T-all} + A_{T-O} \times L'_{O-O} \times Y_{O-all}) \qquad \text{Eq. 5.4}$$

$C^{GHG}_{fuel-all}$ and $C^{PM}_{fuel-all}$ indicate the contribution (in %) to GHG emissions and PM health impacts, respectively, by the combustion of either coal, petroleum, natural gas, or coke (4 rows) in each sector-region combination of the EXIOBASE3 database (7987 columns). Since each column sums up to 100%, the resulting footprints are the same as in Eq. 5.1 and 5.2 However, the application of the fuel-specific contribution matrices allows the type of fossil fuels combusted at the different life-cycle stages of the global plastics value chain to be distinguished, as illustrated in Figure 5.1b1 and Figure 5.4b1.

We derived $C^{GHG}_{fuel-all}$ and $C^{PM}_{fuel-all}$ from the element-wise product of the fuel sector outputs of the monetary transaction matrix of EXIOBASE3 ($T^{mon}_{fuel-all}$, in Euro), the inverted fuel price vector ($p_{fuel}^{phy/mon}$, in t/Euro), and the fuel-specific impact factor vector for GHG emissions ($f_{fuel}^{GHG/phy}$, kg CO_2-eq/t) and PM health impacts ($f_{fuel}^{PM/phy}$, DALYs/t), respectively, and by dividing each element by the column sum of the resulting matrix:

$$C^{GHG}_{fuel-all} = \frac{T^{mon}_{fuel-all} * p_{fuel}^{phy/mon} * e_{fuel}^{GHG/phy}}{\sum_{fuel}(T^{mon}_{fuel-all} * p_{fuel}^{phy/mon} * e_{fuel}^{CC/phy})} \qquad \text{Eq. 5.5}$$

$$C_{fuel-all}^{PM} = \frac{T_{fuel-all}^{mon} * p_{fuel}^{phy/mon} * e_{fuel}^{PM/phy}}{\sum_{fuel}(T_{fuel-all}^{mon} * p_{fuel}^{phy/mo} * e_{fuel}^{PM/phy})} \quad \text{Eq. 5.6}$$

We derived the inverted fuel price vector ($p_{fuel}^{phy/mon}$, kg/Euro) from the element-wise division of the total output of each fuel sector indicated by the physical MRIO table of EXIOBASE3 for the year 2011 (x_{fuel}^{phy}, in kg) by the respective total output indicated by the monetary MRIO table of EXIOBASE3 for the year 2011 (x_{fuel}^{mon}, in Euro) since physical IO data are only available for the year 2011 in EXIOBASE3:

$$p_{fuel}^{phy/mon} = \frac{x_{fuel}^{phy}}{x_{fuel}^{mon}} \quad \text{Eq. 5.7}$$

We compiled fuel-specific GHG emissions factors ($e_{fuel}^{GHG/phy}$, kg CO_2-eq/t) for coal, petroleum, natural gas, and coke[61]. For coal, we weighted the emission factor of anthracite, bituminous coal, sub-bituminous coal, lignite, and peat with the extracted volumes indicated by the UN IRP Material Flows Database[62]. Fuel and region-specific PM health impact factors per amount of fuel ($e_{fuel}^{PM/phy}$, DALYs/t) were calculated based on a global coal emission inventory[52] (with a few outliers and the small units below 50 MW with lower data quality being removed) in combination with a highly resolved regionalized PM health impact assessment methodology[63]. Emission factors for petroleum and natural gas were obtained from the European Environment Agency[64]. Health impact factors were approximated based on Oberschelp et al[52, 63] and an average electrical efficiency of 40%, assuming the same spatio-temporal emission distribution patterns as for coal power generation. The health impact factors indicate the disability- adjusted life years (DALYs) per amount of combusted coal, petroleum, natural gas, and coke for each of the 49 regions covered by EXIOBASE3 for the year 2015. For coke we assumed the same region-specific PM health impact factors as for coal.

5.4.8 Fossil resources used as fuels and feedstock

Fossil resources are used both as fuels and feedstock for plastics production. While fossil resources used as fuels release GHG emissions during plastics production and related upstream activities, fossil resources used as feedstock only release GHG emissions if plastics are incinerated or composted. We calculated the GHG emissions of fossil resources used as fuels for plastics production ($FP_{i,comb}^{resin+manu}$) by applying Eq. 5.1 and 5.2 to the combustion-related GHG emissions indicated by EXIOBASE3 separately. To derive the GHG emission potential of fossil resources used as feedstock for plastics resin production ($E_{GHG,feedstock}^{resin}$, in kg CO_2-eq), we subtracted the GHG emissions directly released through plastics resin production ($E_{GHG,direct}^{resin}$, in kg CO_2-eq) from the GHG emission potential of the fossil resource input into plastics resin production ($E_{GHG,input}^{resin}$, in kg CO_2-eq) for the year 2015:

$$E_{GHG,feedstock}^{resin} = E_{GHG,input}^{resin} - E_{GHG,direct}^{resin} \quad \text{Eq. 5.8}$$

We derived the GHG emission potential of the fossil resource input into plastics resin production ($E_{GHG,input}^{resin}$) from the element-wise product of the monetary transaction matrix of EXIOBASE3 ($T_{fuel-resin}^{mon}$, in Euro), the inverted price vector of fossil resources ($p_{fuel}^{phy/mon}$, in t/Euro), and the fuel-specific GHG emission factor vector ($e_{fuel}^{GHG/phy}$, kg CO_2-eq/t) for the year 2015:

$$E_{GHG,input}^{resin} = T_{fuel-resin}^{mon} * p_{fuel}^{phy/mon} * e_{fuel}^{GHG/phy} \quad \text{Eq. 5.9}$$

5.4.9 Incineration of plastics

We estimated the annual increase in the global carbon footprint of plastics (I_{GHG}^{inc}) for the scenario that all plastics produced in 2015 were incinerated:

$$I_{GHG}^{inc} = \frac{FP_{GHG,prod}^{plastics} + E_{GHG,feedstock}^{resin} - s}{FP_{GHG,prod}^{plastics}} - 1 \quad \text{Eq. 5.10}$$

Thereby, $FP_{GHG,prod}^{plastics}$ refers to the carbon footprint of global plastics production (based on Eq. 5.1), and s refers to GHG emissions savings through heat and electricity recovery during plastics waste incineration. According to the ecoinvent 3.4[37] life-cycle database, the incineration of one kg of plastics generates on average 3.92 MJ of electricity and 7.66 MJ of useful heat, which we multiplied with the life-cycle GHG emissions of the global electricity (0.544 kg CO_2-eq/ MJ)[45, 65] and heat mix (0.073 kg CO_2-eq /MJ)[66] as well as global plastics production in 2015 to assess carbon savings through energy recovery, as done by Zheng and Suh[17]. This estimation assumes a scenario in which all plastics produced in 2015 end up as waste. In reality, some plastics end up in stocks (e.g., infrastructure), while some plastics produced in previous years add to the waste. Further, heat and electricity savings (s) are based on average values[37].

5.4.10 Climate change scenarios

To evaluate how the carbon footprint of plastics evolves until 2030 under different climate change scenarios, we applied the procedure described above (Eq.1–7) on a forward-looking version of EXIOBASE3[35], which is based on climate change scenarios of the International Energy Agency (IEA)[34]. The forward-looking MRIO database involves different measures required to pursue the 2-degree and 6-degree scenarios until 2100 as projected by the Energy Technology Perspectives of the IEA[34]. The most important measures include increased investment in renewable energy technologies and improvements in material and energy efficiency on the basis of the growing world population and GDP. An overview of the measures implemented is provided in Table 1 in Wiebe et al[35]. Note that the USA's current boom in shale gas extraction may increase the USA's domestic plastics production and related GHG emissions in the future,[67, 68] which was not accounted for in the scenarios used here[34, 35].

5.5 References

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Chapter 6

Conclusions and Outlook

6.1 Synthesis

This thesis provides an improved MRIO methodology and database to create more transparency in global value chains and their impacts to support sustainable decision making. In this context, Chapter 2 provides a methodology for assessing the scope 3 impacts of any sectors and regions of any MRIO database without double counting and tracking them along the global value chain (Research Gap (RG) and Objective (Obj.) 1)[1]. The methodology is extended to downstream GHG emissions and PM health impacts (of mainly fossil fuel combustion) in Chapter 4 and 5 (RG and Obj. 2)[2, 3]. Chapter 3 provides an automated, transparent, and time-efficient approach to improve the resolution, quality, and indicator coverage of an existing MRIO database (RG and Obj. 3)[4]. It is applied to compile a database with high regional and sectoral resolution and broad indicator coverage in Chapter 3 and 4. The database covers a cutting-edge set of environmental impact categories, including climate change and PM health impacts, water stress, and land-use related biodiversity loss, and adds the socioeconomic indicators value added and workforce (RG and Obj. 4). The relevance, versatility, and applicability of the methodology and database of this thesis has been illustrated by several case studies[1-4]. Chapters 2 and 4 provide a case study on the production of materials, food, and fuels (summarized as material production in this thesis) globally and for the G20, respectively (RG and Obj 5). An in-depth analysis of the role of coal combustion is shown in Chapter 4 for the production of metals and construction materials, and in Chapter 5 for global plastics production. A detailed analysis of the EU's food supply chain and the associated water and land footprint is presented in Chapter 3 (RG and Obj 6).

6.1.1 Methodology

The scope 3 impact assessment of this thesis allows assessing the cumulative upstream (supply chain) and midstream (direct) impacts of any sector and region of an MRIO database. The principle of the methodology is to set the sectors and regions of interest as a target, called target-sector-regions, as done in Dente et al[5, 6] for the GHG emissions of Japan's material production. In this thesis, the target can be chosen flexibly, such as global material production (Chapter 2), food consumed by the EU (Chapter 3), global metals production (Chapter 4), and global plastics production (Chapter 5). Once the target is set, the global economy is split into the target economy (e.g., global material production) and the non-target economy, which is the remaining global economy (e.g., everything else than global material production, such as further manufacturing, construction, service, electricity, transport, Chapter 2). The principle of the methodology is to split total global impacts into scope 3 impacts of the target economy, and the remaining impacts of the non-target economy, as done in all case studies of this thesis (Chapter 2–5). It also means that if the entire global economy is set as a target, the methodology becomes the same as the standard Leontief model, which basically prevents double counting for the entire economy by allocating total global impacts to either the producing or consuming sector and region.

The relevance of this thesis' methodology has been highlighted by all case studies. It was found for example, that compared to the methodology of this thesis, standard production-based accounting[7-17] underestimates the scope 3 GHG emissions and PM health impacts of total global material production by 20–25% and those of global plastic production by 60%. The reason for this is that standard production-based accounting only accounts for direct impacts and thus neglects upstream impacts, as it allocates the upstream impacts to the sector in the upstream supply chain where they are caused (e.g., the impacts caused in the upstream chain of material production by the electricity and transport sector are allocated to the electricity and transport sector instead of material production). Likewise, standard consumption-based accounting[7-18] underestimates the scope 3 impacts of total global materials production by 30–75% and those of global plastics production by 80% compared to this thesis' methodology. This is because standard consumption-based accounting only accounts for the impacts of materials directly consumed by the final demand (e.g., food and fossil fuels for heating and car driving), as it allocates the impacts of those materials used by the industry to the sector of end use instead of the material sector (e.g., the scope 3 impacts of metals used for electronics, cement used for construction, food used in restaurants, and fossil resources used for transport are allocated to these end-use sectors instead of the material sectors). On the other hand, standard scope 3 accounting[16, 17, 19] overestimates the scope 3 impacts of total global material production by 20–45% and those of global plastics production by 30% compared to this thesis' methodology. This is attributed to double counting of the impacts of material sectors which are 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). Conclusively, this means that none of the previous MRIO approaches allowed for a meaningful assessment of the scope 3 impacts of materials production. The methodology of this thesis is not only relevant for global materials production, but for various other industries and economies, which is discussed in Section 6.2.1.

This thesis' methodology also enables tracking the scope 3 impacts of target-sectors-regions along the global value chain. The improved global value chain mapping is particularly relevant as it allows identifying the different leverages in the upstream, midstream, and downstream chain of sectors and regions to efficiently reduce impacts. In the case of GHG emissions and PM health impacts of materials production, it showed for example that actions should be taken in the upstream chain by switching to renewable electricity, and in the midstream and downstream chain by reducing and replacing the use of high-impact materials such as steel and cement (Chapter 2 and 4). The global trade analysis showed that high-income regions need to invest in their material supply chains, as they have contributed to the rising environmental footprints by outsourcing their resource extraction and material production to lower-income regions with less stringent environmental policies, higher water stress, and more biodiversity loss (Chapter 2–5). For instance, to reduce the EU's water stress and biodiversity loss footprint, the EU should source food from regions with low impacts and seek to replace high-impact food products with alternative local products (Chapter 3). For plastics production, investment in renewable energy production and improved energy efficiency measures have a particularly strong leverage in the upstream and midstream chain, while measures in the downstream chain should aim to reduce, reuse, and recycle plastics (Chapter 5).

While the methodology of Chapter 2 allows tracking scope 3 impacts of sectors such as materials in the “downstream chain” (e.g., to assess the carbon footprint of steel used in construction), the approach of Chapter 4 and 5 enables assessing “downstream impacts” of fossil fuels by allocating GHG emissions and PM health impacts to the type of fossil fuels that causes the emissions, such as combustion of coal, oil, or gas. The importance of this allocation has been emphasized by the case study on the G20 (Chapter 4) and the in-depth analysis of global plastics production (Chapter 5). Combined with the methodology from Chapter 2, it showed that the rise in global coal-related GHG emissions was mainly driven by the G20’s production of construction materials and metals (Chapter 4). In 2015, almost half of global coal was used for the production of these materials in China and India. Likewise, it revealed that the rising carbon and PM health footprint of plastics is driven by coal combustion (Chapter 5). Coal-based emissions have quadrupled since 1995, causing half of the plastics-related carbon and PM health footprint in 2015. In 2015, 6% of global coal electricity was used for plastics production and plastics accounted for 4.5% of global GHG emissions in 2015, which is higher than previously assumed. The reason why previous studies have underestimated the global carbon footprint of plastics[20, 21] (despite double counting) is because they calculated with the global mean energy mix and did not account for the increased reliance on coal energy in the plastics sector, as done in this thesis. This is also the reason why in contrast to earlier estimates[22-24], which assumed equal amounts of oil used as fuel and feedstock in plastics production, this thesis shows that twice as much fossil carbon is combusted as fuel for plastics production than is contained as a feedstock. It was found that even in a worst-case scenario where all plastics would be incinerated, the lion’s share of GHG emissions would still occur in the production phase. This means that previous studies have underestimated the relative significance of the production versus the disposal phase, and thus the strong leverage to reduce the carbon (and PM health) footprint of plastics by renewable energy investments.

6.1.2 Database

While previous MRIO databases were limited in their spatial and sectoral resolution[25-32], the highly resolved MRIO database (R-MRIO database) of this study allows for a detailed global value chain analysis and the associated impacts, as shown by the example of the EU’s food supply chain (Chapter 3) and the G20’s material value chains (Chapter 4). A particular focus was set on improving the data quality for biomass sectors and the associated water stress and biodiversity loss, as it was found in Chapter 2 that one-third of these impacts were caused by biomass production in those regions with limited resolution in EXIOBASE3. The relevance of the improved resolution has been demonstrated by the results on the EU’s water stress and biodiversity loss footprint, which increased by up to 20% and 5%, respectively, after considering the EU's imports of biomass products from countries with high level of water stress and biodiversity loss (Chapter 3).

Other than previous MRIO databases and studies[7-9, 11, 25-48], which were limited in the indicator coverage, this thesis provides an indicator set addressing four of the key environmental issues listed in the UNEP's SDG agenda[49]: climate change impacts, PM health impacts, water stress, and land-use related biodiversity loss. These indicators have been implemented into EXIOBASE3 (Chapter 2 and 5), Eora26 (Chapter 3), and the R-MRIO database (Chapter 3 and 4) based on the most recent impact assessment methods recommended by UNEP-SETAC[50]. The importance of this indicator set has been underlined by the case studies in Chapter 2–5, such as by the uneven distribution of different environmental impact categories across material sectors globally (Chapters 2–5), and among country-footprints, such as between the G20 members (Chapter 4) and the EU members (Chapter 3). The relevance of the PM health impact assessment has been highlighted in Chapter 5, where coal burning was shown to drive the rising PM health footprint of plastics. The need for the regionalization in water and land impacts has been emphasized by the strong variability among country's water and land footprints if local conditions on water scarcity and ecosystem value were taken into account (Chapter 3, Appendix E.2: Figure E.1). These results point to the need for improved supply chain management and the use of regional advantages to reduce water stress and biodiversity loss (Chapter 4 and 5).

To address the social and economic pillar of sustainability, this thesis also included the indicators value added and workforce. Similar to previous studies[7-10, 12, 15], the case studies (Chapter 2–5) pointed out that that many high-income regions outsource environmental impacts and low-paid workforce to lower-income regions, while generating most of the value added domestically. However, other than previous studies, the improved methodology revealed that this imbalance is almost exclusively attributed to international trade of materials (Chapter 2 and 4), such as food (Chapter 3) and plastics (Chapter 5). The magnitude of this imbalance was highlighted for example in Chapter 4, showing that the number of workers employed worldwide to supply Australia's material demand is bigger than the number of people working in Australia's entire economy. Likewise, it was shown in Chapter 5, that although 70% of the workforce required for the EU's plastics consumption was employed abroad, 80% of the related value-added was created domestically.

6.2 Scientific relevance

The following section highlights the scientific relevance of this thesis' improved methodology and database by comparing it with the literature. It highlights the broad relevance and applicability of this thesis' methodology by showing that none of the previous MRIO approaches allowed for a meaningful scope 3 assessment for most target industries and economies, and for most impact categories. Furthermore, this section compares this thesis' approach to assess downstream impacts of material resources (physical allocation) to the monetary-based allocation of Dente et al[5, 6, 51]. Finally, this section discusses the benefits of this thesis' highly resolved MRIO database compared to the database of Bjelle et al[48].

6.2.1 Methodology

In addition to material, this thesis' methodology is also relevant for assessing scope 3 impacts (including direct and upstream impacts) of several other industries (Figure 6.1a): Compared to the methodology of this thesis, standard production- and consumption-based accounting[7-15] significantly underestimates the scope 3 impacts of most target industries (up to 99%), while standard scope 3 accounting[16, 17, 19] significantly overestimates impacts due to double counting (up to 100%). In this context, the underestimation by standard production-based accounting indicates the share of upstream impacts in total scope 3 impacts (e.g., 90% of the scope 3 GHG emissions of electronics and machinery are released in the upstream chain and the remaining fraction is released directly), while the underestimation by standard consumption-based accounting provides an estimate of the downstream use by the industry (e.g., ~40% of the electronics and machinery are used by industries and the remaining fraction is used by households, Figure 6.1a). The double-counted share provides a measure of the linkages among the target industry itself (e.g., about half of globally produced electronics and machinery is used for the production of electronics and machinery itself).

This thesis' methodology is also important for assessing scope 3 impacts of economies, including direct and cumulated upstream impacts of a nation's production, consumption, an trade of commodities and services (Figure 6.1b): Compared to this thesis' methodology, standard production- and consumption-based accounting[7-15] significantly underestimates the scope 3 impacts of most target economies (up to 99%), while standard scope 3 accounting[16, 17, 19] significantly overestimates impacts due to double counting (up to 200%). While the underestimation by standard production-based accounting indicates the share of supply chain impacts in total scope 3 impacts (e.g., two thirds of Switzerland's scope 3 GHG emissions are released in the supply chain abroad and the remaining fraction is released domestically), the underestimation by standard consumption-based accounting provides an estimate of the exports (e.g., ~25% of Switzerland's scope 3 GHG emissions are attributed to exports and the remaining fraction is attributed to Swiss consumption). The double-counted share provides a measure of the linkages among the target economy itself (e.g., ~80% of commodities and services produced by the Swiss economy are used by the Swiss economy itself).

Thus, the results of Figure 6.1 indicate that none of the previous MRIO approaches allowed for a meaningful scope 3 impact assessment of most target industries and economies, as done in this thesis. Also, these results underline the relevance of this thesis' enhanced global value chain mapping: They indicate that most industries and economies have a significant upstream chain (indicated by the underestimation of production-based accounting), midstream chain (indicated by the overestimated share due to double counting), and downstream chain (indicated by the underestimation of consumption-based accounting) that could not be comprehensively modeled by previous MRIO methodology[7-17, 19], but was addressed here.

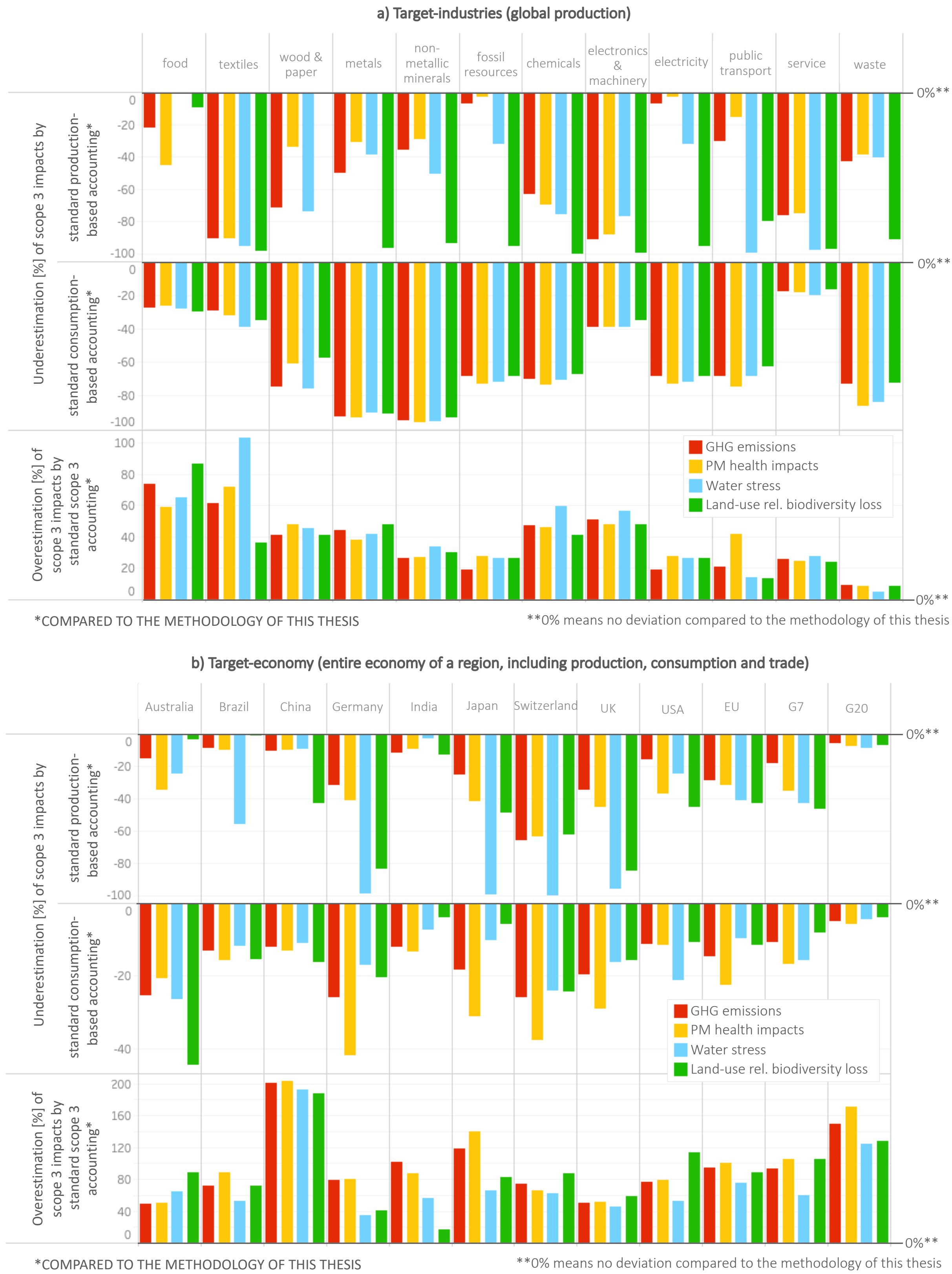

Figure 6.1. Underestimation and overestimation of total scope 3 impacts (including cumulative upstream and direct impacts) of a) target-industries and b) target-economies (including a region's production, consumption, and trade) by standard MRIO methodologies (standard production- and consumption based accounting[7-15] and standard scope 3 accounting[16, 17, 19]) compared to this thesis' methodology. The grouping of the target-industries is listed in Table E.1 of the Appendix E.1.

In contrast to the scope 3 assessment, which allows assessing the scope 3 impacts of any industry, economy, and impact category of an MRIO database, this thesis' approach to assess downstream impacts enables allocating GHG emissions and PM health impacts to the type of material resources causing the emissions (Chapter 4 and 5). For GHG emissions released in the downstream chain of material production, these are mainly combustion-related emissions of coal, oil, gas and coke, and to a lesser extent, waste-related emissions of chemicals and biomass due to incineration, composting, landfills, and waste water treatment. Thus, this thesis' downstream approach differs from the monetary-based allocation of ref[5, 6, 51]. A comparison of the two downstream approaches is shown in Figure 6.2 by the example of global GHG emissions, where scope 3 emissions are based on Chapter 2, while downstream emissions were calculated based on Dente et al[5] and Chapter 4, respectively. In the approach of Dente et al[5], downstream GHG emissions of material resources are comparably small and distributed among all material resource types. Due to the monetary allocation in Dente et al [5], more than one-third of global 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 material resources. The approach taken in this thesis 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 6.2).

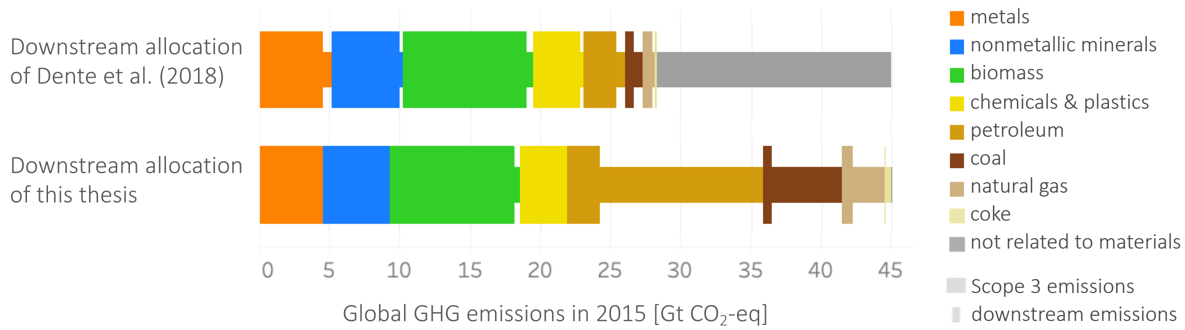

Figure 6.2. Comparison of the downstream allocation of Dente et al[5] (based on monetary inputs) and this thesis (Chapter 4) for global GHG emissions divided by material resource type. Scope 3 emissions are based on Chapter 2.

Differences between the results of Dente et al[5] (which is based on a Japanese input output table) and this thesis (where the method of ref[5] was extended to MRIO analysis) can also be observed for GHG emissions of Japan's material resources, which are far higher in this thesis (Figure 6.3). This is attributed not only to differences in the underlying databases (discussed in Chapter 2), and the downstream allocation (discussed above), but also because this thesis includes scope 3 GHG emissions of all materials produced, consumed, and traded by Japan, while ref[5] excludes exports as well as materials embodied in imports (e.g., metals embodied in imported electronics). In contrast to ref[5], this thesis' methodology (Chapter 2 and 4) further allows mapping the entire value chain of Japan's material-related GHG emissions. An example is shown in Figure 6.4 at the aggregate level, illustrating the role of imports (f2) and exports (a2), and Japan's heavy dependence on oil for materials production and use (c–e), the latter mainly for services, transportation, and heating (b–c).

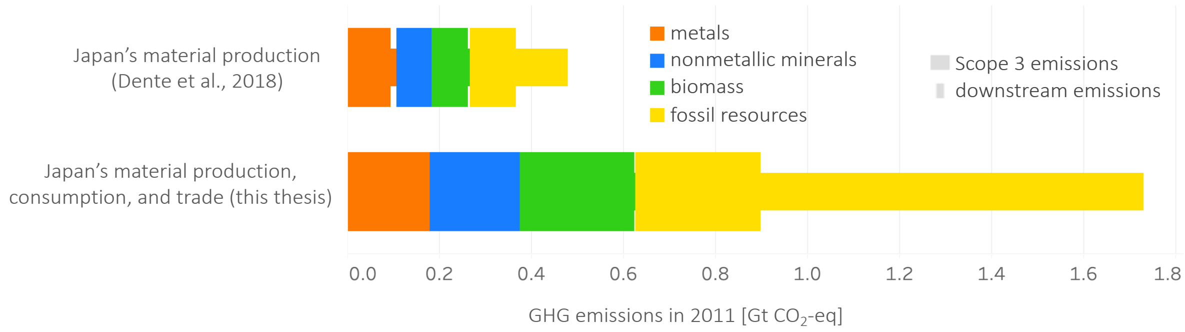

Figure 6.3: Comparison of the results from Dente et al[5] on GHG emissions of Japan's material production to the GHG emissions of Japan's total material production, consumption, and trade based on Chapter 2 and 4 of this thesis (Year 2011). This figure is also shown in Figure C.2 of the Appendix C.

6.2.1 Database

An MRIO database with similar resolution as here has been built upon EXIOBASE3 by Bjelle et al[47], but several differences exist: Unlike ref[47], this thesis' database is consistent with the original EXIOBASE3 database, meaning it equals EXIOBASE3 when aggregated back to its regional resolution (Chapter 3). Thus, this thesis' approach to resolve the database is more transparent and can be applied analogously to add data from other MRIO databases and data sources to further improve the quality and resolution of the R-MRIO database (see Section 6.4 on the limitations and outlook). In addition, ref[47] was limited to the emissions embodied in bilateral trade approach, which does neither allow to assess scope 3 impacts of sectors and regions nor to analyze the supply chain of a region's footprint as illustrated by the EU's water stress and biodiversity loss footprints in Chapter 3. Also, this thesis' database includes a set of impact categories, while Bjelle et al[47] covered only land use and related biodiversity loss[48].

Differences between the results of Bjelle et al[48] and Chapter 3 are shown in Figure 6.5 for land-use related biodiversity loss. While the global extinction rate found here (~11% global pdf*year in 2015) is in the range of previous estimates[52-54], the global extinction rate of ref[48] (~400% global pdf*year in 2015) is almost 40 times higher compared to this thesis and previous estimates, and exceeds the maximum value of 100% (total global extinction) by a factor of four. The reason for this is that ref[48] is based on LC-IMPACT[55], where characterization factors (CFs) are on average 40 times higher compared to those used in this thesis (based on UNEP-SETAC[50] and Chaudhary et al[56], Appendix E.2: Figure E.2). Results of ref[48] also differ on a relative scale both from a country's production and consumption perspective with highest differences for small regions and islands due to higher data uncertainty (Figure 6.5). Differences also exist because ref[48] applied country average CFs from LC-IMPACT[55], while in this thesis, ecosystem level CF were applied on global crops production data modeled by Pfister et al[57] and aggregated to the region level of EXIOBASE3 (similar to Lutter et al[58]). Further differences are attributed to the underlying land use data: while land use data of Bjelle et al[47, 48] differ from EXIOBASE3, this study's land use data are consistent with EXIOBASE3 (when aggregated back to its original regional resolution). This explains the strong difference for Taiwan's domestic biodiversity loss, as explained in Chapter 3 for land use. Differences in consumption-based impacts are also attributed to differences in consumption and trade pattern due to the different approach applied to construct the database (see Chapter 3).

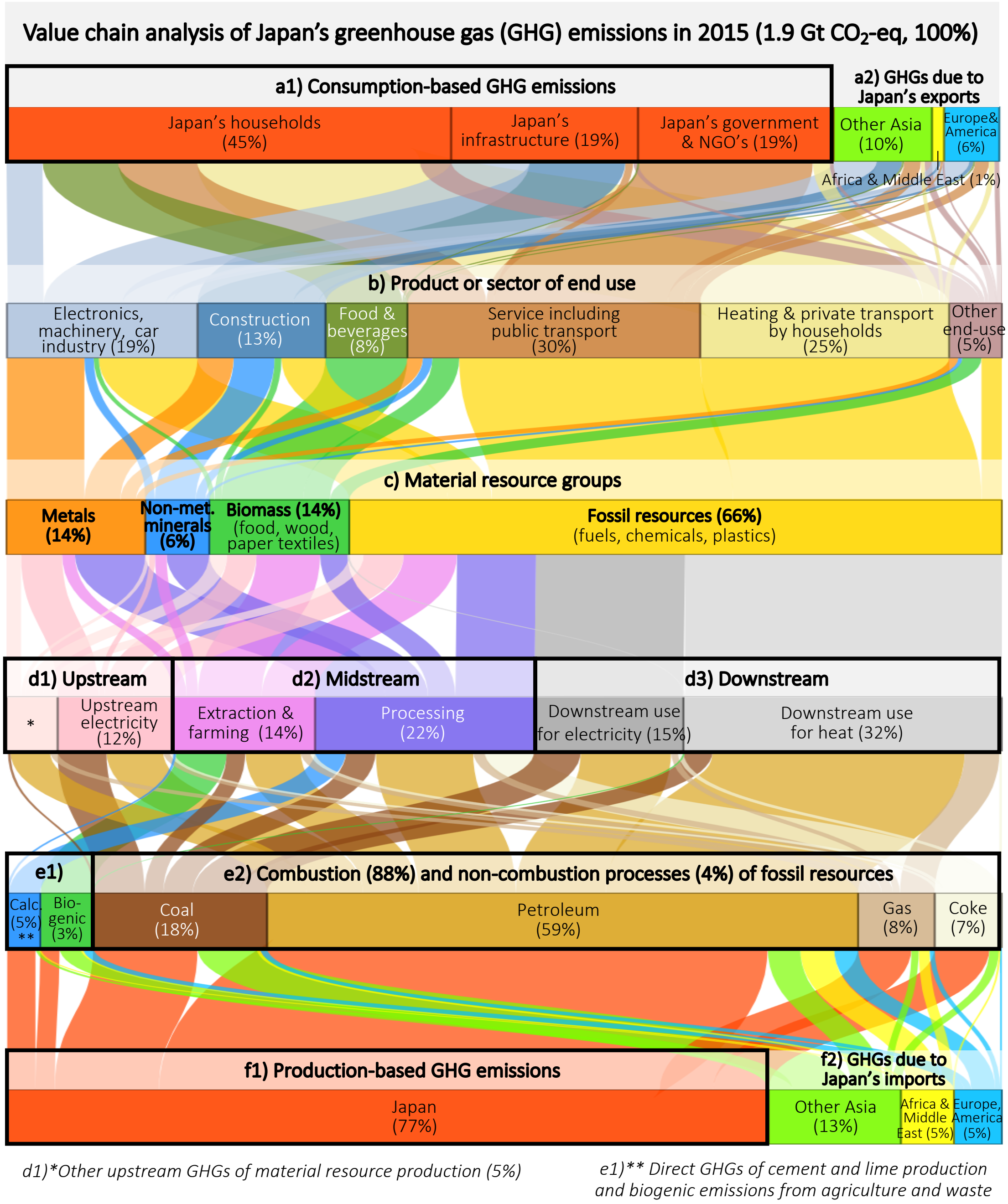

Figure 6.4. Value chain analysis of GHG emissions related to Japan's production, consumption, and trade of materials, including Japan's consumption-based GHG emissions (a1, carbon footprint) and Japan's domestic GHG emissions related to exports (a2) in 2015 (totally 1.9 Gt CO_2-equivalents, 100%). Each bar sums up to 100% and shows the GHG emissions from different perspectives in the global value chain, such as a) Japan's final demand category (households, infrastructure, government, and NGO's) and other regions where materials are finally consumed, b) the product or sector where materials are finally used for supplying final consumption, c) the four material resource groups, d) the split by upstream, midstream, and downstream emissions of material resources, e) the processes which release GHG emissions, and f) the regions where GHG emissions are released, which includes Japan's domestic GHG emissions (f1) and GHG emissions released abroad due Japan's imports (f2). This figure is also shown in Figure C.3 of the Appendix C.

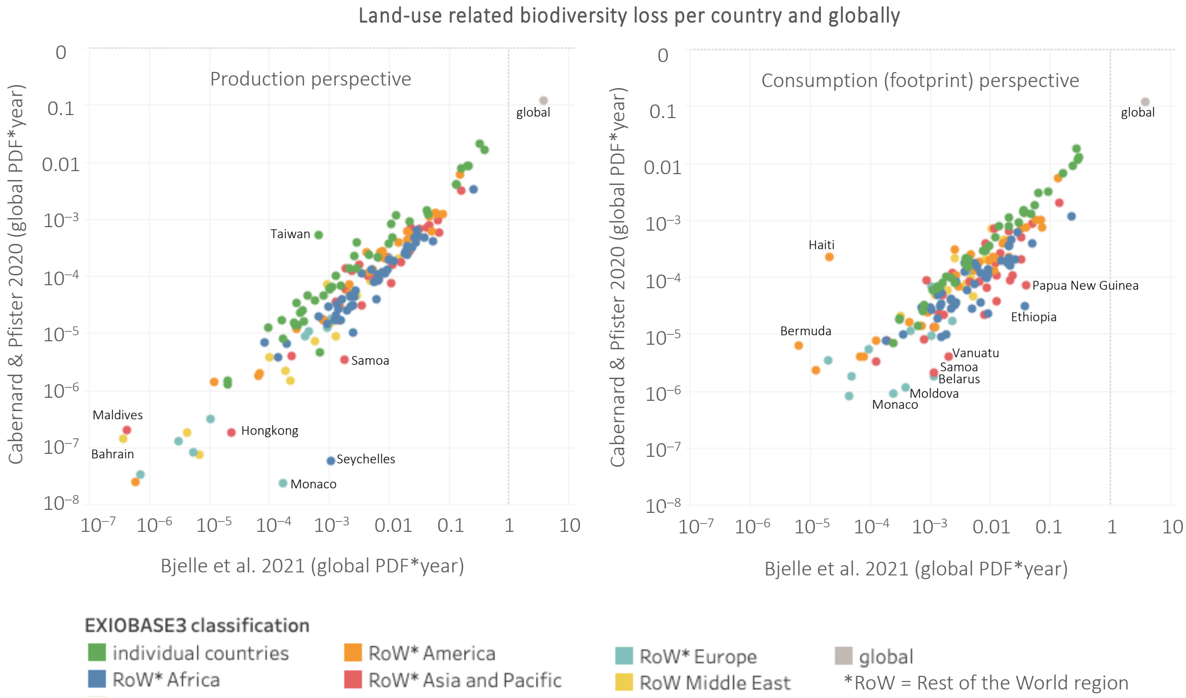

Figure 6.5. Comparison of land-use related biodiversity loss from a production and consumption perspective for all countries covered by the R-MRIO database of this thesis (Chapter 3) to Bjelle et al[48].

6.3 Practical relevance

The practical relevance of this thesis' methodology and database (>2700 downloads) has been underlined by its use for several reports of the International Resource Panel (IRP) of the UNEP[59-61], the Partnership for Action on Green Economy of five UN agencies[62], the European Commission's Knowledge Centre for Bioeconomy[63], and the Swiss Federal Office for the Environment[64], including requests from the G20 presidency[59]. Moreover, this thesis' findings were cited by the Swiss Federal Council[65], taken up in the UNEA guidelines[66], and made headlines in the *nature* highlights[67], a study in *nature geoscience*[68], the Guardian[69], the Independent[70], SRF Wissenschaftsmagazin[71], the World Economic Forum[72], GEO[73], Tagesanzeiger[74], Blick[75], and many other media[76-92]. Also, this thesis' methodology and database were applied in two co-authored studies for assessing the environmental impacts of information and communication technologies[93-95] and Swiss mobile phones[96]. This section summarizes the main findings and highlights the resulting policy implications of these reports and studies. In addition, this section summarizes the relevance of this thesis' software tool for analyzing the sustainability performance of global value chains to provide science-based decision support for policy makers and industry (RG and Obj. 7).

6.3.1 Policy implications for sustainable materials production and consumption

The methodology and impact assessment of Chapter 2 has been applied to assess the environmental impacts of natural resource use in the Global Resources Outlook of the IRP[61]. A key result was that the extraction and processing of material resources accounts for half of global GHG emissions and more than 90% of global water stress and biodiversity loss, which was cited by the Swiss Federal Council[65], made headlines in the Guardian,[69] and was taken up in the UNEA guidelines[66] on innovative pathways to achieve sustainable consumption and production. It was further shown that the environmental impacts of materials production have increased over the past two decades, pointing to the importance of sufficiency instead of (only) decoupling measures. Another key conclusion was that material resources were mainly used for private consumption in high-income regions, while they have been used to build infrastructure in emerging economies, thus highlighting importance of material-efficient design and substitution of high impact materials to mitigate the environmental impacts of the expected infrastructure growth in developing regions.

Upon request of the G20 presidency, the results of the Global Resources Outlook[61] were downscaled for all G20 member states[59] by using the methodology from Chapter 2 and the database from Chapter 4. The objective of the analysis was to investigate status, trends, and solutions in natural resource use and the associated environmental and socioeconomic impacts of the G20. The factsheets present an in-depth analysis for all G20 member states, and complement the synthesis on the G20's material resource value chains and the related environmental and socioeconomic impacts of Chapter 4. In a follow-up project, the same factsheet was prepared for Poland[60]. Also, another IRP report on natural resource use in West Asia is currently under preparation, using the method and database from Chapter 2 and 3.

The method of Chapter 2 has been applied in a study on the carbon footprint of materials[68] published in *nature geoscience*. Other than Chapter 2, the study focuses on structural materials (e.g., metals, cement, wood, textiles, paper), excluding food and fossil fuels. The study provides an in-depth analysis on the global carbon footprint of structural materials and their downstream use by construction, machinery, electronics, and other industries. It confirmed the results of Chapter 2 that the carbon footprint of structural materials has been driven by building infrastructure in emerging economies, particularly China.[68]

6.3.2 Policy implications for national policy assessment schemes

In a UNEP's report on Green Economy Progress (GEP)[62], the database of Chapter 3 has been used to add carbon, water stress, and biodiversity loss footprints to the GEP framework. This improvement is of particular importance, since the UNEP's GEP Framework aims to provide environmental indicators to facilitate cross-country comparisons of national efforts towards greener economies[97, 98], but was limited in consumption-based accounting and regionalization in water and land impact assessment. The need for these improvements was also highlighted by the case studies of this thesis (Chapter 2–5), showing that many high-income regions, such as the EU, strongly rely on imports of materials, food, and fuels from lower-income regions, which was neglected in the previous version of the GEP framework.

The importance of the EU's reliance on food imports was further highlighted in a report on future transitions of the EU's bioeconomy towards sustainable development by the European Commission's Knowledge Centre for Bioeconomy[63]. In this context, the method of Chapter 2 and results of Chapter 4 were used to provide an overview on the international dimension of the EU's bioeconomy. The analysis showed that more than one-third of the overall biomass input to the EU bioeconomy is imported, pointing to the EU's strong reliance on imports

(Figure 6.6). The results on biodiversity loss and employment effects of the EU's bioeconomy provided an overview on the trade-offs in sustainability between the EU and other regions. It showed that most biodiversity loss is caused outside the EU due to imports of mainly cattle meat and oil seeds (Figure 5 of ref[63]), as analyzed in detail in Chapter 3. The employment effects pointed to the EU's reliance on low-paid workforce for food imports, particularly vegetables, fruit, and nuts (Figure 6 of ref[63]). These results underline the need for expanding current national policy assessment schemes, e.g., the EU's Green Deal[99, 100], from production-based to consumption-based accounting to account for supply chain impacts due to trade.

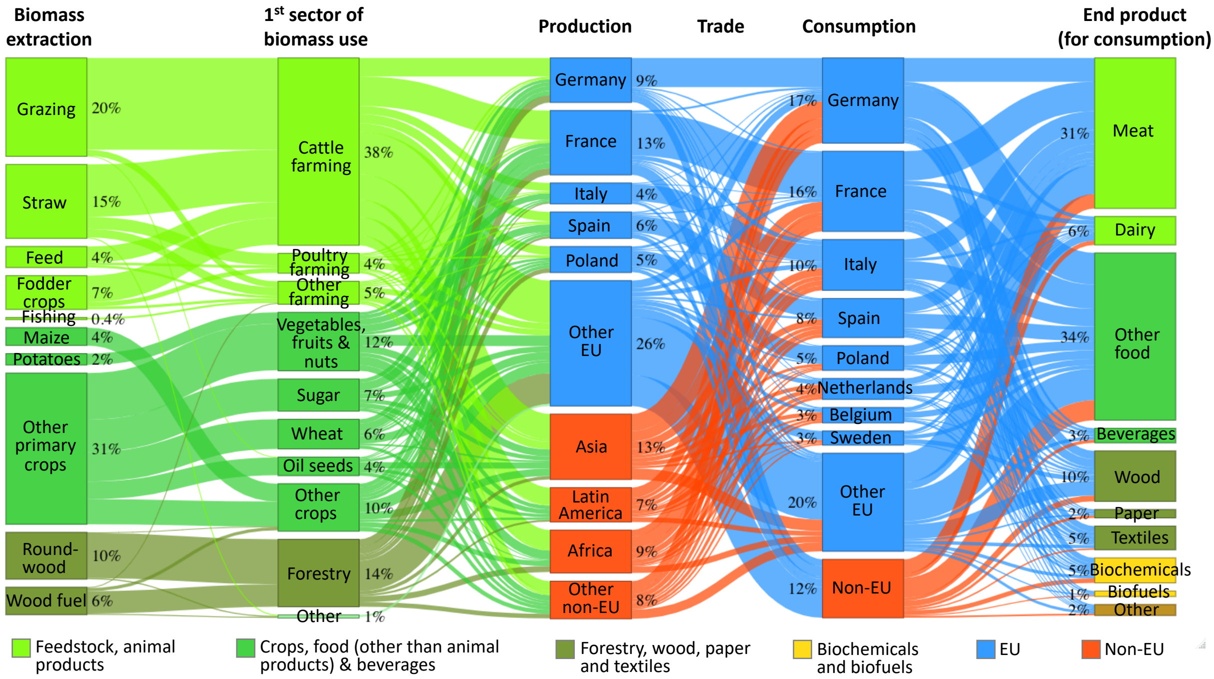

Figure 6.6. Flows of the EU's domestic, imported and exported biomass in 2015 based on the method of Chapter 2 (Figure 3 in a report on the EU's bioeconomy[63]).

6.3.3 Policy implications for the ICT sector

In a review on the carbon footprint of information and communication technology (ICT)[95], the method from Chapter 2 has been applied to assess the carbon footprint of ICT manufacturing for the past and future, using the same climate change scenarios[101, 102] as in Chapter 5, which made headlines in the Independent[70] and other media[88, 103]. The study showed that the carbon footprint of ICT manufacturing reached 1.1 Gt CO_2-eq in 2015 and is projected to reach 1.16 and 1.64 Gt CO_2-eq in 2030 if the world implemented the IEA measures for a 2-degree and 6-degree scenario, respectively[95]. It further revealed that 60% of the carbon footprint of ICT manufacturing was caused in China in 2015[95]. Based on these results, it was concluded that previous estimates all systematically underestimated the carbon footprint of ICT both for the past and the future, possibly by as much as 25%, due to the same reasons explained in Section 6.1.1: On the one hand, previous estimates did not account for the full scope 3 emissions of ICT manufacturing as done in this thesis. On the other hand, they calculated with the global mean energy mix and thus neglected the increased reliance on coal due to the shift of ICT production to China, similar as shown for plastics in Chapter 5.

The method of Chapter 2 was further applied to analyze the role of material resources in ICT. The results have been presented at the LCA forum[93] on digital transformation and were summarized in a co-authored study of Itten et al[94]. The analysis shows that over the past two decades, the material footprint of ICT manufacturing has quadrupled, while the related carbon footprint has doubled[94]. It further shows that out of the 1.1 Gt CO_2-equivalents released by ICT manufacturing in 2015, more than half was attributed to the production of materials. It concludes that efficient environmental policies should tackle materials like iron, steel, plastics and chemicals, which contribute half of the material-related impacts of ICT manufacturing. Similar to the case studies of this thesis, the study showed that high-income regions, such as the USA, EU, and Switzerland, outsource the vast majority of the material-related impacts of ICT manufacturing (mainly to China) and rely on low-paid labor abroad (mainly Asia), but generate most of the value added domestically. Thus, the study points to the importance of improved supply chain management for high-income regions in the ICT sector[94].

6.3.4 Policy implications on urban mining

One incentive to reduce material-related impacts of ICT in Switzerland has been investigated in a collaborative study[96] with Antoinette van der Merwe from the Swiss Minerals Observatory[104] at the Institute of Science, Technology and Policy (ISTP). The aim of the collaboration was to elaborate if the mail-back postage method applied to collect Swiss retired mobile phones is cost-effective to increase recycling rates of Swiss mobile phones if a) only the market price of metals is considered and if b) also the external costs of primary metals are considered. The external costs of metals embodied in a Swiss mobile phone were calculated by combining the life-cycle inventory database *ecoinvent*[105] with the highly resolved MRIO database from Chapter 3 (based on the method from Chapter 2), and by monetizing the environmental impacts with factors identified by Galgani et al[106].

The analysis revealed that the external costs of metals embodied in a Swiss phone are more than ten times higher than the current market price of these metals (CHF 17.86 vs CHF 1.62, Figure 6.7). The external costs are mainly attributed to the impacts related to metal depletion, freshwater eutrophication, and human toxicity, while the other eleven considered impact categories contribute to a minor fraction. Despite the low amount of gold embodied in a phone, gold contributes to the largest share of both the market value of metals in a phone (CHF 1.47) and the external costs (CHF 13.92). In addition to gold, tin contributes considerably to the external costs due to metal depletion. The supply chain analysis of metals embodied in Swiss phones reveals that about 60% of the external costs occur in North America, Asia and the Pacific, since most of gold and tin were mined in these regions. Since no metals are mined in Switzerland, no external costs occur in Switzerland.

The study concludes that the mail-back postage method is only cost-effective if the external costs were taken into account. The study further shows that extrapolating the external costs to the 6.4 to 7.1 million old cell phones estimated to be stored unused in Swiss households, the value of embodied metals would be CHF 124 to 138 million if both the market price and external costs were considered. These results highlight the need and economic potential of future policies that internalize the external costs of primary metals production into the end-price of mobile phones to incentivize their recycling.

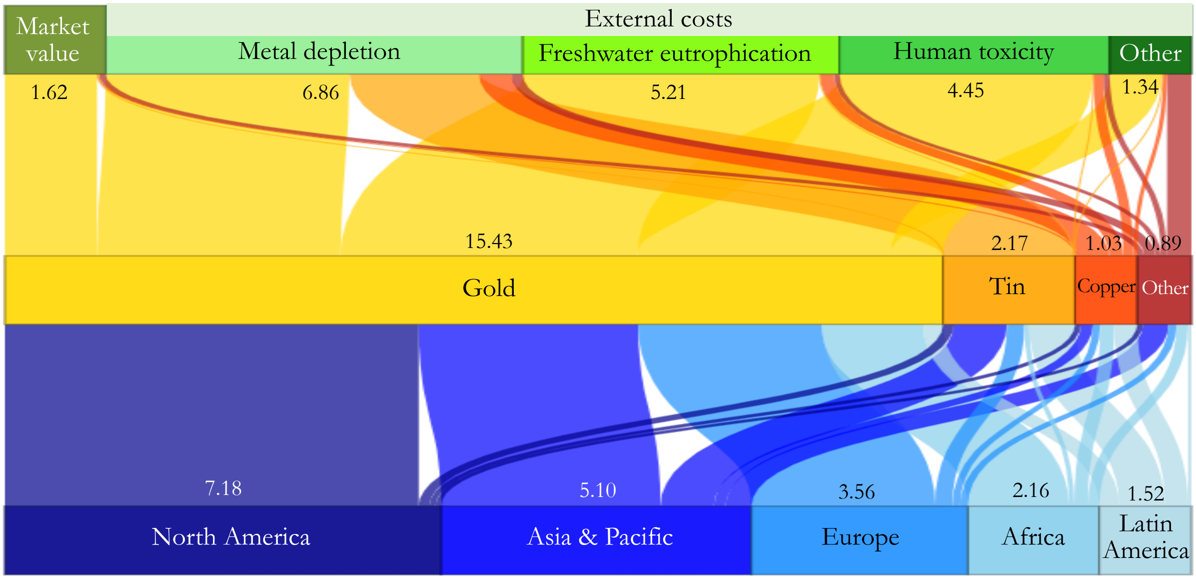

Figure 6.7. Total external costs (in CHF) of metals embodied in an average Swiss mobile phone. The total market value is CHF 1.66 and the total external cost is CHF 17.86 (Figure 1 in van der Merwe, Cabernard and Günther[96]).

6.3.5 Policy implications for Swiss plastics consumption

This thesis' findings on the growing carbon footprint of plastics (which was shown to be higher than expected due to the shift of plastics production to coal-based economies, Chapter 5), made headlines in the *nature* highlights[67], SRF Wissenschaftsmagazin[71], the World Economic Forum[72], GEO[73], Tagesanzeiger[74], Blick[75], and many other media[76-87, 89-92]. Moreover, the results on the environmental footprint of plastics have been downscaled to the case of Switzerland for a postulate report on plastics by the Swiss Federal Office of the Environment (under preparation)[64]. It shows that over the past two decades, Switzerland's carbon and PM health footprint of plastics has increased by 45% and 62%, respectively (Figure 6.8). In 2015, Switzerland's plastics related carbon footprint reached 6 billion tons of CO_2-eq and 6'500 DALYs, contributing to 5% of Switzerland's total carbon footprint and 4.5% of Switzerland's total PM health footprint.

The breakdown by life cycle phases shows that 70% and 85% of Switzerland's carbon and PM health footprint of plastics, respectively, are attributable to primary production of plastics, while product manufacturing, recycling, and incineration, account for a smaller share (Figure 6.8). In primary production, two-thirds of the emissions are released through the provision of heat and electricity, and a smaller share is due to the extraction and processing of fossil resources, transportation, and other upstream activities. The main reason for Switzerland's rising carbon and PM health footprint of plastics is the increase in consumption and shift of plastic production to Asia, especially China, where most energy for the production of plastics is provided by coal. As a result, 85% and 95% of Switzerland's carbon and PM health footprint of plastics, respectively, was generated abroad in 2015, more than half of it in Asia.

In accordance to Chapter 5, the report finds that previous studies have underestimated the relative significance of the production versus the disposal phase of plastics, and thus the strong leverage to reduce the carbon (and PM health) footprint of plastics by renewable energy investments. The analysis shows that implementing the measures proposed by the IEA for a 2-degree scenario[101, 102] would reduce Swiss plastics consumption by 10% and associated GHG emissions by 40% from 2015 to 2030. In addition to enhanced reducing, reusing and recycling of plastics, investing in clean energy production in the plastics supply chain abroad, such as in China, is thus an efficient measure to reduce Switzerland's carbon and PM health footprint of plastics (similar to other high-income regions, such as the EU and the USA, as discussed in Chapter 5).

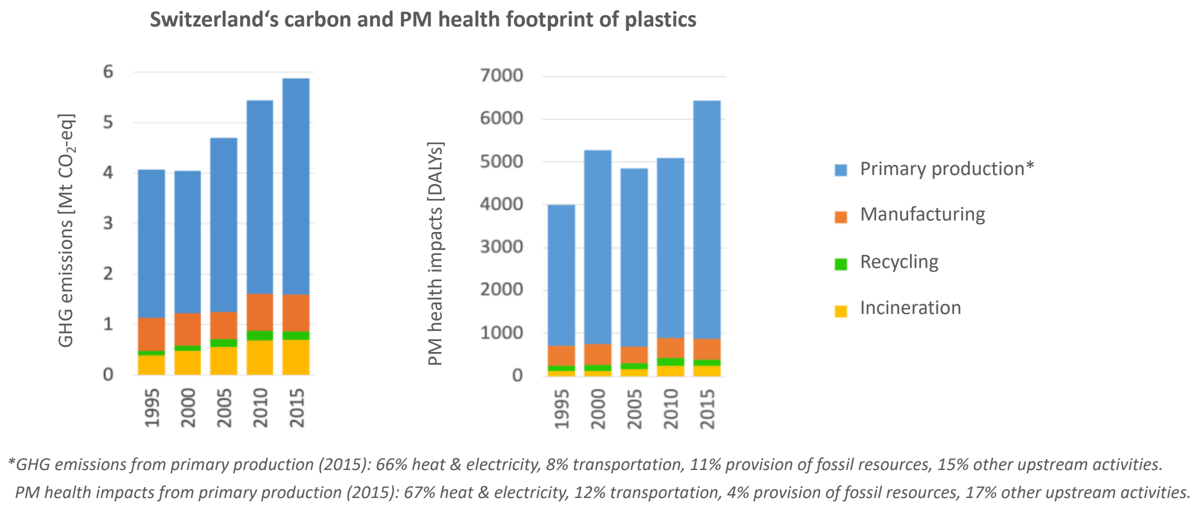

Figure 6.8: Swiss carbon and PM health footprint of plastics divided by key life cycle phases from 1995 to 2015 (Figure 2 in a postulate report on plastics[64] by the Swiss Federal Office of the Environment).

6.3.6 Software tool for science-based decision support for policy makers and industry

The methodology of Chapter 2 is provided as an open-source software tool[1]. Other than the UN's Sustainable Consumption and Production Hotspot Analysis Tool[107], which is restricted to standard production and consumption-based accounting and limited in the indicator set, this thesis' software tool allows assessing the total scope 3 impacts of any industries and economies, mapping the upstream, midstream and downstream value chain, while covering a cutting-edge set of environmental and socioeconomic indicators. The tool can be applied by researchers, industries, policy makers, and NGOs to assess the environmental and socioeconomic impacts of sectors, products, and countries in detail, such as locating the hotspots and leverages in the global chain to derive efficient policies for sustainable development. One application example is the report of Winkler et al[108], where this thesis' software tool was used to assess and track the scope 3 GHG emissions of the United Kingdom's economy. Based on the analysis, the study highlighted the limitation of standard production and consumption-based accounting and the need for future policies that account for the total scope 3 impacts of industries and economies (Figure 1 and 2 of ref[108]). Another example is the study of Tavora and Pereira[109], where this thesis' software tool was applied to analyze the environmental and socioeconomic impacts of Brazil's food and beverage industry. The study concludes that this thesis' methodology can "help integrate water, energy and food, resources into national policy decision-making processes, allowing the identification of negative impacts that should be avoided or mitigated, as well as positive impacts that should be encouraged".

6.4 Limitations and Outlook

Since the comparison with literature showed that previous approaches either under- or overestimated scope 3 impacts for most target industries and economies (see e.g., Figure 6.1), this thesis' methodology can be applied by researchers, industries, and policy makers for a more meaningful scope 3 impact assessment of various commodities, industries, and nations (link tool)[1]. This allows to identify hotspots in the global value chain for efficient sustainability policies, as shown in this thesis by several case studies (Chapters 2–5). Furthermore, this thesis' methodology allows calculating scope 3 impacts both including and without double counting. The derived double counting factor might be used by future work as a measure for the circularity between sectors and regions (Chapter 2).

Future work can also use this thesis' methodology and database (link database) to assess and track the scope 3 impacts of companies upstream and downstream the global value chain, if a company represents a major share of a nation's industrial sector covered in the database (e.g., the SBB for the Swiss railway sector). This is currently done by the startup GreenFo[110]. Together with economic incentives, such improved transparency would allow individual companies to benefit from increased consumer demand for green products and services[111]. However, as this thesis' database is limited to the national level, further work is needed to improve the data quality for those companies that represent a lower share of a nation's industrial sector, such as by the integration of company data into the MRIO database. Also, further improvements are needed for those companies located in countries with limited resolution in EXIOBASE3 (see also Section 6.2.1).

Unlike the scope 3 impact assessment, which can be applied to any sector, region, and impact category of an MRIO database, the downstream approach of this work allows attributing GHG emissions and PM health impacts to the material resource causing the emissions. These are mainly fossil fuels for combustion. In addition, it can be applied for linking downstream impacts of fossil fuels to the region where they were extracted (e.g., coal mined in Indonesia, which is burned to generate heat and electricity for plastics production in China, and thus releases GHG emissions in China, see Chapter 5). However, further work is needed to better distinguish between fossil resources used as fuel and feedstock for plastics production (e.g., to investigate the use of coal as a feedstock for plastics production, such as in China[112] and South Africa[113], which could not be clearly distinguished from the use of coal as a fuel in this thesis). Similarly, and especially in view of the future energy transition, further work is also needed to distinguish GHG and PM emissions of wood and other biofuels, which have been allocated to fossil resources in this thesis's downstream approach (see e.g., Figure 6.2).

While the methodology of this thesis allows for a more meaningful assessment of the scope 3 impacts of any sector and region of any MRIO database, the results are only as reliable and accurate as the quality and the spatial, sectoral, and temporal resolution of the underlying database and impact assessment. Despite the improvements addressed in this thesis (e.g., Section 6.1.2), there are many limitations in the quality and resolution of the database and impact assessment. These limitations are outlined in the following and discussed in the context of future work and related ongoing projects.

6.4.1 Quality and resolution of the MRIO database

In contrast to Bjelle et al[47, 48] and current MRIO databases (EXIOBASE3[25], Eora26[30], GTAP), this thesis' database was not balanced by matrix balancing calculations, but by calculating the residual value added as done for the GRAM database[28, 29]. When comparing these two approaches, Wiebe and Lenzen[114] found differences in the results, but it was not clear which approach leads to superior results. This thesis' approach has the benefit that it alters the data as little as possible and keeps the calculation traceable[28, 29, 114]. It was further shown that the level of detail and the reliability of the underlying data have a stronger effect on the results than the balancing approach[114, 115]. This highlights the need for caution when analyzing the results of countries aggregated as rest of the world (RoW) regions in EXIOBASE3, which underlie higher data uncertainty[30, 116]. The reason for this is the lack of IO tables for many small and/or economically less developed countries. This points to the need for future work to improve the data quality in these countries.

To improve the data quality for the RoW regions, future work can apply the approach from Chapter 3 to add more information to the highly resolved MRIO (R-MRIO) database. This information can be integrated from other MRIO databases, such as GTAP[32], which has a higher regional and sectoral resolution than EXIOBASE3 and Eora26, respectively, or the Food and Agriculture Biomass Input−Output (FABIO) Model[117], which covers 191 countries and 130 agriculture, food, and forestry products in physical units. In addition, data can be integrated from national input-output databases and other data sources. For example, data from the British Geological Survey (BGS) can be integrated to enhance the data quality of metals and mining sectors (as it was done for the biomass sectors in Chapter 3). Similarly, data from comtrade can be integrated to improve bilateral trade data for various commodities.

Future work is also needed to improve the sectoral resolution of the R-MRIO database, which is currently limited to 163 sectors (based on EXIOBASE3). Although another version of EXIOBASE3 with a higher resolution of 200 products exists and was used in Bjelle et al[47, 48], this version has several limitations, such as the lack of data on recycling and several gaps in the environmental inventory data. Improvements in the sectoral resolution of the R-MRIO database are particularly important for metals, since many metals, which play a key role for the energy transition (e.g., lithium and cobalt), are aggregated as a single group in EXIOBASE3. Several limitations also hamper an analysis of global gold trade: One limitation is that gold is aggregated with silver and platin group metals (PGM) in the precious metals sector of EXIOBASE3. Another limitation is that, although two-thirds of global gold are refined in Switzerland, Swiss gold trade is not included in current MRIO databases. While data on large-scale gold mining and trade could be integrated from BGS and comtrade (based on the approach of Chapter 3), there are almost no data on refined gold quantities, as well as on artisanal small-scale mining. Moreover, data on Swiss gold trade is only available since 2012, and there are many inconsistencies and gaps for the period afterwards, some of which are the result of illegal gold mining and trading. Furthermore, there is a lack of a financial sector in current MRIO databases.

To improve the quality and resolution of this thesis' R-MRIO database for metals and to evaluate the role of Switzerland in global gold trade, a second version of the database, called R-MRIO database II, is currently in preparation in a collaborative study with Désirée Ruppen of the Swiss Minerals Observatory[104] at the ISTP. In a first step, the collaboration aims to improve the quality of the database by integrating the GTAP10 database[32], mining and metals processing data from the BGS, and bilateral trade data from comtrade, following the approach of Chapter 3. In a second step, the collaboration aims to disaggregate the precious metals mining and refining sectors into gold, silver, and PGM, respectively. For a material flow analysis, considering the ore grades and purities of mined and traded gold, silver, and PGM, is applied to fill the gap in refined quantities at the country-level. Applying the method from chapter 2 to the R-MRIO database II will allow to map the Swiss gold value chain, similar to the example shown in Figure 6.9 for Swiss copper trade. The results will be compared with current gold statistics and reports to identify specific gaps and limitations in current reporting of (Swiss) gold trade.

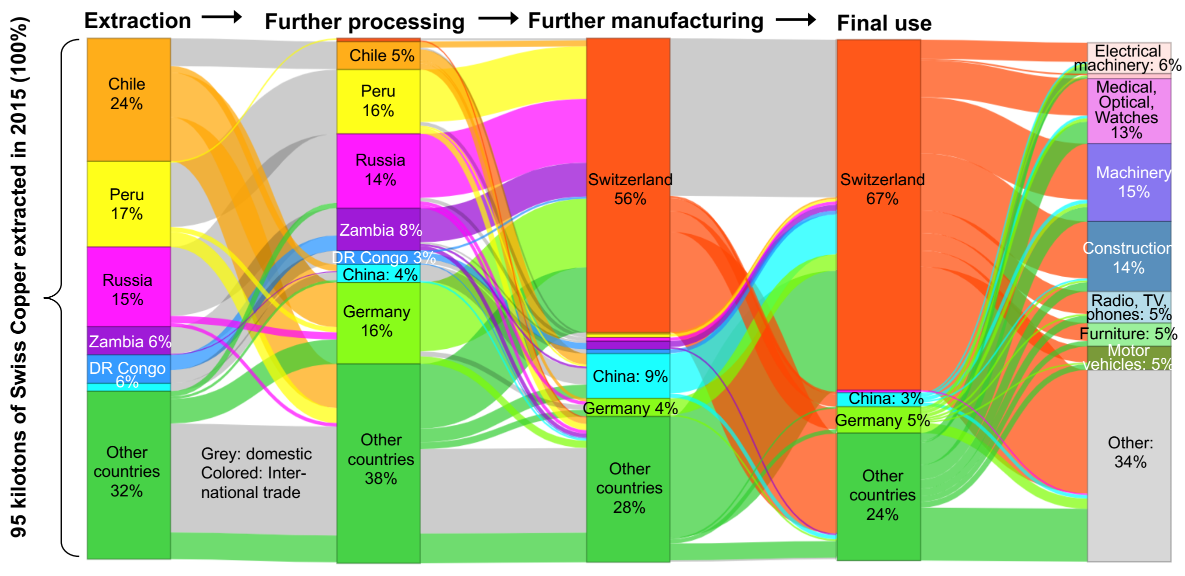

Figure 6.9. Value chain analysis of copper traded and used by Switzerland in 2015, calculated with a preliminary version of the R-MRIO II database, building on the database of Chapter 3 and using the method from Chapter 2.

Since this thesis' R-MRIO database is limited to the country level, it does neither allow for an in-depth analysis of those companies that represent a lower share of a nation's industry, nor for specific regions, cities, and towns within a country. Therefore, further work is needed to improve the spatial resolution of the global MRIO database at the national and company level. While many national MRIO tables with high spatial and sectoral resolution have been constructed, such as for Australia[118], China[119], Japan[120, 121], the USA[122, 123], and Switzerland[124], a link to a global MRIO database like EXIOBASE3[25] is lacking. For example, Froemelt et al[124] have developed a spatially resolved MRIO database for Switzerland by combining a highly detailed bottom-up model for Switzerland with top-down macroeconomic approaches. The database called SwissLab distinguishes 794 sectors for 2352 regions corresponding to all municipalities in Switzerland. However, SwissLab has the limitation that it aggregates the rest of the world as a single region. This is a severe drawback since most of Switzerland's carbon, water stress, and biodiversity loss footprint is generated abroad (based on the results of this thesis). Therefore, future work is needed to link national MRIO databases, such as SwissLab, with this thesis' global R-MRIO databases, similar as done for Australia's wine industry by creating nested MRIO tables to link local impacts to global consumption drivers[125]. To address this gap and combine the complementary benefits of the global R-MRIO database and SwissLab, the two databases are linked in a master thesis of Niklaus Brunner, using the methodology of Chapter 2. The resulting database enables for a detailed global environmental footprint analysis of Swiss cantons, cities, and cantons. Also, combining highly detailed bottom-up models with top-down macroeconomic approaches, as done by Froemelt et al[124], should be considered to further improve the quality and resolution of this thesis' database. As this thesis' MRIO database is based on monetary values, future work might also construct hybrid MRIO database, as done in Ye et al[126] (by hybridizing China's physical biomass system with monetary supply chains).

Limitations also exist with respect to the temporal resolution and coverage of this thesis' database. The database is limited to the time span from 1995 to 2015 on an annual basis and data from 2012 to 2015 underlie high uncertainty due to now-casting. Future work should improve the now-casted time span by integrating current data, as well as create MRIO tables that cover the time span to the present. This would allow to examine the effects of current national and international environmental policies and agreements (e.g., Paris Agreement), recent trade wars (e.g., USA vs. China), and the Corona pandemic on the environmental impacts of global value chains. Further work is also needed to address interannual fluctuations, which is particularly relevant for Swiss gold trade, where data fluctuate widely on a monthly basis. One approach to improve temporal resolution in MRIO analysis is the Sequential Interindustry Model, which allows the static framework of MRIO analysis to be transformed into a dynamic process by integrating production data to account for sudden changes, such as natural disasters[127, 128]. Further work should also improve future scenarios in MRIO analysis, since the climate change scenarios used in Chapter 5 are limited to the energy investment measures proposed by the IEA[101, 102]. For example, these scenarios did not account for the expected exponential growth in plastics production, as discussed in the case study on plastics (Chapter 5).

6.4.2 Environmental assessment

Many limitations exist regarding the impact assessment of this thesis. Concerning climate change impacts, one limitation of this work is that GHG emissions associated with land use change, such as wildfires, droughts, and changing ecosystems (which are accelerating due to climate change), are not considered[11]. Another problem is that methane emissions from shale gas extraction are vastly underestimated in general[129]. Although data on GHG emissions from land-use change and shale gas extraction are highly uncertain, they may become more available in the future through remote sensing monitoring of these emissions[130, 131]. Therefore, future work may integrate remote sensing data on GHG emissions from land use change and shale gas extraction to improve the climate change impact assessment in MRIO databases.

The health impact assessment of this thesis is limited to outdoor PM emissions ($PM_{2.5}$, NO_x, SO_x, and NH_3) and therefore neglects indoor PM emissions. Outdoor PM emissions are the largest contributor to global PM health impacts (since 2008)[132], have increased over the past decades, and are accelerated by international trade (as shown in this thesis). Although indoor PM emissions have decreased over the past decades[132] and occur locally, future work should include indoor PM emissions in global MRIO databases to provide a complete picture of total PM health impacts. Future work is also needed to improve this thesis' health impact assessment of outdoor PM emissions to better account for regional variability, temporal changes, and human exposure (e.g., population density around emission sources). The health impact assessment of this thesis is based on PM emissions from EXIOBASE3[14] and the impact methodology from UNEP-SETAC[50, 133] (Chapter 2–4). In Chapter 5, emissions were scaled with fuel and region specific PM health impact factors based a on a global coal emission inventory[134] in combination with a highly resolved regionalized PM health impact assessment methodology[135] to allocate PM health impacts to the type of fuel combusted. Future work could integrate this high-resolution global coal emission inventory dataset[134] into the R-MRIO database and improve the impact assessment by using the regionalized PM health impact assessment method from Oberschelp et al[135] rather than just scaling it, as was done in Chapter 5.

This thesis' water and land impact assessment is limited particularly for mining sectors. One reason is that mining-related water and land use data are hardly available. Another reason is that the mining-related water and land impact assessment was based on country average annual CFs[50, 56, 136]. Concerning water, a better estimate might be the production-weighted water use CFs from Northey et al[137], which have been developed for 25 minerals based on the spatial distribution of global mine production[138] across watersheds and nations, using the water stress index from Pfister et al[139]. However, one limitation of Northey et al[137] is that the spatial distribution of minerals production might not be a reasonable proxy of the spatial distribution of water use due to strong variability in water use requirements of mining operations (even for the same commodity)[140-142]. Thus, further research is needed to gather inventories on mining-related water and land use data on a global scale and to develop country-specific CFs for mining sectors. These CFs should take into account the spatial distribution of mining-related water and land use, local water scarcity[139], and vulnerability of ecosystems, as was done for agriculture and forestry in ref[50, 55, 56, 136].

A global-scale data set of mining areas has been compiled only recently based on satellite images[143]. Linking this global-scale data set of mining areas with the SNL metals and mining database[138], the global ecoregions[144], and the biodiversity impact assessment from UNEP-SETAC[50] would allow for a more accurate assessment of global mining-related biodiversity loss. As part of the collaboration with the Swiss Minerals Observatory[104] at the ISTP, the new version of this thesis's database (R-MRIO database II, see Section 6.4.1) aims to address this gap to improve the global mining-related biodiversity loss impact assessment. The study aims to analyze trade pattern of global mining-related biodiversity loss and Swiss gold trade by applying the methodology from Chapter 2 to the improved R-MRIO database II.

Since Maus et al[143] manually compiled the global-scale data set of mining areas by the visual analysis of satellite images, this procedure was very labor-intensive. Consequently, it did neither allow to screen larger areas beyond active mines indicated by SNL metals and mining database[138], nor to detect illegal mining and evaluate temporal trends in mining-related land use. Thus, future work might develop an automated procedure for detecting mining areas based on satellite images. This could be achieved by the use of machine learning algorithms[145], similar as done by Saavedra and Romero[146] to detect illegal mining areas in Colombia, which could be trained using the global-scale data set of mining areas of Maus et al[143].

Another limitation of this thesis' land impact assessment is the time trend: In EXIOBASE3, land use declines after 2011 as data afterwards are now-casted[25]. Future work can address this limitation by adding land use data from FAOSTAT (similarly as done in Chapter 3, but instead of scaling land use data from EXIOBASE3, the data needs to be directly adopted from FAOSTAT). Another limitation is that the UNEP-SETAC[50, 147] land use impact assessment applied here does not account for intensification of pastures. However, intensification may have led to an increase in pasture-related biodiversity loss, which has been neglected in this work and other studies[48]. Thus, further research is needed to consider the level of intensification, particularly for pastures, but also for crops and forestry where only two levels of intensification were distinguished[50]. In this context, future work is also needed to account for extensive farming, such as organic agriculture and agroforestry.

Although land use is the largest contributor to global biodiversity loss[53, 148], other impact categories like climate change, water stress, acidification, ecotoxicity, and eutrophication also have negative effects on ecosystem health[50, 149-152] that were not considered in this thesis. Similarly, acidification, ecotoxicity, and eutrophication affect water quality, which was not covered by the water stress indicator of this thesis[153, 154]. Therefore, future research is needed that aims to incorporate these interactions into the R-MRIO database by adding further impact categories like eutrophication, acidification, and ecotoxicity. This could be addressed to some extent by integrating bottom-up life cycle inventories from *ecoinvent*[105]. However, future work is needed to improve spatial and temporal coverage of life-cycle inventories. One possibility might be the use of hyperspectral satellite data, which are expected to become more available in future[155-157]. Using machine learning algorithms, information from hyperspectral satellite data[158, 159] might be combined with measured environmental parameters (e.g., measured soil parameters around mining areas)[160-164]. This could enable the development of predictive models to monitor environmental parameters (e.g., heavy metal pollution and acidification in mining areas) that could be used to improve spatial and temporal coverage of life cycle inventories.

6.4.3 Socioeconomic impact assessment and monetization of external effects

While this thesis' approach to improve the resolution and quality of the R-MRIO database is suitable for analyzing environmental and social footprints such as workforce (with caution for RoW countries with high data uncertainty), it is not suitable for analyzing footprints of value added. The reason for this is that the value added was calculated as a residual to balance the R-MRIO database (see Chapter 3). Thus, further work is needed to model value added, as well as its components, such as taxes and compensation of workforce, on a high spatial and sectoral resolution. This is also important to extend the database for social LCA, since previous MRIO databases[25-32] and related studies[10, 165-168] are limited in the resolution and coverage of social indicators. The workforce indicator included in this thesis, indicating the full-time equivalents of employed people, addresses one aspect in social LCA. However, the workforce accounts were derived only from EXIOBASE3, since no workforce accounts are indicated by Eora26. Thus, the uncertainty is particularly high for RoW countries.

The integration of country and sector specific data on workforce, e.g. from the Social Hotspot Database[169], is an important step for improving workforce accounts and adding other social aspects, such as the risks that the workforce is exposed[61, 165]. This research gap was addressed to some extent in the Global Resources Outlook[61] by combining EXIOBASE3 with the Social Hotspot Database[169] to add a work risk factor (similar as done in Zimdars et al[165]). This work was followed by a project thesis[170] of Anita Ni who combined the R-MRIO database of Chapter 3 with the Social Hotspot Database[169]. In this context, 129 social risk indicators were implemented and grouped into five social impact categories, following a similar approach as Zimdars et al[165], but with higher spatial resolution. Applying the methodology of Chapter 2 to the socially extended R-MRIO database allowed to analyze the supply chain of social impacts related to Swiss metals consumption[170]. However, future work is needed to improve the resolution and data quality of the socially extended R-MRIO database. To this end, inventory data on social impacts need to be improved, especially in the mining and metals sectors, whose resolution is also limited in the Social Hotspot Database[169]. Moreover, future work is needed to integrate forced or illegal labor (modern slavery), as done in Shilling et al[171] for the MRIO database GTAP[32] based on data from the International Labor Organization[172] and Walk Free Organization[173].

In the collaborative study with Antoinette van der Merwe from the Swiss Minerals Observatory[104] at the ISTP, the external costs of metals embodied in a Swiss mobile phone were calculated by combining the life-cycle inventory database *ecoinvent*[105] with the highly resolved MRIO database from Chapter 3, and by monetizing the environmental impacts with factors from Galgani et al[106] (see Section 6.3.4). Although ref[106] also provides monetization factors for social impacts, the study[104] was limited to environmental costs, since data on social impacts of metals embodied in Swiss mobile phones are lacking. This points to the need for future research on social impacts in the metals supply chain of Swiss mobile phones. Another limitation is that the monetization factors of Galgani et al[106] are subject to high uncertainty, but a transparent documentation of the methodology and the uncertainties is currently lacking. In addition, the monetization factors refer to the global average and thus neglect regional variability (e.g., an impact in one region may differ from the same impact in another region). Moreover, the monetization is limited in the considered impact categories (e.g., the impact categories water stress and biodiversity loss were not addressed). There are several other LCA-based monetization methods[174-182] with different advantages and limitations in terms of indicator coverage, geographic scope, assumptions made, and consideration of uncertainties. When comparing these methods, it was found that the monetization factors of the same impact category usually differ by a factor of two, and in some cases up to a factor of five[182]. Thus, further research is needed to provide uniform monetization factors for various environmental and social impacts with high regional coverage and taking uncertainties into account.

6.4.4 Designing Sustainable Global Supply Chains

The work of this thesis feeds into a follow-up project of the Swiss Minerals Observatory[104] at the ISTP on designing sustainable global supply chains[183]. The interdisciplinary project aims to identify the origin of environmental and social impacts and ecosystem service trade-offs in global value chains. For this purpose, the work of this thesis is connected to ongoing research activities on sustainable trade and supply chains from several other ETH departments (D-BAUG, D-GESS, D-ITET, D-USYS). In this context, the interdisciplinary project aims to improve the resolution of the R-MRIO database for several key commodities, including gold, cobalt, lithium, and cocoa. In collaboration with the Institute for Spatial and Landscape Development, the project aims to combine the land-use related biodiversity loss impact assessment with ecosystem services, such as habitat for wildlife, clean water supply, and climate regulation[184-187]. Applying the methodology of this thesis to the extended R-MRIO database will allow mapping global supply chains and related ecosystem services in detail. Based on this, recommendations for increasing the sustainability of global supply chains will be derived for the Swiss and European markets.

6.5 References

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Appendix A

A new method for analyzing sustainability performance of global supply chains and its application to material resources

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A.1 Methods: Implementation of environmental indicators

Health Impacts. Direct emissions of particulate matters (PM) and precursor emissions of PM, including $PM_{2.5}$, NO_x, SO_x, and $NH_{3,}$ are indicated by EXIOBASE3 for each sector-region combination separately. To estimate the health impacts of PM emissions in the unit of disability adjusted life years (DALYs), we multiplied each type of PM emissions ($PM_{2.5}$, NO_x, SO_x, and $NH_{3,}$) with sector-specific characterization factors (in DALYs/kg). These sector-specific characterization factors were derived from UNEP-SETAC[1] and Fantke et al[2], who provide characterization factors for $PM_{2.5}$, NO_x, SO_x, and NH_3 emitted to different compartments (outdoor urban, outdoor rural, indoor urban and indoor rural) and in terms of $PM_{2.5}$ at different heights (ground level, low stack, high stack, very high stack). Since we cannot apply a distinction of emission locations according to population density in EXIOBASE3, we assumed for all material-extracting sectors outdoor rural emissions (with ground-level emissions for $PM_{2.5}$), while for material-processing sectors we built the average over outdoor rural and outdoor urban emissions. For the remaining economy we assumed the average of outdoor urban emissions.

Water stress. We summed up all types of blue water consumption listed by EXIOBASE3 to derive the total blue water consumption for each sector-region combination. Next, we multiplied this vector with sector and region-specific characterization factors to convert it into water stress (in m^3 of H_2O equivalents). For agricultural sectors, these characterization factors were derived by applying the UNEP recommended AWARE characterization factors from Boulay et al[3] on global agricultural water consumption data modeled on watershed and monthly level by Pfister and Bayer[4]. Next, we aggregated these characterization factors on the sector and region level of EXIOBASE3 as done in previous research for EXIOBASE2[5, 6]. This allowed us to derive sector-specific characterization factors for the production of rice, wheat, other cereals, oil seeds, sugar, fibers, other crops and the remaining agriculture for each of the 49 regions. For non-agricultural sectors, we aggregated the country average annual characterization factors of the AWARE method[3] to the 49 regions of EXIOBASE3. The resulting characterization factors are listed in the matlab folder under files/CF/CF_waterstress.txt (link).

Land-use Related Biodiversity loss. Different land-use types listed by the satellite matrix of EXIOBASE3, were multiplied with region-specific characterization factors to convert the land-use area into the associated global species loss using LCIA methods. For land-use by crops, we first applied the characterization factors from UNEP-SETAC[1] and Chaudhary et al[7] on global production of 160 crops modeled by Pfister et al[8] (~10 km x 10 km spatial resolution). Next, we aggregated the results in global species loss (global PDF years) according to the land-use types listed by EXIOBASE3 (namely cereals nec, other crops, fodder crops, oil seeds, paddy rice, fibers, sugar, vegetables, fruit and nuts, and wheat) and according to the region level of EXIOBASE3 (similar to Pfister and Lutter[6]). This allowed us to quantify the biodiversity loss (in global PDF years) related to each land-use type and for each region in the year 2000. Finally, we divided these results (in global PDF years) through the respective area of land-use type per region (in km^2) listed by the satellite matrix of EXIOBASE3 to derive the final region-specific characterization factors of each crop type and region (in global PDF years/km^2). For the remaining land-use types, such as intensive forestry, extensive forestry, pasture and urban land-use, we aggregated the country average characterization factors from Chaudhary et al[7] to the 49 regions of EXIOBASE3. The resulting characterization factors are listed in the matlab folder under Files/CF/CF_landuse.txt (link). We excluded the land-use type *'other land use'* since EXIOBASE3 does not specify the meaning of this type of land use. Since *'other land use'* is mostly occupied by households (>90%), its neglection hardly influenced our analysis (which relates to global material production and thus the economy).

A.2 Results

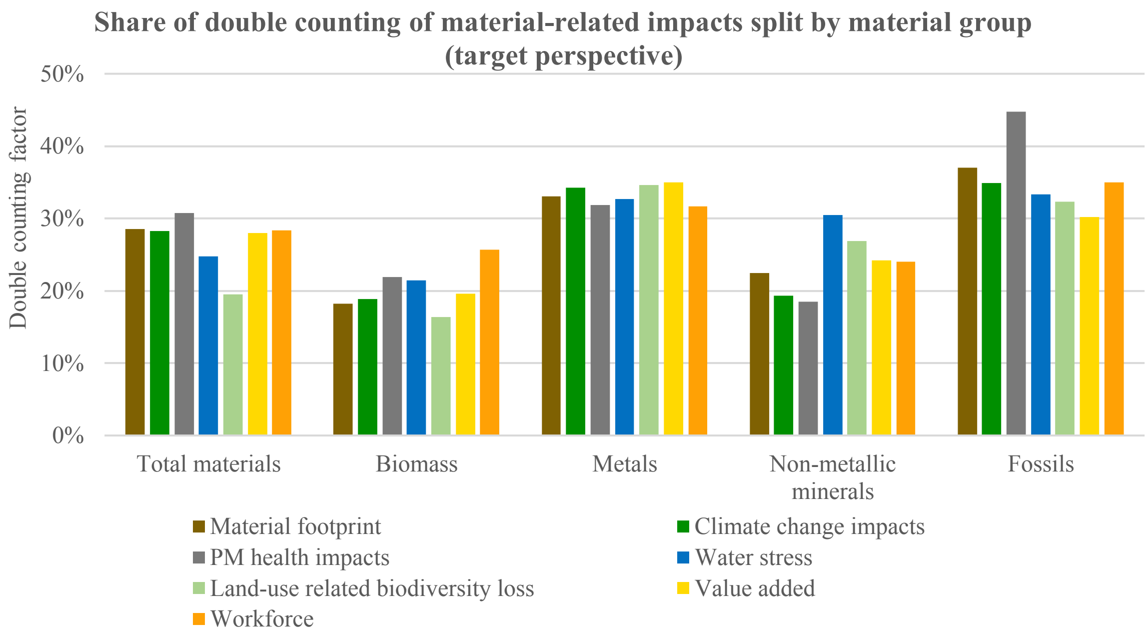

Figure A.1. Percentage of overestimation due to double counting per material group (target perspective) and impact category (Reference year: 2011).

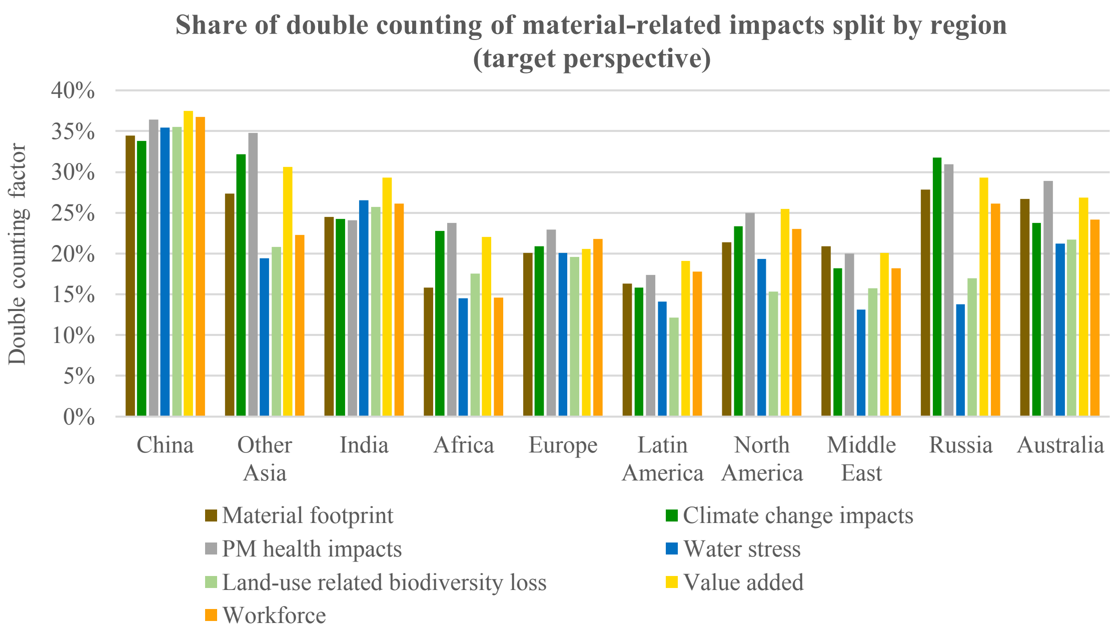

Figure A.2. Percentage of overestimation due to double counting per region (target perspective) and impact category (Reference year: 2011).

Table A.1. Percentage of overestimation due to double counting per material sector and impact category (Reference year: 2011).

75 Material sectors	Material Extraction	Climate Change	PM Health Impacts	Water Stress	Land-use related bio-diversity loss	Value Added	Workforce
Processing of meat cattle	12%	13%	12%	12%	14%	13%	11%
Processing of meat pigs	16%	17%	17%	15%	16%	15%	16%
Processing of meat poultry	30%	30%	30%	32%	26%	25%	34%
Production of meat products nec	23%	25%	25%	24%	24%	20%	23%
Processing vegetable oils and fats	38%	33%	33%	28%	39%	36%	33%
Processing of dairy products	14%	16%	17%	15%	12%	20%	15%
Processed rice	20%	22%	28%	20%	11%	18%	19%
Sugar refining	22%	21%	22%	24%	23%	24%	33%
Processing of Food products nec	21%	21%	22%	21%	17%	19%	27%
Re-processing of secondary wood material	15%	18%	22%	16%	12%	14%	15%
Pulp	24%	25%	25%	22%	23%	23%	24%
Re-processing of secondary paper	23%	25%	27%	25%	21%	23%	26%
Manufacture of coke oven products	75%	74%	80%	66%	68%	73%	66%
Petroleum Refinery	28%	27%	30%	31%	29%	25%	29%
Processing of nuclear fuel	56%	58%	58%	49%	54%	61%	57%
Plastics, basic	22%	29%	32%	21%	18%	19%	19%
Re-processing of secondary plastic	21%	21%	21%	21%	21%	19%	21%
N-fertiliser	38%	35%	42%	41%	29%	39%	38%
P- and other fertiliser	49%	50%	52%	52%	49%	49%	51%
Chemicals nec	39%	38%	39%	36%	33%	35%	38%
Manufacture of glass and glass products	44%	40%	43%	40%	37%	37%	36%
Re-processing of secondary glass into new glass	23%	24%	24%	24%	23%	24%	23%
Manufacture of ceramic goods	10%	9%	10%	10%	9%	9%	9%
Manufacture of bricks, tiles and construction products	8%	10%	9%	8%	8%	11%	9%
Manufacture of cement, lime and plaster	8%	10%	9%	8%	9%	12%	10%
Re-processing of ash into clinker	10%	13%	13%	9%	12%	15%	11%
Manufacture of other non-metallic mineral products	33%	36%	36%	37%	34%	30%	30%
Manufacture of basic iron and steel	34%	35%	33%	33%	35%	37%	32%
Re-processing of secondary steel	32%	35%	30%	30%	32%	34%	30%
Precious metals production	45%	48%	48%	47%	45%	47%	48%
Re-processing of secondary preciuos metals	46%	48%	51%	52%	53%	51%	52%
Aluminium production	32%	33%	32%	32%	32%	33%	31%
Re-processing of secondary aluminium	35%	37%	35%	33%	34%	37%	35%
Lead, zinc and tin production	36%	40%	37%	39%	40%	40%	39%
Re-processing of secondary lead	43%	41%	40%	41%	41%	41%	41%
Copper production	27%	28%	27%	25%	24%	28%	27%
Re-processing of secondary copper	41%	38%	43%	46%	46%	44%	43%
Other non-ferrous metal production	47%	49%	47%	46%	48%	47%	45%
Re-processing of secondary other non-ferrous metals	36%	37%	31%	39%	40%	37%	38%
Casting of metals	15%	13%	15%	15%	14%	13%	13%
Transport via pipelines	44%	51%	50%	44%	41%	47%	45%

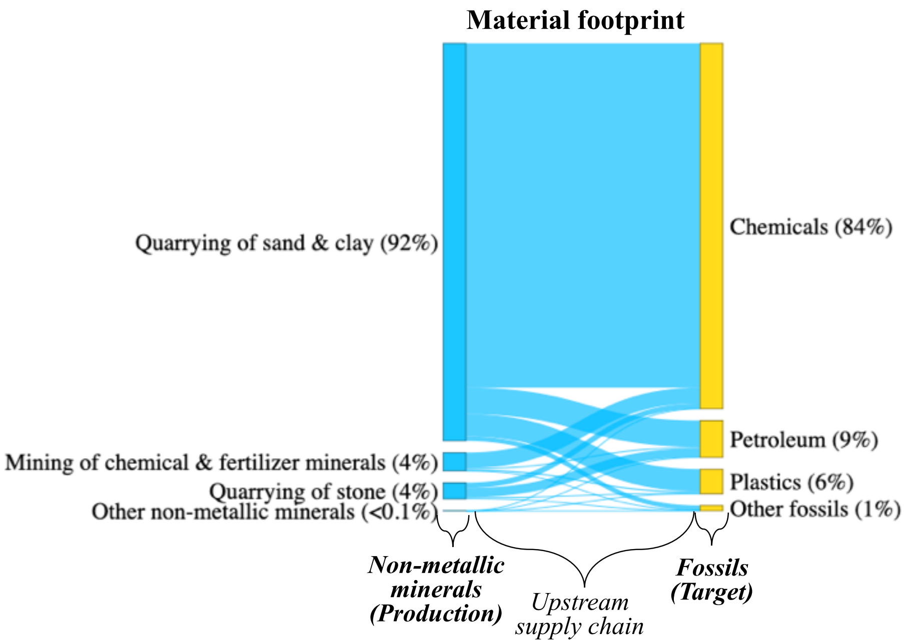

Figure A.3. Sectoral linkages of the material footprint between non-metallic minerals (production perspective) and fossils (target perspective). This Figure relates to Figure 2.2 of Chapter 2.

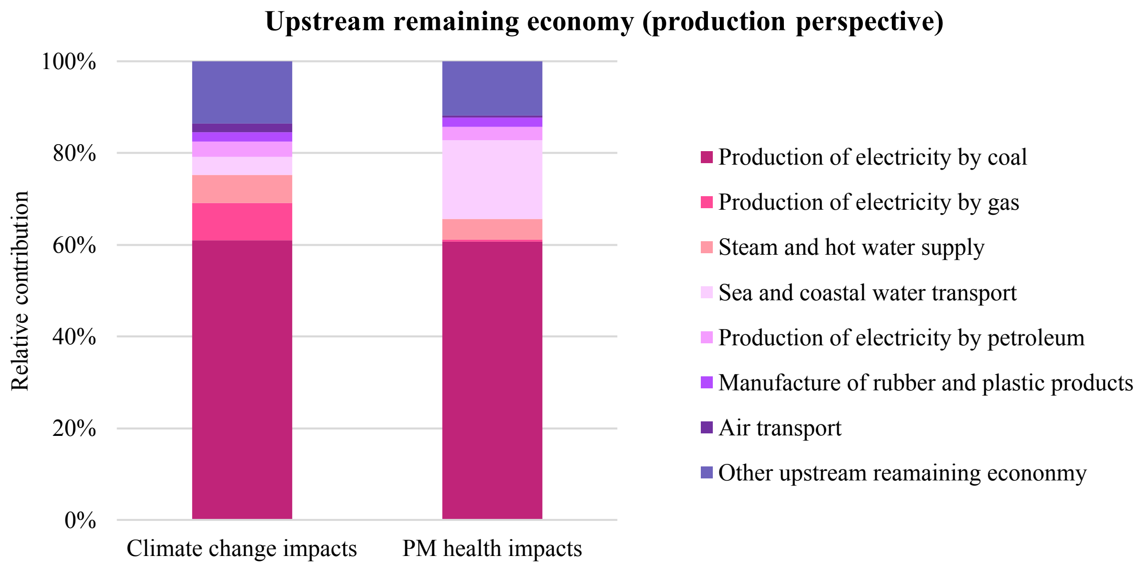

Figure A.4. Climate change impacts and PM health impacts caused by the remaining economy in the upstream supply chain of material production (production perspective). This Figure relates to Figure 2.2 of Chapter 2.

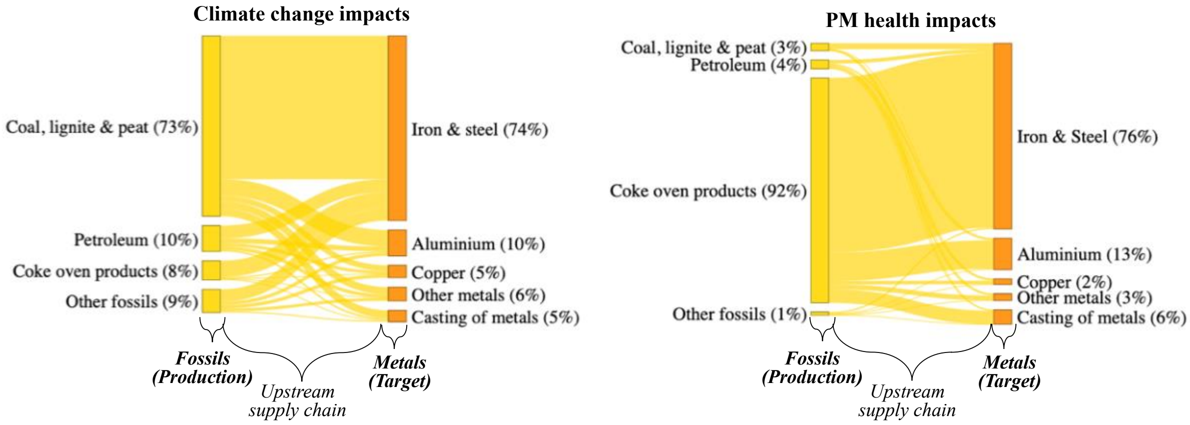

Figure A.5. Sectoral linkages between fossils (production perspective) and metals (target perspective) in terms of climate change impacts (left) and PM health impacts (right). This Figure relates to Figure 2.2 of Chapter 2.

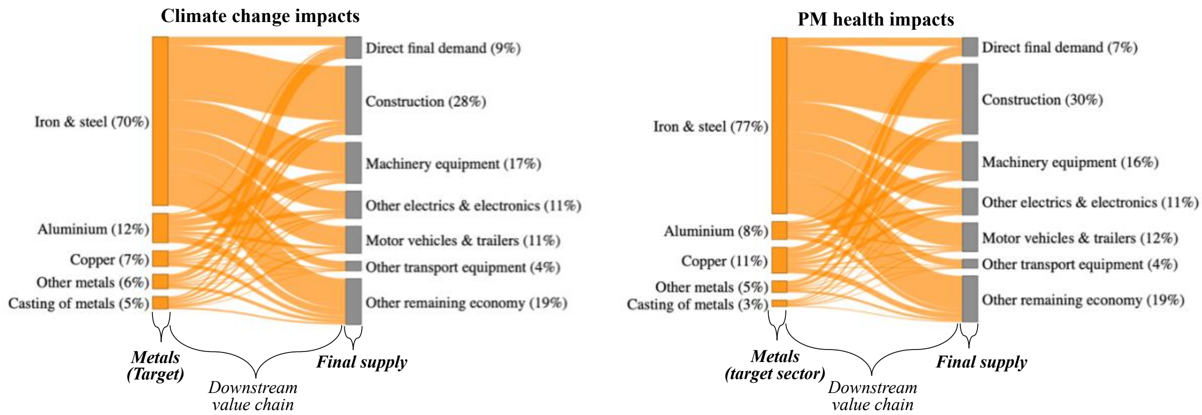

Figure A.6. Sectoral linkages between metals (target perspective) and the sector of final consumption (consumption perspective) in terms of climate change impacts (left) and PM health impacts (right). This Figure relates to Figure 2.2 of Chapter 2.

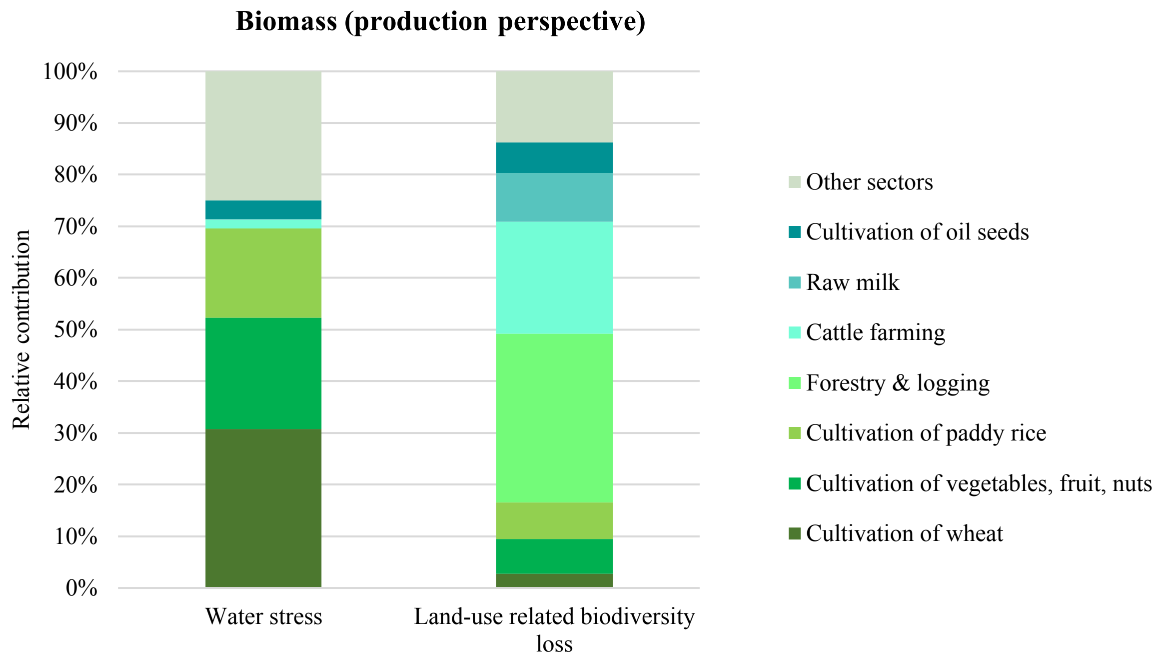

Figure A.7. Water stress (left) and land-use related biodiversity (right) loss split by major biomass sectors (production perspective). This Figure relates to Figure 2.2 of Chapter 2.

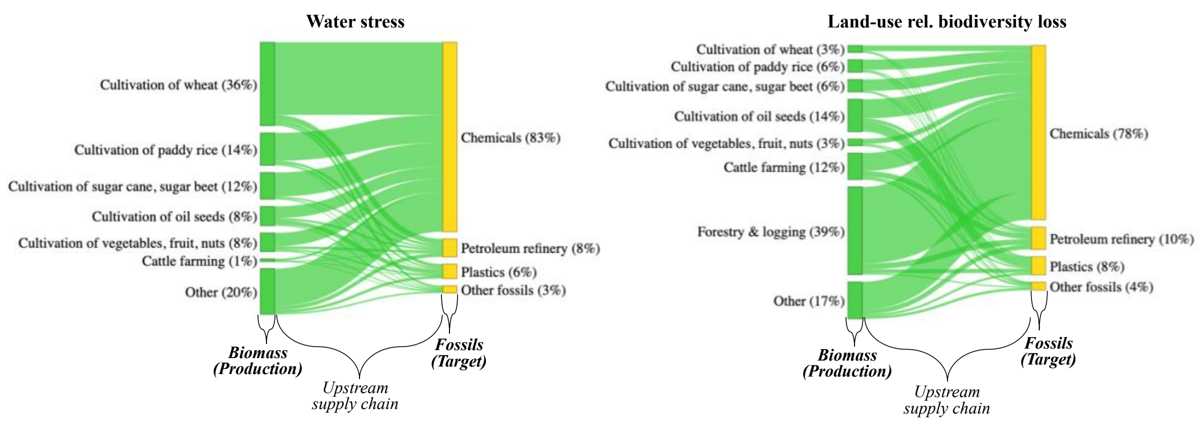

Figure A.8. Sectoral linkages between biomass (production perspective) and fossils (target perspective) in terms of water stress (left) and land-use related biodiversity (right). This Figure relates to Figure 2.2 of Chapter 2.

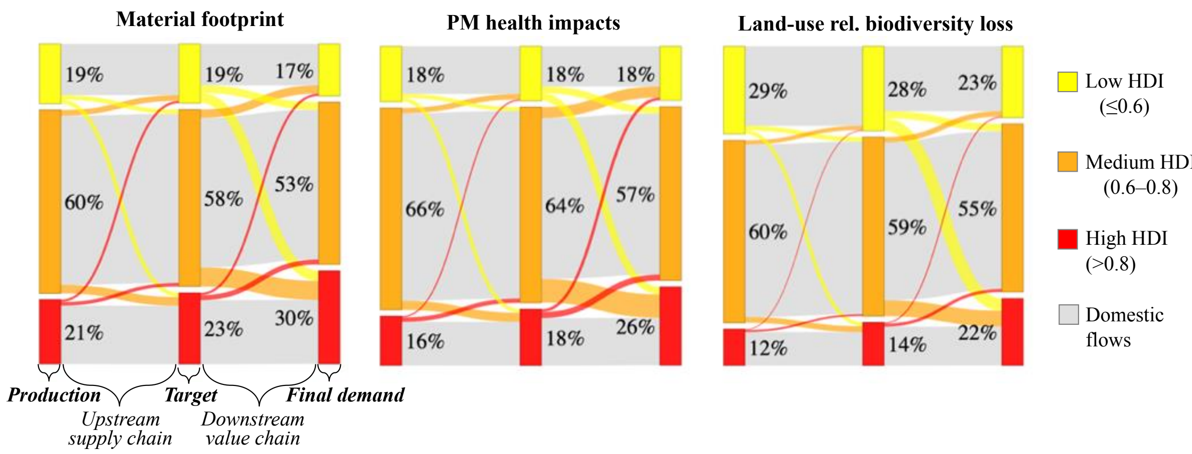

Figure A.9. Regional shares (split by the HDI) of global MR impacts from production, target and consumption perspective and trade relations within the upstream and downstream supply chain. The colors of the bars reflect the regions development stage and the colors of the flows stands for the exports of the respective regions to regions with other development stage. Grey flows refer to domestic flows.

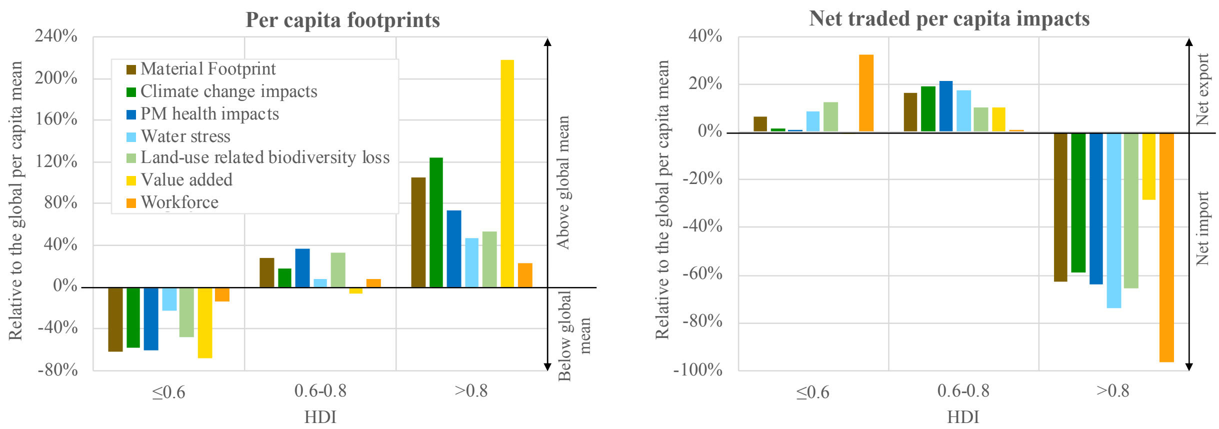

Figure A.10. Material-related per capita footprints (left) and net traded per-capita impacts (right) classified by the HDI of the respective region. The values are given as a share of the global per capita average of the respective indicator (Reference year: 2011).

Interpretation of Figure A.10. The evaluation reveals a considerable increase in per-capita footprints with increasing HDI (Figure A.10). Thereby, per-capita footprints are distinctly above the global average for regions with HDI >0.8, slightly above the global average for regions with HDI of 0.6–0.8 and distinctly below the global average for regions with HDI ≤0.6 for all indicators, except value added, which is also lower for the regions with HDI 0.6-0.8. Exemplarily, regions with HDI >0.8 cause five times higher per-capita MR climate change impacts than regions with HDI <0.6. This difference is even more severe for MR value added, which is ten times higher for regions with HDI >0.8 than regions with HDI ≤0.6 (Figure A.10).

The evaluation of MR net traded per capita footprints shows that regions with HDI >0.8 displace 60–70% of their environmental footprints to regions with HDI <0.8 (the shares are relative to the global per capita mean, Figure A.10). For workforce, an even higher fraction (97%) is imported by highest developed regions (HDI >0.8). However, the same regions (HDI

>0.8) generate a comparably low net value added in less developed regions (28%, relative to the global average). Thereby, regions with HDI ≤0.6 stand out by particularly high net exports of workforce but a zero net trade balance in terms of value added (Figure A.10).

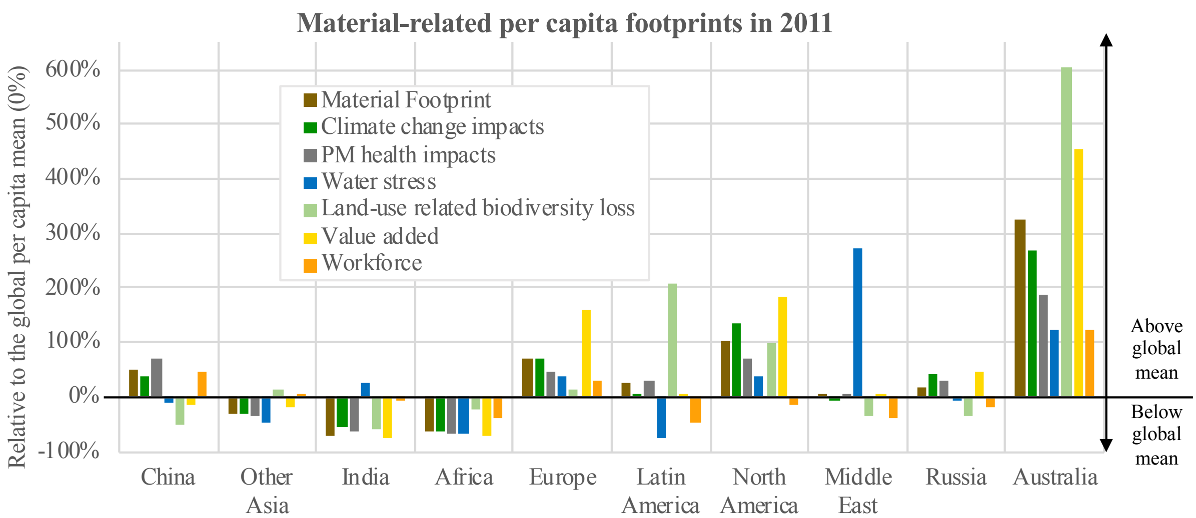

Figure A.11. Material-related per capita footprints split by regions in 2011 compared to the global per-capita average in 2011.

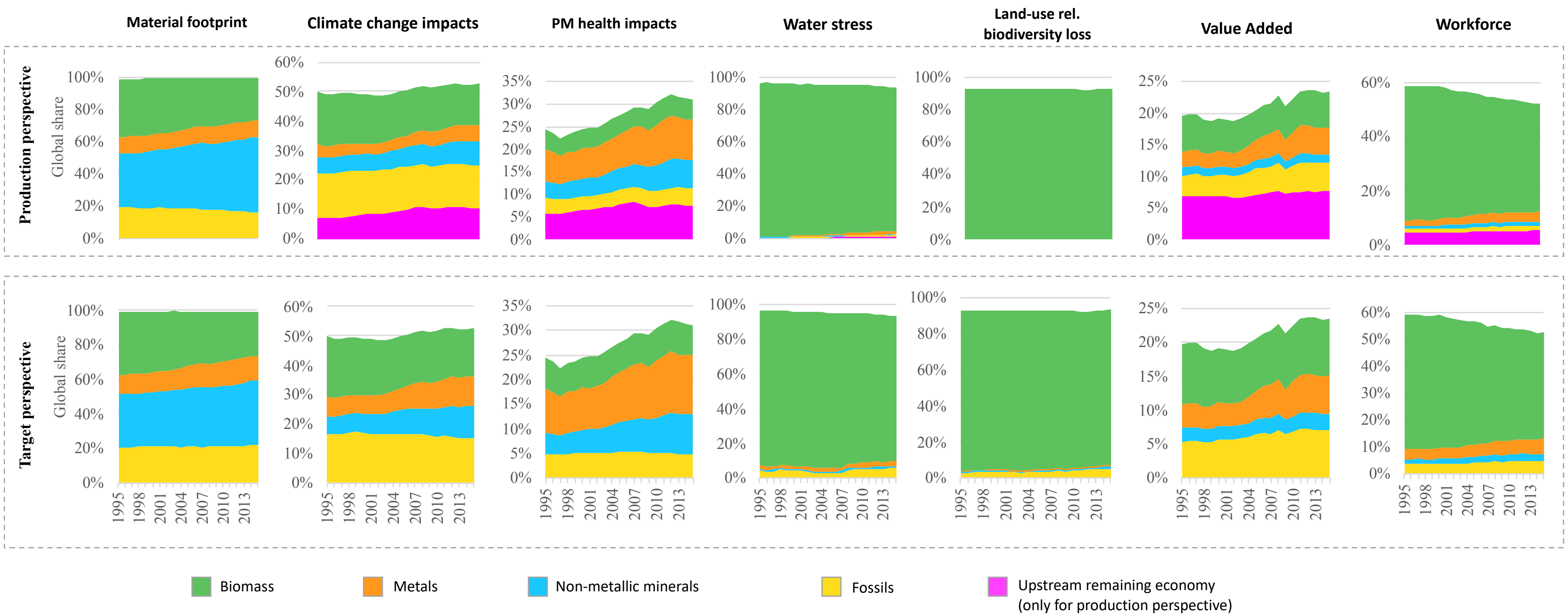

Figure A.12. Temporal development of materials' share in total global impacts split by the major material groups and the upstream remaining economy (only for production perspective).

A.3 Discussion

Comparison with Dente et al[9]. The basic procedure of the method applied in this study was originally developed by Dente et al[9] to quantify Japan's cumulated climate change impacts of semi-finished materials without double counting. Applied on a Japanese IO table, Dente et al[9] estimated a total of 400 Mt CO_2 that arise in Japan's upstream supply chain of material production. Thereby, the majority was caused by metals (38%), followed by biomass (24%), fossils (19%), and non-metal minerals (19%). For comparison, we compiled climate change impacts of Japan's material production from the dataset created in this study. Our results indicate considerable higher impacts with 700 Mt CO_2 equivalents that arise in Japan's upstream supply chain of material production. Based on our results, a comparably higher fraction is attributed to fossils (39%) and a lower fraction to metals (26%), biomass (21%), and non-metal minerals (14%). On the one hand, these differences may be attributed to the reason that Dente et al. [9] did not include all types of materials. Another reason may be that single IO tables only include direct imports and exports, whereby our results (based on MRIO) account for the entire global supply chain of Japan's MR imports and exports. Finally, the different results show that MRIO and IO based assessments have considerable uncertainties due to differences in sector resolution and definition, environmental extensions and integration of international trade data.

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Appendix B

A highly resolved MRIO database for analyzing environmental footprints and Green Economy Progress

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B.1 Introduction

Table B.1. Comparison of global MRIO databases, such as EXIOBASE3[3], Eora and Eora26[4, 5], GTAP[6], WIOD[7], OECD-ICIO[8], and GRAM[9, 10].

MRIO database	Coverage			Environmental & socio-economic extensions				
	Countries + RoW regions	Sectors	Timeframe	GHG	PM	Water	Land	Work-force
EXIOBASE3	44 + 5	163	1995–2016	+	+	+	+	+
Eora26	189	26	1990–2015	+	+	+	+/–	–
Full Eora	189	26-500	1990–2015	+	+	+	+/–	+/–
GTAP	121 + 20	65	2004, 2007, 2011, 2014	+	–	+/–	+	+
WIOD 2016	43 + 1	56	2000–2014	Only CO_2	–	–	–	+
WIOD 2013	40 + 1	35	1995–2009	+	–	+	+	+
OECD ICIO	64 + 1	34	2005–2015	–	–	–	–	–
GRAM	53 + 2	48	1995–2010	Only CO_2	–	–	–	–

RoW: Rest of the world regions

GHG: Greenhouse gas emissions

PM: Particulate matter emissions

+/– incomplete: In Eora26 and Full Eora, forestry and infrastructure land are not covered and workforce is not provided; GTAP only covers water used for irrigation.

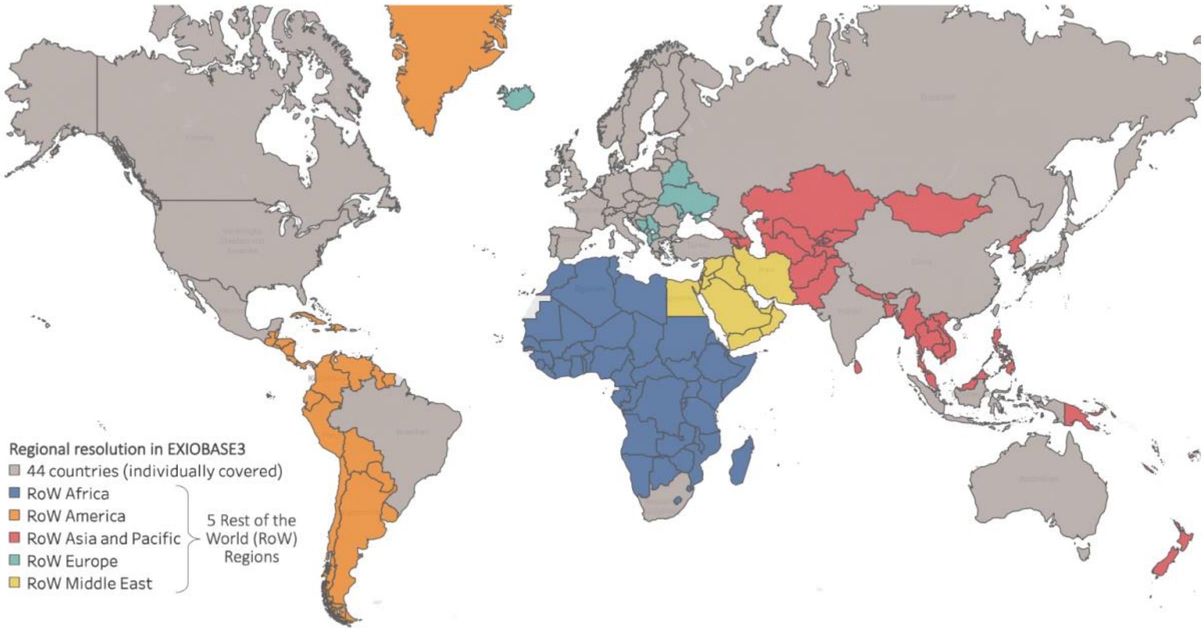

Figure B.1. Regional resolution in EXIOBASE3: 44 individually covered countries (grey) and five aggregated Rest of the World (RoW) Regions (colored).

B.2 Methods

Paragraph B.1: Greenhouse gas emissions and particulate matter emissions in Eora26

The satellite matrix of Eora26 includes greenhouse gas (GHG) emissions from different data providers: I-GHG, PRIMAPHIST, EDGAR, CDIAC, and IEA (Figure B.1). Only PRIMAPHIST and I-GHG provide data for all types of GHG emissions (Figure B.1). Since Eora26 recommends not to use I-GHG (as explained in the IndicatorNotes.docx on the Eora26 homepage), we used data from EDGAR for CO_2 emissions and data from PRIMAPHIST for all the other GHG emissions of the economy. For CO_2, we used data from EDGAR instead of PRIMAPHIST, because data from EDGAR are similar to those of EXIOBASE3 (Figure B.1), and since CO_2 emissions provided by PRIMAPHIST were strongly negative or equal to zero for some countries (Figure B.2). For the emissions of the final demand, we used data from I-GHG, because it was the only data provider for the final demand (Figure B.1). I-GHG was also the only data provider for particulate matter (PM) emissions of the economy and the final demand. In both cases (GHG emissions of households and PM emissions of the economy and households), we considered only those emissions, where we assumed that they refer to anthropogenic activities and we neglected those extensions referring to natural emissions (e.g. wildfires, Figure B.1).

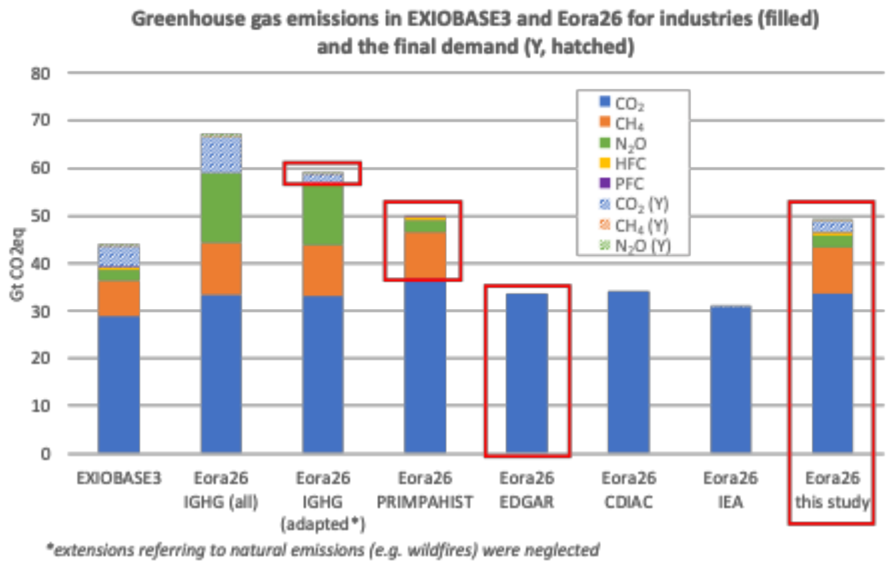

Figure B.2. Comparison of greenhouse gas emissions in EXIOBASE3 and Eora26 (different data providers). The red bars show how greenhouse gas emissions were implemented in Eora26 in this study to match it with EXIOBASE3.

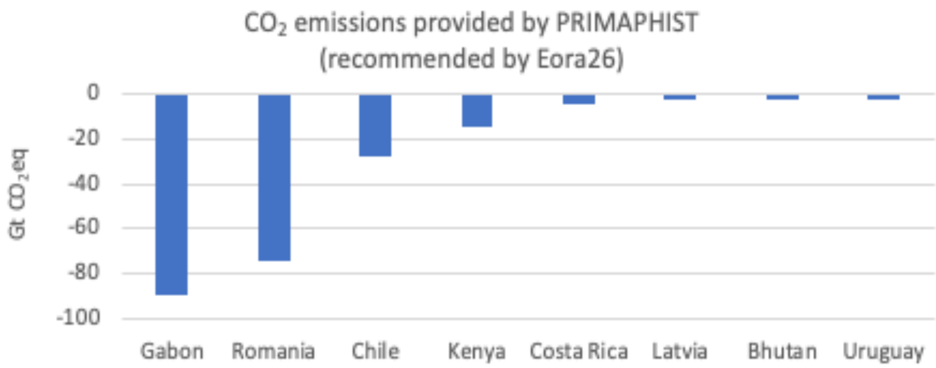

Figure B.3. Negative CO_2 emissions provided by PRIMAPHIST in Eora26.

Paragraph B.2: R-MRIO database matches in sum EXIOBASE3

In the entire procedure of Chapter 3 (Section 3.2.3–3.2.5), we weight the values of EXIOBASE3 with country and sector-specific relative shares derived from FAOSTAT[11], and previous studies[12-15], but do not change the absolute numbers. Thus, the total sum of the disaggregated transaction and final demand matrices is the same as in EXIOBASE3:

$$\Sigma_{c,s} T^{Exio-Eora-final} = \Sigma_{c,s} T^{Exio-Eora} = \Sigma_{\Sigma c,s} T^{Exio} \quad \text{Eq. B.1}$$

$$\Sigma_{c,s,f} Y^{Exio-Eora-final} = \Sigma_{c,s,f} Y^{Exio-Eora} = \Sigma_{\Sigma c,s,f} Y^{Exio} \quad \text{Eq. B.2}$$

The same applies for the impact categories, where the total impacts equal in sum those of Cabernard et al[1], which were built on EXIOBASE3:

$$\Sigma_{c,s} Q\_T^{Exio-final} = \Sigma_{c,s} Q\_T^{Exio-Eora} = \Sigma_{\Sigma c,s} Q\_T^{Exio} \quad \text{Eq. B.3}$$

$$\Sigma_{c,f} Q\_Y^{Exio-Eora} = \Sigma_{\Sigma c,f} Q\_Y^{Exio} \quad \text{Eq. B.4}$$

B.3 Results and Discussion

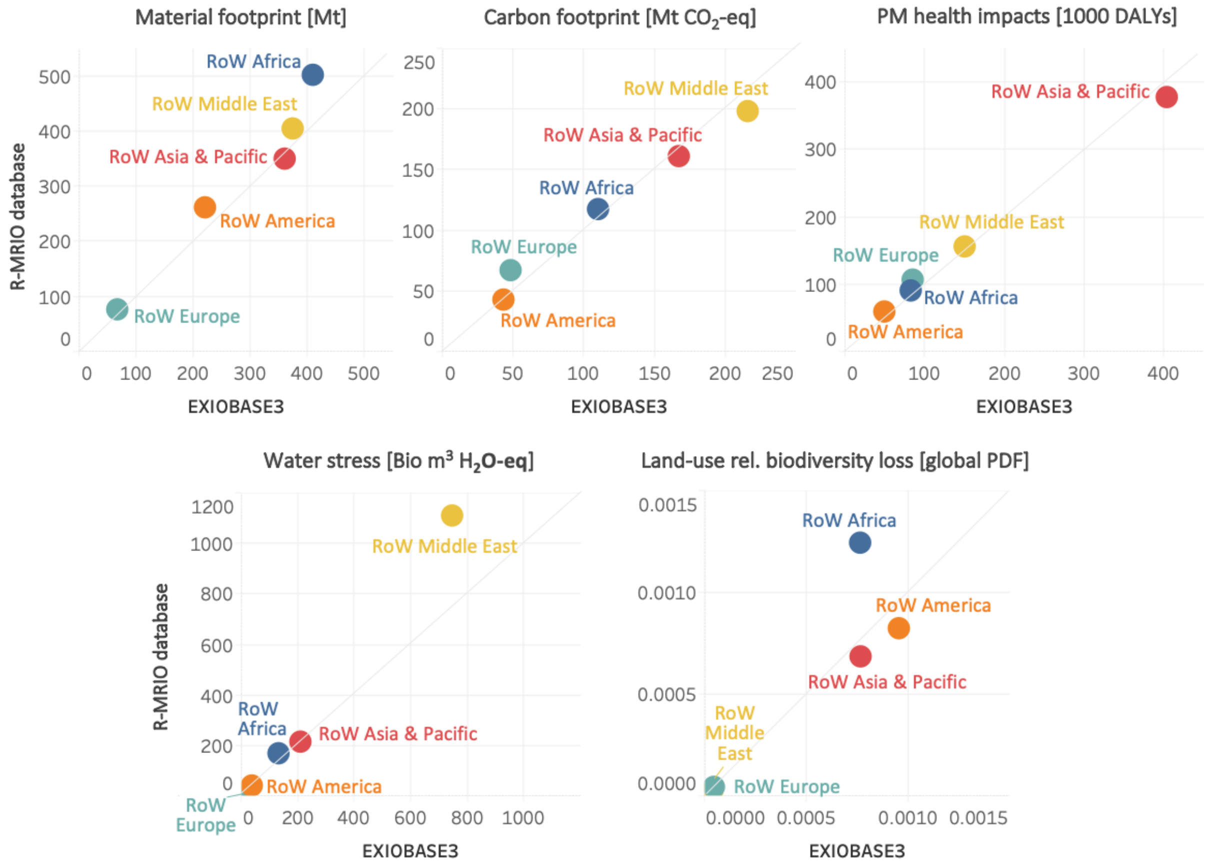

Figure B.4. EU’s environmental footprints displaced to RoW regions calculated with the R-MRIO database of this study (y-axis) compared to the same footprints calculated with the tool of Cabernard et al[1] (based on EXIOBASE3) in 2015. The spatial disaggregation of the RoW Middle East drives the EU’s higher water stress footprint calculated with the R-MRIO database. The spatial disaggregation of the RoW Africa is the major reason for the EU's higher land-use related biodiversity loss derived from the R-MRIO database.

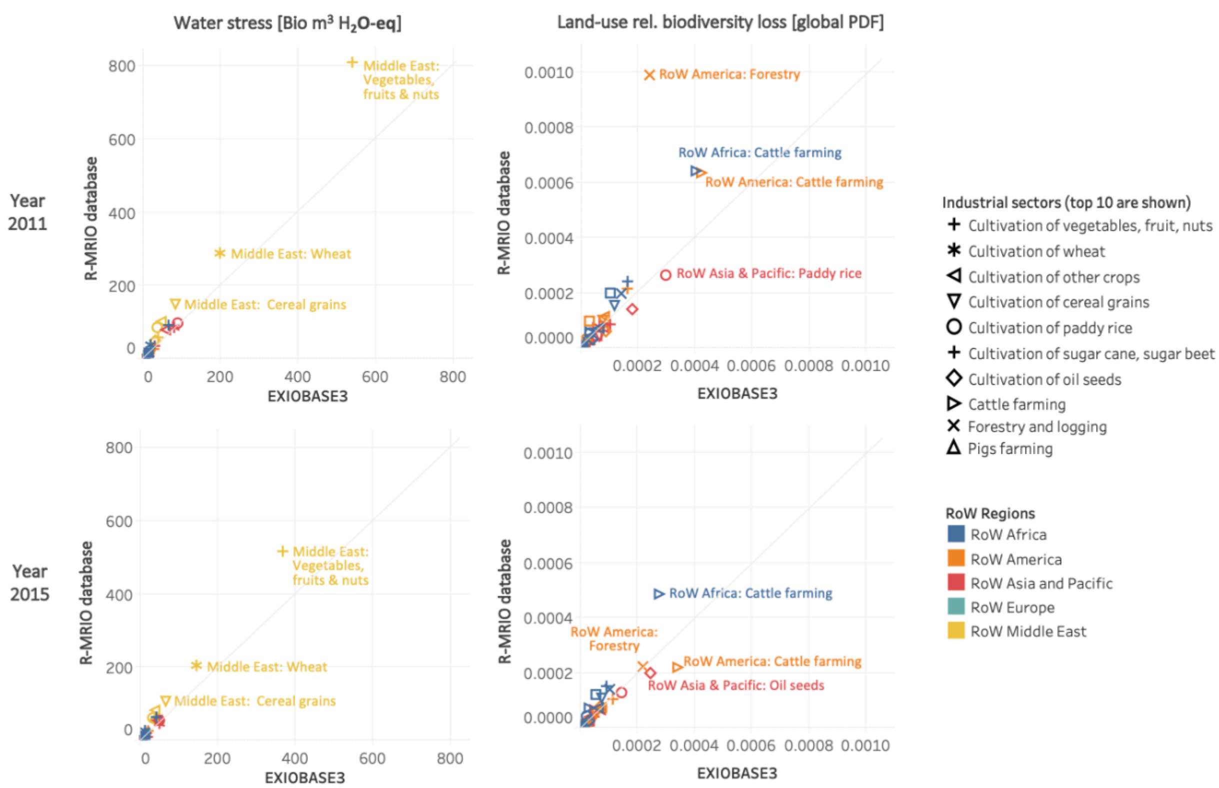

Figure B.5. EU's water stress and biodiversity loss footprints displaced to sectors in RoW regions calculated with the R-MRIO database of this study (y-axis) and the tool of Cabernard et al[1] (based on EXIOBASE3) in 2011 and 2015. The EU's displaced impacts to RoW regions are higher in 2011 than 2015. This is attributed to forestry in RoW America for land-use related biodiversity loss in 2011.

Table B.2. Comparison of domestic land-use accounts of EXIOBASE3 and Bjelle et al[2] in 2015.

	EXIOBASE3 [km²]	Bjelle et al (2020) [km²]	Difference compared to EXIOBASE3 [%]
Austria	8.51E+04	8.03E+04	-5.69%
Belgium	2.78E+04	3.06E+04	10.32%
Bulgaria	9.25E+04	1.10E+05	18.42%
Cyprus	8.55E+03	9.00E+03	5.30%
Czech Republic	8.62E+04	7.88E+04	-8.57%
Germany	3.77E+05	3.55E+05	-5.91%
Denmark	4.33E+04	4.33E+04	0.12%
Estonia	5.52E+04	4.32E+04	-21.84%
Spain	5.28E+05	4.99E+05	-5.40%
Finland	3.04E+05	2.84E+05	-6.39%
France	5.01E+05	5.88E+05	17.30%
Greece	1.44E+05	1.26E+05	-12.31%
Croatia	3.59E+04	5.48E+04	52.56%
Hungary	9.67E+04	9.21E+04	-4.69%
Ireland	8.54E+04	7.02E+04	-17.75%

Italy	2.92E+05	2.90E+05	-0.69%
Lithuania	6.10E+04	6.41E+04	5.19%
Luxembourg	2.47E+03	2.50E+03	0.93%
Latvia	6.99E+04	6.42E+04	-8.16%
Malta	3.17E+02	2.38E+02	-25.02%
Netherlands	5.04E+04	3.57E+04	-29.10%
Poland	2.74E+05	3.10E+05	12.96%
Portugal	8.98E+04	8.87E+04	-1.29%
Romania	2.11E+05	2.36E+05	11.93%
Sweden	4.06E+05	3.94E+05	-3.13%
Slovenia	1.97E+04	2.03E+04	3.48%
Slovak Republic	5.13E+04	4.89E+04	-4.61%
United Kingdom	3.18E+05	2.48E+05	-21.91%
United States	8.29E+06	7.74E+06	-6.59%
Japan	3.98E+05	4.10E+05	3.10%
China	8.68E+06	7.00E+06	-19.41%
Canada	5.74E+06	3.41E+06	-40.47%
South Korea	1.18E+05	1.05E+05	-11.14%
Brazil	6.12E+06	6.95E+06	13.61%
India	3.33E+06	3.07E+06	-7.98%
Mexico	1.95E+06	1.91E+06	-2.12%
Russian Federation	1.25E+07	1.02E+07	-18.73%
Australia	4.63E+06	4.87E+06	5.04%
Switzerland	4.06E+04	3.60E+04	-11.46%
Turkey	6.70E+05	7.61E+05	13.63%
Taiwan	4.23E+04	3.58E+04	-15.32%
Norway	2.73E+05	2.62E+05	-4.08%
Indonesia	2.06E+06	1.81E+06	-12.36%
South Africa	9.75E+05	1.19E+06	22.52%
RoW Asia and Pacific	8.94E+06	8.81E+06	-1.45%
RoW America	8.46E+06	8.12E+06	-4.02%
RoW Europe	8.92E+05	1.09E+06	21.96%
RoW Africa	1.65E+07	1.72E+07	3.93%
RoW Middle East	1.30E+06	1.11E+06	-14.61%
Global	9.63E+07	9.03E+07	-6.20%

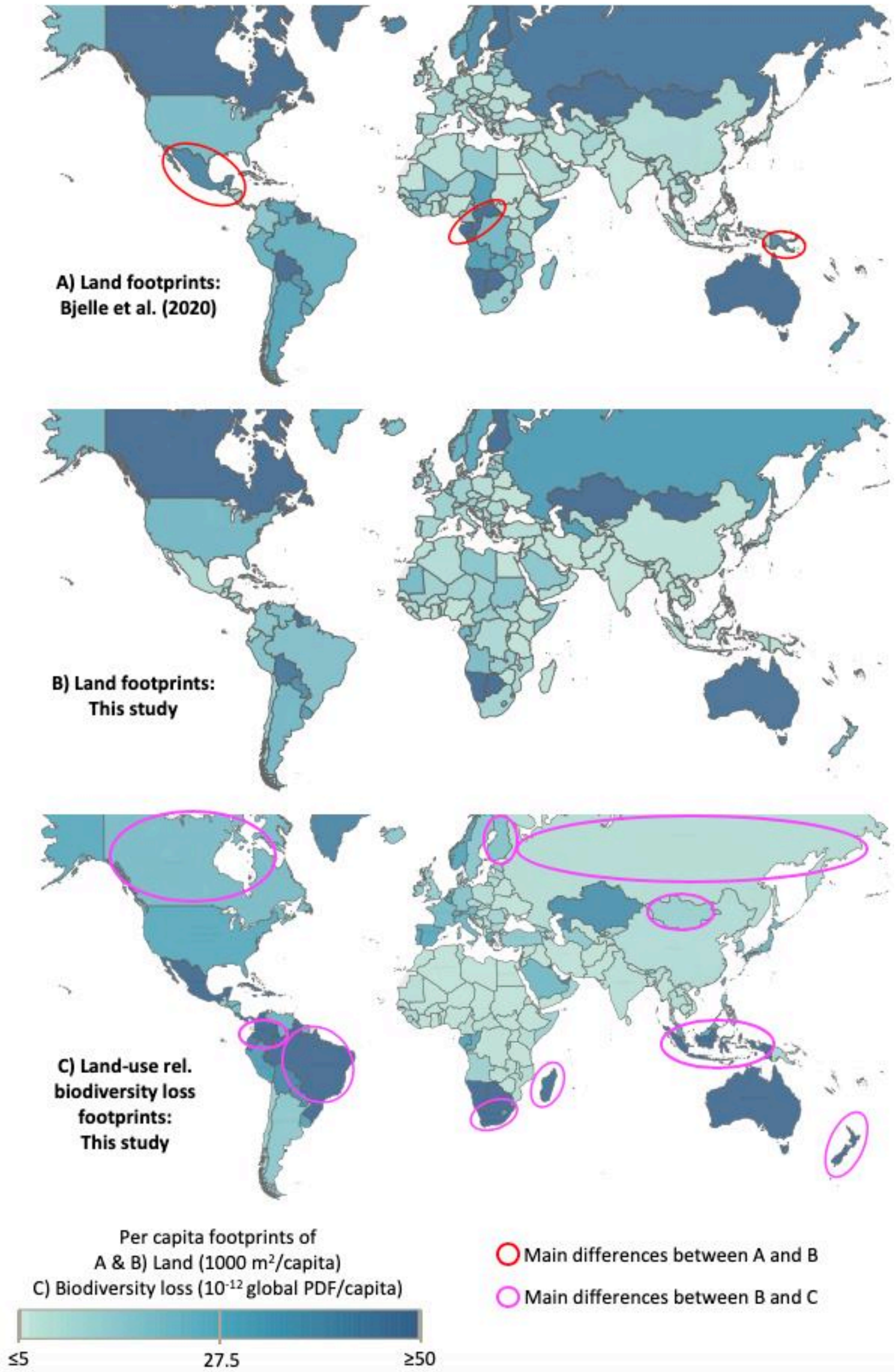

Figure B.6. Comparison of per-capita land use footprints calculated with the R-MRIO database of this study (B) to those of Bjelle et al[2] (A) and to land-use related biodiversity loss footprints calculated with the R-MRIO database of this study (C).

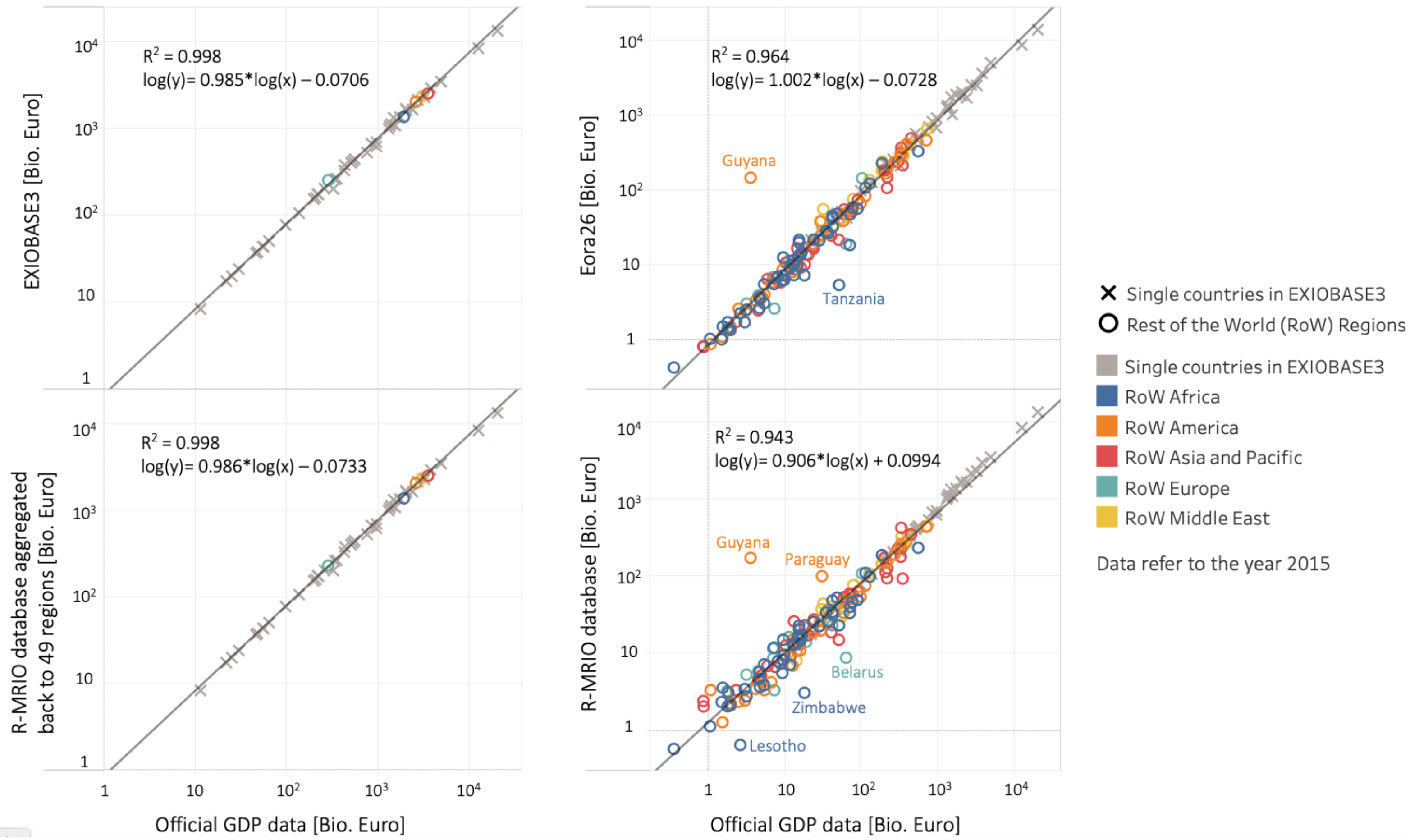

Figure B.7. Domestic value added in EXIOBASE3, Eora26, and the R-MRIO database of this study plotted against official GDP reported by the United Nations for the year 2015[16]. The domestic value added of the 49 regions almost perfectly match with the official GDP for both EXIOBASE3 and the R-MRIO database of this study (when aggregated back to the 49 regions). For Eora26, inconsistencies between modelled domestic value added and official GDP already occur particularly for RoW countries. These inconsistencies become stronger in the R-MRIO due the taken approach, where the value added was calculated as a residual to balance the R-MRIO database. Thus, this approach is not suitable to model value added footprints. The data are attached to the SI of the article (SI_R-MRIO_ValueAdded.xlsx, spreadsheet "VA vs GDP for 49 regions" and "VA vs GDP for 189 countries").

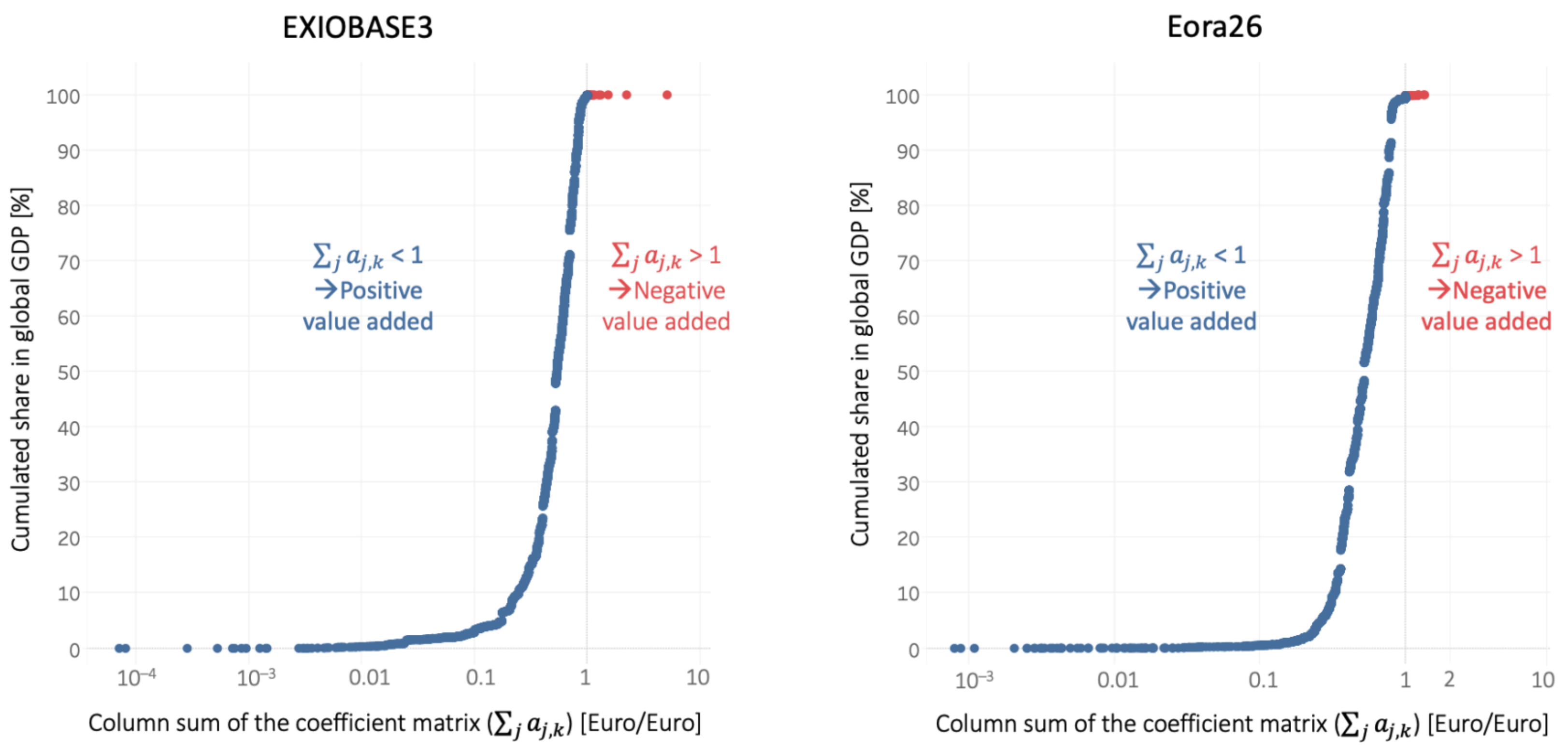

Figure B.8. Cumulated share of each sector-region combination in global GDP sorted by the column sum of the coefficient matrix ($\sum_j a_{j,k}$) in EXIOBASE3 (7987 data points for 163 sectors of 49 regions) and Eora26 (4914 data points for 26 sectors of 189 countries) for the year 2015 (log-scale). Coefficients exceeding one ($\sum_j a_{j,k} > 1$) indicate negative value added, meaning a sector is subsidized. The figures show that the output of all sector-region combinations with negative value added contribute to a minimal fraction (<0.1%) of the global GDP.

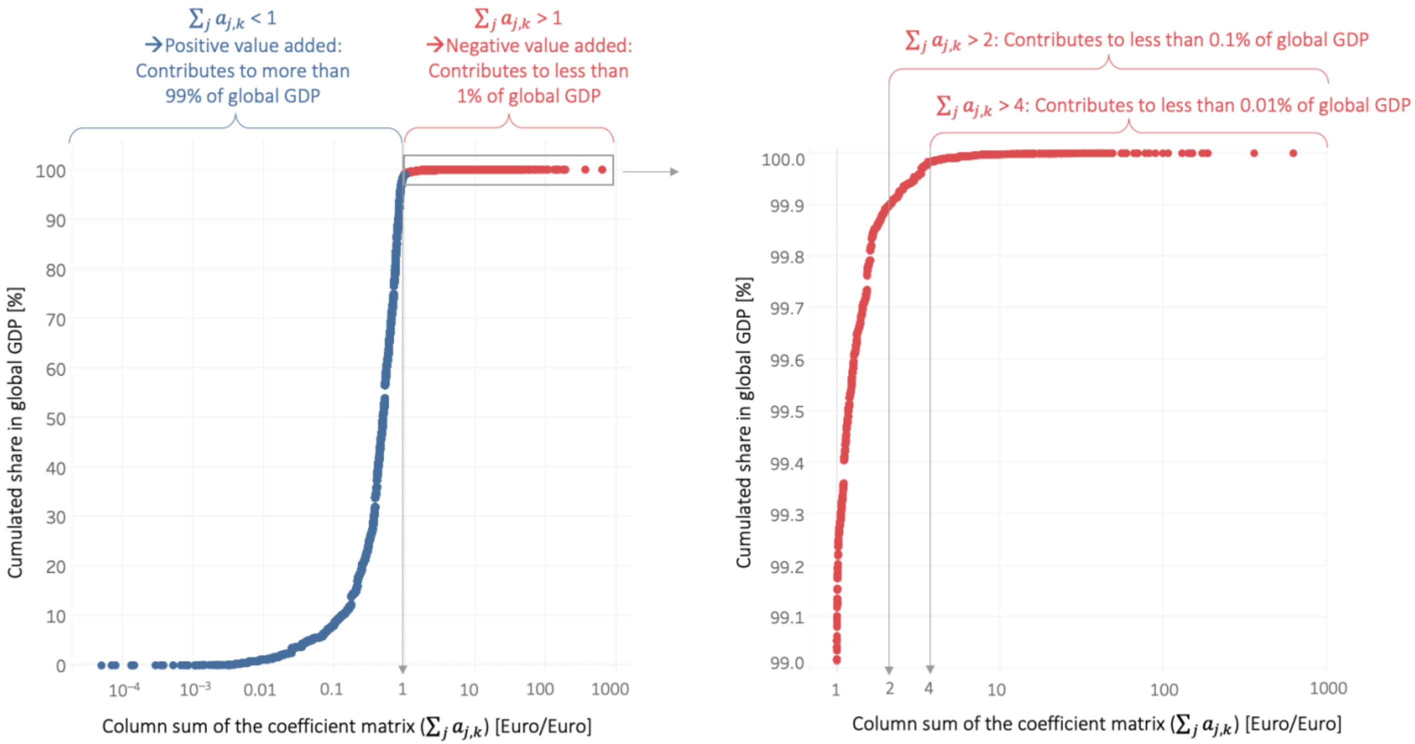

Figure B.9. The left figure shows the cumulated share of each sector-country combination in the global GDP sorted by the column sum of the coefficient matrix ($\sum_j a_{j,k}$) for the R-MRIO database of this study (30'807 data points for 163 sectors of 189 countries) in 2015 (log-scale). The right figure shows the same for the coefficients exceeding one ($\sum_j a_{j,k} > 1$), which indicates negative value added. It shows that all sector-country combinations with negative value added contribute to a minor fraction (<1%) of the global GDP. The right figure shows that the more negative the value added is compared to the respective output (which is indicated by higher values for the column sums of the coefficient matrix ($\sum_j a_{j,k}$)), the lower the contribution to the global GDP (right Figure). The data are attached to the SI (SI_R-MRIO_ValueAdded.xlsx, spreadsheet "negative VA in R-MRIO").

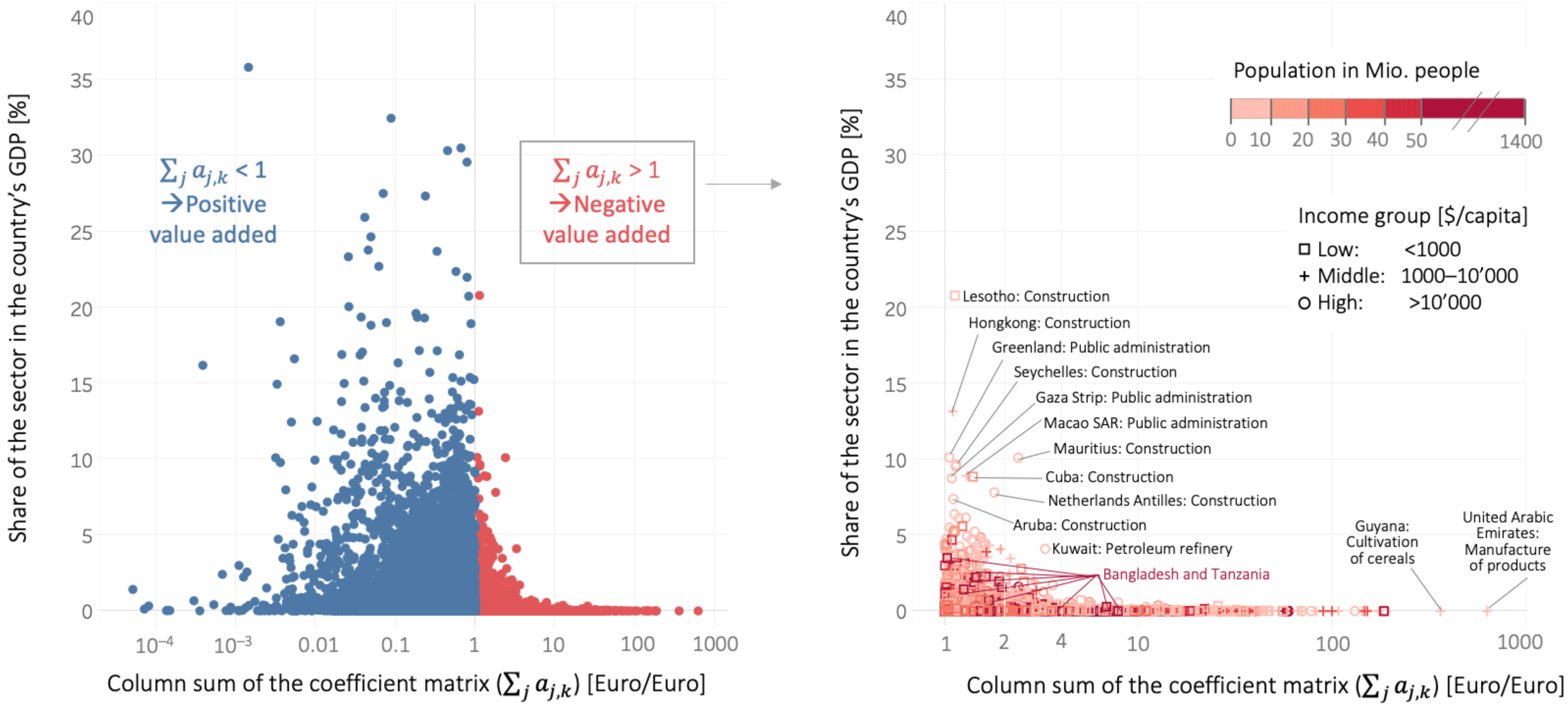

Figure B.10. The left figure shows the share of each sector in the respective country's GDP sorted by the column sum of the coefficient matrix ($\sum_j a_{j,k}$) for the R-MRIO database of this study (30'807 data points for 163 sectors of 189 countries, log-scale). The right figure shows the same for the coefficients exceeding one ($\sum_j a_{j,k} > 1$), which indicates negative value added. The countries are colored by population number and marked by income group. The right Figure shows that negative value added involves mainly sectors of small countries and islands with low population number, as well as a few sectors of countries with higher population number but low income (e.g. Bangladesh and Tanzania). Countries with low income are often subject to higher data uncertainty, resulting in negative value added in the R-MRIO database (due to the balancing through value added). The data are attached to the SI (SI_R-MRIO_ValueAdded.xlsx, spreadsheet "negative VA in R-MRIO").

B.4 References

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Appendix C

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

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C.1 Introduction

Paragraph C.1: Previous accounting schemes in MRIO analysis

None of the previous standard accounting schemes was meaningful for assessing scope 3 impacts in MRIO analysis[1-30]: The reason for this is that standard production-based accounting neglects upstream impacts of material resource production, as it allocates the upstream impacts to the sector in the upstream chain where they are caused (e.g., the impacts caused in the upstream chain of material production by the electricity supply are allocated to the electricity sector). Likewise, standard consumption-based accounting[1-9, 28, 29, 31] only allows assessing the impacts of material resources directly consumed by the final demand (e.g., fossil fuels for heating and car driving), as it allocates the impacts of those materials used by the industry to the sector of end use instead of the materials (e.g., the impacts of minerals used for construction are allocated to the construction sector). On the other hand, standard scope 3 accounting leads to double counting[28-30]. Double counting occurs when the scope 3 impacts of several sectors and regions located in each other's supply chain are added up[32-35]: For example, part of the scope 3 emissions of oil production (Sector A, Figure C.1) is also included in the scope 3 emissions of steel production (Sector B), because some of the oil is used for steel production (and vice versa, some of the steel is used e.g. in machinery for oil production). The same issue exists for regions due to trade. For example, part of the scope 3 emissions of Region A is also included in the scope 3 emissions of Region B due to exports from Region A to B, and vice versa (Figure C.1). In the methodology of ref[36], double counting is prevented by allocating the double counted impacts to either the supplying or receiving sector or regions, and by mapping the linkages between them (e.g., if steel is used for coal production the impacts related to coal are counted either in the steel sector or in the coal sector by adopting different perspectives; see ref[36] for a detailed explanation).

Paragraph C.2: Downstream impacts in MRIO analysis

Although the inclusion of downstream impacts is optional in scope 3 impact assessment[37], downstream impacts are critical with respect to fossil resources since their combustion causes the vast majority of global climate change and particulate-matter (PM) related health impacts[38, 39]. In standard MRIO analysis, downstream impacts have not been analyzed due to two major reasons. One reason is that their additional inclusion leads to further double counting. For example, some of the downstream emissions of oil production (Sector A), are already counted as scope 3 emissions of steel production (Sector B, Figure C.1). Another reason is that there is no clear allocation mechanism for downstream impacts. For example, if some of the produced oil is combusted for transporting some of the produced steel by ship, the direct emissions of transport via ship (Sector C, Figure C.1) can be either allocated to the oil and steel producing sector depending on their monetary inputs, or to the actual resource that releases them, which would be the oil sector. Dente et al[34, 35, 40] proposed a method to account for downstream emissions of materials without double counting based on the monetary inputs of materials into the downstream chain. This means that if e.g., 5% of the total monetary input of shipping is related to transporting steel, 5% of the direct emissions released by ship transport are charged as downstream emissions of transporting steel. This procedure is debatable as the emissions of shipping actually originate from oil combustion. Thus, the existing approach does not allocate the downstream impacts to the actual material resource that releases the emissions, such as oil, gas, or coal.

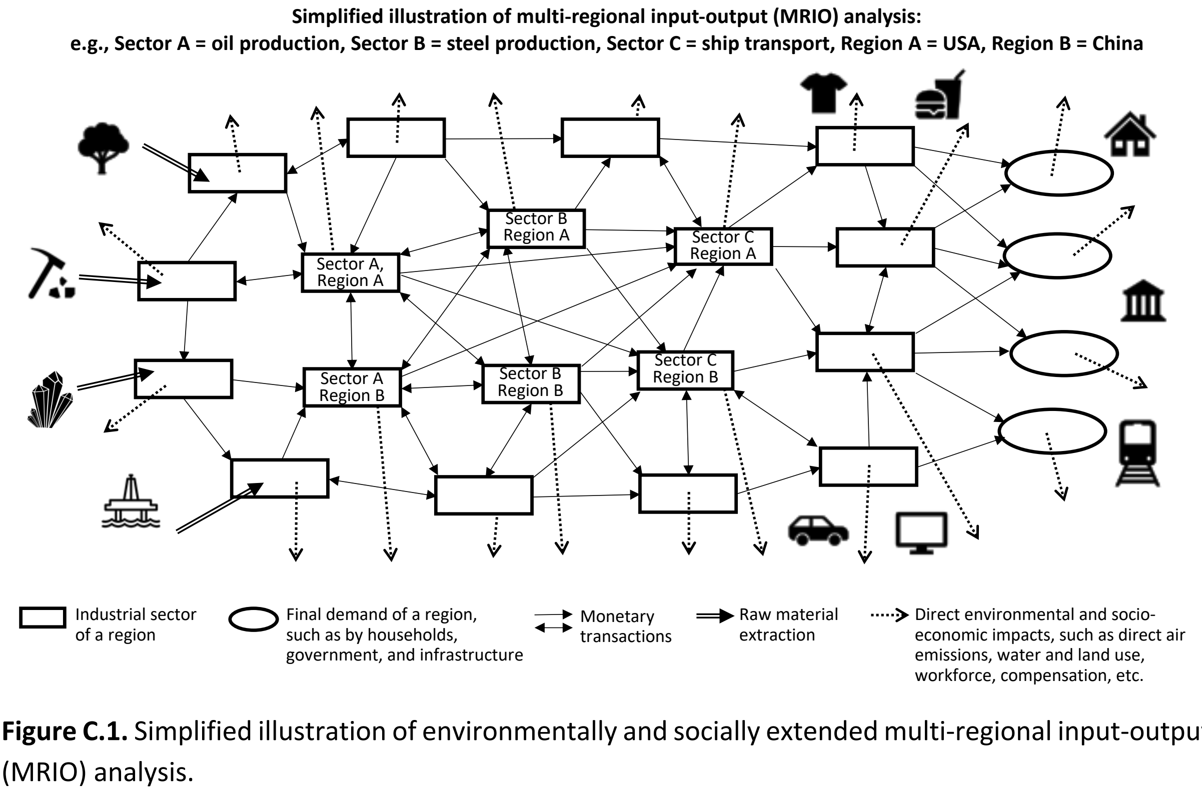


Figure C.1. Simplified illustration of environmentally and socially extended multi-regional input-output (MRIO) analysis.

C.2 Methods

Paragraph C.3: G20 database

Our methodology is based on multiregional input-output (MRIO) analysis. This concept aggregates the global economy into specific regions and industrial sectors and records their transactional flows and environmental accounts for a specific time frame. Current MRIO databases have different benefits and limitations. EXIOBASE3[41] and Eora26[42, 43] are the only MRIO databases covering a set of environmental indicators with time series from 1995 to 2015. These two databases complement each other in their spatial and sectoral resolution: EXIOBASE3 features a higher sectoral resolution (163 sectors) but is limited in its regional resolution since it covers only 44 countries and aggregates the rest of the world (RoW) into five RoW regions. Therefore, EXIOBASE3 covers all G20 members except Saudi Arabia and Argentina, which are aggregated under "RoW Middle East" and "RoW Latin America", respectively, together with many other countries of these regions. In contrast, Eora26 features a higher regional resolution (189 countries), covering all G20 members separately, but is limited in its sectoral resolution (only 26 sectors).

Due to its higher sectoral resolution, we primarily used EXIOBASE3 and extended it to Saudi Arabia and Argentina. For this extension, we followed the same five steps described in Cabernard et al[44]: First, we disaggregated the "RoW Middle East" and "RoW Latin America" regions by adding sector-specific data of Saudi Arabia and Argentina from Eora26. Second, we scaled the extended MRIO database with agricultural data from FAOSTATFAOSTAT [45]. Third, we implemented a set of environmental and socioeconomic indicators and added the inventory from Eora26. Fourth, we scaled the water and land inventory with data from previous work[46-49]. Fifth, we applied the most recent impact assessment methods recommended by UNEP-SETAC[50] as done by ref[36, 44]. These methods consider where the emissions (GHG and PM emissions) and resource consumption (water and land) take place and what environmental impacts are caused. The impact assessment includes GHG emissions, PM health impacts, water stress, and land-use-related biodiversity loss.

The indicators *'GHG emissions*, *'PM health impacts'*, *'water stress'*, and *'land-use related biodiversity loss'* were implemented following the most recent impact assessment methods recommended by UNEP-SETAC[50] as done before in ref[36, 44]: For GHG emissions, we derived the amount of emitted CO_2 equivalents by weighting each GHG listed by the satellite matrix of EXIOBASE3 (CO_2, CH_4, N_2O, hydrofluorocarbons and perfluorinated compounds) with the respective global warming potential (note that the satellite matrix of EXIOBASE3 does not include GHG emissions related to land use and land-use changes and forestry). For the indicator PM health impacts, we quantified human's burden of disease in 'disability adjusted life years' (DALYs) by weighting each type of PM emissions listed by the satellite matrix of EXIOBASE3 ($PM_{2.5}$, NO_x, SO_x, and NH_3) with sector-specific impact factors adapted from UNEP-SETAC[50] and Fantke et al[51]. The indicator water stress was derived by weighting the total blue water consumption indicated by the satellite matrix of EXIOBASE3 with sector and region-specific impact factors adapted from Boulay et al[52]. This allowed us to account for regional and temporal differences in water scarcity and crop production patterns based on previous research[18, 47]. The resulting unit (m^3 of H_2O equivalents) refers to the scarcity-equivalent volume of water consumed under global average water scarcity conditions. In terms of land-use related biodiversity loss, we weighted the area of different land-use types provided by the satellite matrix of EXIOBASE3 (different types of crops, forestry, pastures and infrastructure) with region-specific impact factors adapted from UNEP-SETAC[50] and Chaudhary et al[53]. This allowed us to quantify the global potentially disappeared fraction of species (global PDF years), which indicates the fraction of global species that are committed to extinction due to human land-use.

The resolved database distinguishes 163 sectors for 51 regions, covering each G20 member and a set of environmental and socioeconomic indicators, including value added, and workforce. These data are provided as time series from 1995 to 2015. The resolution of the G20 database only differs from EXIOBASE3 by distinguishing Saudi-Arabia from the "Rest of the Middle East" and Argentina from the "Rest of Latin America". Except for these disaggregated regions, the values equal those of EXIOBASE3 and Cabernard et al[36] for the environmental impacts. For the disaggregated regions, we weighted the values of EXIOBASE3 with country and sector specific shares derived from Eora26, FAOSTAT[45], and previous studies[46-49]. This is why the total global output and the global impacts of the resolved database still equal EXIOBASE3 (and the environmental impacts of ref[36] built on EXIOBASE3)[44].

Paragraph C.4: Production and consumption-based impacts

To assess the total environmental and socioeconomic impacts from a production and consumption perspective, we applied the common Leontief framework[54] to the G20 database:

$$F_{i,all}^{total} = diag(D_{i-all}) \times L_{all-all} \times Y_{all-all} + F_{i,all}^{hh} \qquad \text{Eq. C.1}$$

with D_{i-all} as the impact coefficients of the indicator (i) for all sector-region combinations of the G20 database which were diagonalized (diag), $L_{all-all}$ as the Leontief Inverse, and $Y_{all-all}$ to the global final demand. While the first term refers to the impacts related to the economy, $F_{i,all}^{hh}$ indicates the direct impacts of the final demand, such as direct GHG emissions released by heating and private transport.

Paragraph C.5: Split into material production and downstream chain

In a next step, we split the total global impacts related to the economy ($D_{i-all} \times L_{all-all} \times Y_{all-all}$) into the impacts caused by material resource production (MP) and the downstream economy (DE):

$$F_{i,all}^{total} = F_{i,all}^{MP} + F_{i,all}^{DE} + F_{i,all}^{hh} \qquad \text{Eq. C.2}$$

where $F_{i,all}^{MP}$ refers to the scope 3 impacts related to the extraction and processing of material resources into ready-to-be used materials, fuels, and food. This includes both upstream impacts (e.g., from electricity supply) and midstream impacts (direct impacts from extraction and processing) of material resource production. $F_{i,all}^{DE}$ refers to the remaining impacts caused in the downstream economy of global material resource production, such as by further manufacturing, construction, service, and other downstream activities. The sum of $F_{i,all}^{DE}$ and $F_{i,all}^{hh}$ equal the total impacts caused in the downstream chain of material resource production.

To assess the scope 3 impacts of material production, we applied the procedure described in Cabernard et al[36]: We defined all material extracting and processing sectors as target (T), and all the other sectors of the G20 database as the remaining economy (O, see SI_Classification_G20.xlsx). However, for those results shown in Figure C.13 and C.14 and discussed in Paragraph S9, we defined all biomass extracting and processing sectors as target (T), and all the other sectors of the G20 database as the remaining economy (O, see SI_Classification_G20.xlsx). This allowed us to calculate the scope 3 impacts of material production (and biomass production in Figure C.13 and C.14):

$$F_{i,all}^{MP} = D_{i-all} \times L_{all-T} \times (Y_{T-all} + A_{T-O} \times L'_{O-O} \times Y_{O-all}) \qquad \text{Eq. C.3}$$

$D_{i,all}$ refers to the impact coefficients of the respective indicator (i, e.g. GHG emissions) of all sector-regions of the MRIO database and L_{all-T} refers to the Leontief inverse (L) of the cumulated inputs of all sector-regions into global material resource production (T). The term in brackets of Eq. C.1 refers to the total final demand for material resources. This includes the the direct final demand for material resources (Y_{T-all}, e.g. food or fuels directly consumed by households) and the indirect final demand for material resources consumed via other end sectors ($A_{T-O} \times L'_{O-O} \times Y_{O-all}$), such as minerals ending up in construction or fuels used for public transport. The latter term was calculated from the matrix product of the direct inputs of global material resource production into the remaining economy (A_{T-O}), the cumulated input of the remaining economy into the remaining economy (L'_{O-O}) and the direct final demand for the remaining economy (Y_{O-all}). A detailed description of the procedure and derivation of all terms is described in Cabernard et al[36].

To allocate the impacts of material resource production to the four material resource groups (metals, non-metallic minerals, biomass, and fossil resources), we diagonalized the cumulated impact coefficients of the material sectors ($D_{i-all} \times L_{all-T}$) in Eq. C.3. This implies that the impacts are allocated to the material sector that is supplied, meaning that if fossil fuels are burned for metals production, the emissions released during fossil fuels production are allocated to metals and not accounted for in fossil fuels, to prevent double counting[34-36].

To assess the impacts of the remaining economy, which are caused in the downstream economy of global material resource production, such as by further manufacturing, construction, service, and other downstream activities ($F_{i,all}^{DE}$), we applied the method of Dente et al[34, 35, 40] to the G20 database:

$$F_{i,all}^{DE} = D_{i-O} \times L'_{O-O} \times Y_{O-all} \qquad \text{Eq. C.4}$$

Thereby, D_{i-O} refers to the impact coefficients of the global remaining economy, L'_{O-O} refers to the Leontief inverse of the remaining economy, and Y_{O-all} indicates the direct final demand for the remaining economy.

Paragraph C.6: Process and fuel type of GHG emissions

Greenhouse gas emissions are released by different processes to the air, such as calcination, biogenic emissions due to agriculture and waste, fuel combustion, and non-combustion related emissions of fossil resources, such as by mining of fossil resources. As these processes are listed as different environmental extensions in EXIOBASE3, we applied the respective impact coefficients (e.g., $D_{GHG,comb-all}$ for combustion-related GHG emissions) on Eq. C.3 and C.4 to allocate GHG emissions to these different processes. For the direct emissions of the G20's final demand ($F_{i,G20}^{hh}$, mainly heating and private transport), all GHG emissions are released by fuel combustion according to EXIOBASE3.

For GHG released by combustion, we further evaluated the type of fossil fuels that was combusted, namely coal, oil, gas and coke, based on the approach of ref[55] (where the carbon footprint of plastics production was split by the type of fossil fuel that was combusted). We extend this approach[55] to split both the GHG emissions of global material production and those released in the downstream chain by the type of fuel that was combusted. In this context, we first derived a fuel-specific global transaction and final demand matrix ($T_{fuel-all}^{GHG}$ and $Y_{fuel-all}^{GHG}$), whose columns indicate the combustion-related GHG emissions for each sector-region combination ($T_{fuel-all}^{GHG}$) and each final demand combination ($Y_{fuel-all}^{GHG}$) of the G20 database. The rows indicate the combusted fuel type, namely coal, petroleum, natural gas, and coke, as well as the region from which the fuel was sourced. We derived $T_{fuel-all}^{GHG}$ and $Y_{fuel-all}^{GHG}$ by the element-wise product of the fuel sector outputs of the monetary transaction and final demand matrices ($T_{fuel-all}^{mon}$ and $Y_{fuel-all}^{mon}$, in Euro), the inverted price vector ($p_{fuel}^{phy/mon}$, in t/Euro) and the emissions factor vector of fuels (e_{fuel}^{phy}, kg CO_2-eq / t):

$$T_{fuel-all}^{CO2} = T_{fuel-all}^{mon} * p_{fuel}^{phy/mon} * e_{fuel}^{GHG/phy} \qquad \text{Eq. C.5}$$

$$Y_{fuel-all}^{CO2} = Y_{fuel-all}^{mon} * p_{fuel}^{phy/mon} * e_{fuel}^{GHG/phy} \qquad \text{Eq. C.6}$$

We calculated $p_{fuel}^{phy/mon}$ from the element-wise division of the total output of each fuel sector indicated by the physical MRIO table of EXIOBASE3 (x_{fuel}^{phy}, in kg) through the respective total output indicated by the monetary MRIO table of EXIOBASE3 (x_{fuel}^{mon}, in Euro):

$$p_{fuel}^{phy/mon} = \frac{x_{fuel}^{phy}}{x_{fuel}^{mon}} \qquad \text{Eq. C.7}$$

For Saudi-Arabia and Argentina, we assumed the same prices as derived for the "Rest of the Middle East" and the "Rest of Latin America", respectively.

We compiled emission factors (e_{fuel}^{phy}, kg CO_2-eq / t) for coal, oil, gas, and coke[56]. For coal, we weighted the emission factor of anthracite, bituminous coal, sub-bituminous coal, lignite, and peat with the extracted volumes indicated by the UN IRP Material Flows Database[57].

In a second step, we calculated the contribution of each fuel type to the combustion-related GHG emissions of the economy ($T_{fuel-all}^{share_{GHG}}$) and the final demand ($Y_{fuel-all}^{share_{GHG}}$). For this we divided each element of the fuel-specific global transaction and final demand matrix ($T_{fuel-all}^{GHG}$ and $Y_{fuel-all}^{GHG}$) by its total fuels input:

$$T_{fuel-all}^{share_{GHG}} = \frac{T_{fuel-all}^{GHG}}{\sum_{fuel} T_{fuel-all}^{GHG}} \qquad \text{Eq. C.8}$$

$$Y_{fuel-all}^{share_{GHG}} = \frac{Y_{fuel-all}^{GHG}}{\sum_{fuel} TY_{fuel-all}^{GHG}} \quad \text{Eq. C.9}$$

Consequently, each column of the resulting matrices sums up to 100%, while its rows indicate the contribution of each fuel type sourced from a specific region to the combustion-related GHG emissions of a specific region-sector ($T_{fuel-all}^{share_{GHG}}$) or final demand combination ($Y_{fuel-all}^{share_{GHG}}$) that is supplied by the fuel.

Finally, we weighted the GHG emissions of global material resource production and its downstream chain (Eq. C.3 and C.4) with the fuel-specific contributions to evaluate the type of fuels burned at the different stages of the global resource value chain:

$$F_{GHG-comb,all}^{MP} = T_{fuel-all}^{share_{GHG}} \times diag(D_{comb-all}) \times L_{all-T} \times (Y_{T-all} + A_{T-O} \times L'_{O-O} \times Y_{O-all}) \quad \text{Eq. C.10}$$

$$F_{GHG-comb,all}^{DU} = T_{fuel-O}^{share_{GHG}} \times diag(D_{comb-O}) \times L'_{O-O} \times Y_{O-all} \quad \text{Eq. C.11}$$

where $D_{comb-all}$ and D_{comb-O} refer to the impact coefficients of fuel combustion of the global economy (all) and the remaining economy (O), respectively.

Similarly, we weighted the direct emissions of the global final demand with the fuel-specific contributions to distinguish the type of fuel burned by heating and private transport:

$$F_{GHG-comb,all}^{hh} = Y_{fuel-all}^{share_{GHG}} \times F_{GHG,all}^{hh} \quad \text{Eq. C.12}$$

The resulting total GHG emissions ($F_{GHG-comb,all}^{MP} + F_{GHG-comb,all}^{DE} + F_{GHG-comb,all}^{hh}$) still equal the global combustion-related GHG emissions as calculated with the common Leontief framework. However, the split into material resource production and downstream use, as well as its weighting with the fuel shares, allows to assess the type of fuels burned at the different stages of the G20's material resource value chain.

Paragraph C.7: Global value chain analysis

While previous studies[1-27] calculated production and consumption-based impacts with the common Leontief framework (Eq. C.1), the split into upstream, midstream and downstream impacts allows to illuminate the intermediate steps in the global value chain without double counting (Eq. C.2–C.12). The decomposition of these equations further allows to map the linkages in the global value chain, as illustrated in Figure 4.2 of Chapter 4 for GHG emissions. This was done by diagonalizing the different terms of the equations above (Eq. C.3–C.4, C.10–C.11), as explained by Cabernard et al[36] for global material resource production. For example, diagonalizing the impact coefficients allows to evaluate the link to the region and sector where the emissions are released and the impacts are caused. In contrast, diagonalizing the cumulated impact coefficients of the material sectors allocates the impacts to the produced raw material, while diagonalizing the final demand provides information on the sector in which material resources ultimately are used rather than produced.

C.3 Results and Discussion

Paragraph C.8. Methodical improvements

Differences between the results of Dente et al[34, 35, 40] (based on a Japanese input output table) and this study (based on the global MRIO database EXIOBASE3[41]) can also be observed for GHG emissions of Japan's material resources, which are far higher in this study (Figure C.2). This is attributed not only to differences in the underlying databases (discussed in ref[36]), and the downstream allocation (discussed above), but also because this study includes scope 3 GHG emissions of all material resources produced, consumed, and traded by Japan, while ref[34] excludes exports as well as material resources embodied in imports (e.g., metals embodied in imported electronics). In contrast to ref[34, 35, 40], this study's methodology further allows mapping the entire value chain of Japan's material-related GHG emissions. An example is shown in Figure C.3 at the aggregate level, illustrating the role of imports (f2) and exports (a2), and Japan's heavy dependence on oil for material resource production and use (c–e), the latter mainly for services, transportation, and heating (b–c).

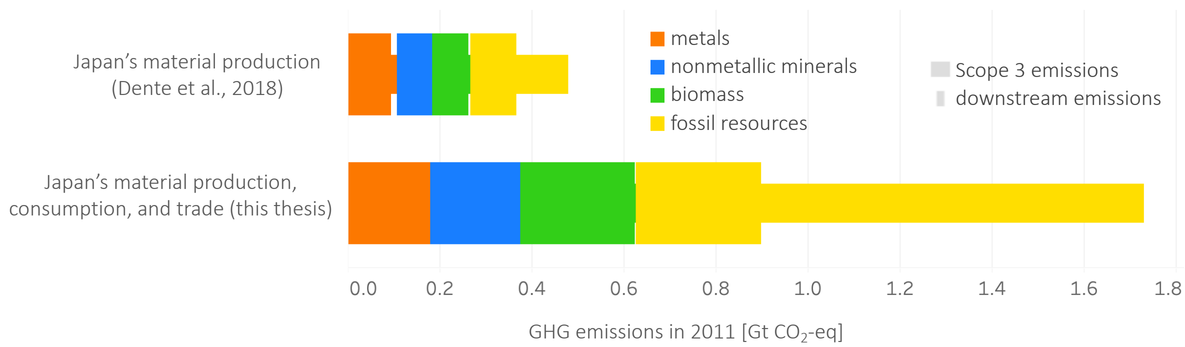
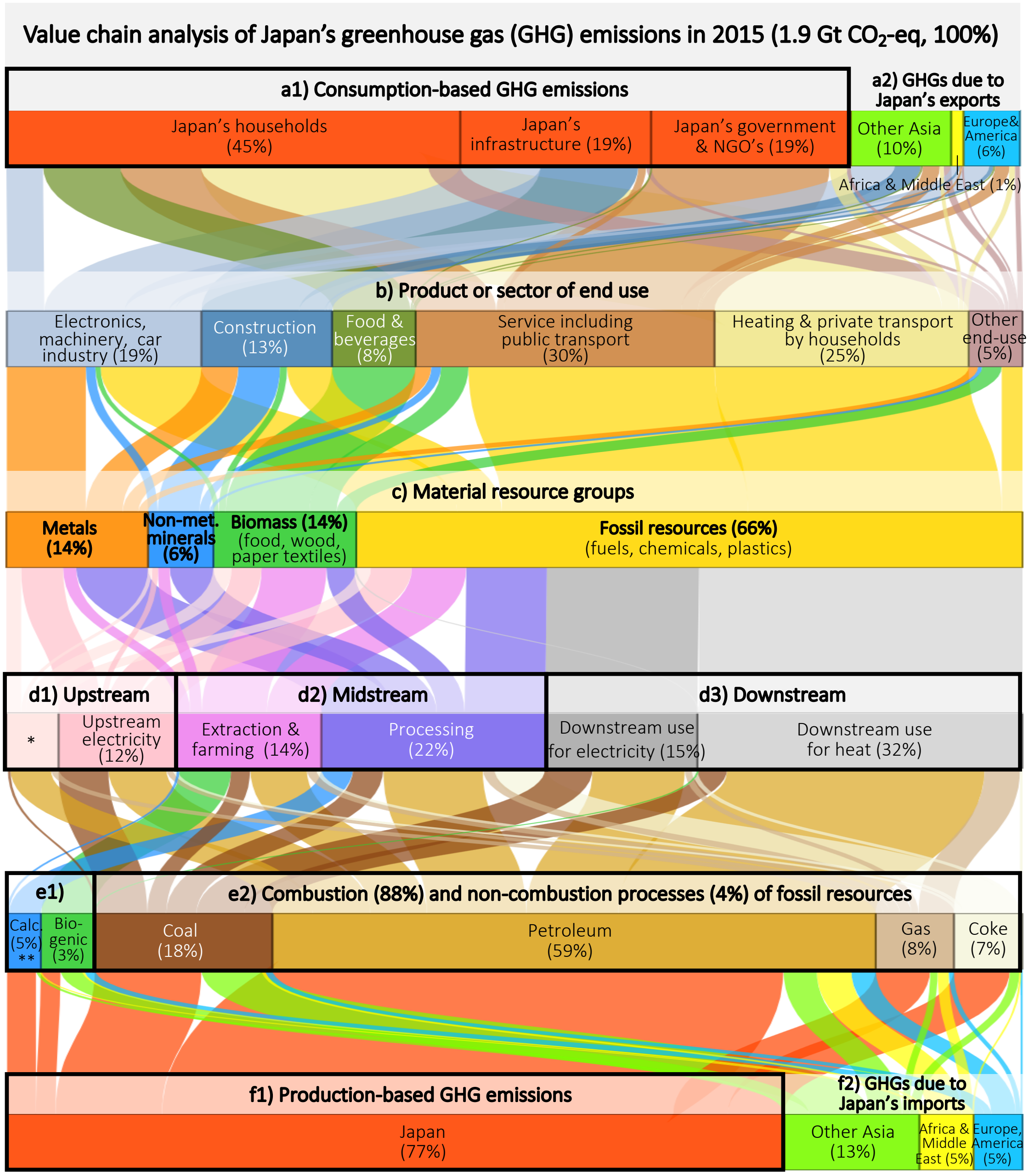


Figure C.2: Comparison of the results from Dente et al[34] on GHG emissions of Japan's material production to the GHG emissions of Japan's total material production, consumption, and trade based on this study's methodology (Year 2011).



*d1)*Other upstream GHGs of material resource production (5%)*

*e1)** Direct GHGs of cement and lime production and biogenic emissions from agriculture and waste*

Figure C.3. Carbon flow analysis of Japan's material value chain, including Japan's consumption-based GHG emissions (a1, carbon footprint) and Japan's domestic GHG emissions related to exports (a2) in 2015 (totally 1.9 Gt CO_2-equivalents, 100%). Each bar sums up to 100% and shows the GHG emissions from different perspectives in the global value chain, such as a) Japan's final demand category (households, infrastructure, government, and NGO's) and other regions where material resources are finally consumed, b) the product or sector where material resources are finally used for supplying final consumption, c) the four material resource groups, d) the split by upstream, midstream, and downstream emissions of material resources, e) the processes which release GHG emissions, and f) the regions where GHG emissions are released, which includes Japan's domestic GHG emissions (f1) and GHG emissions released abroad due Japan's imports (f2).

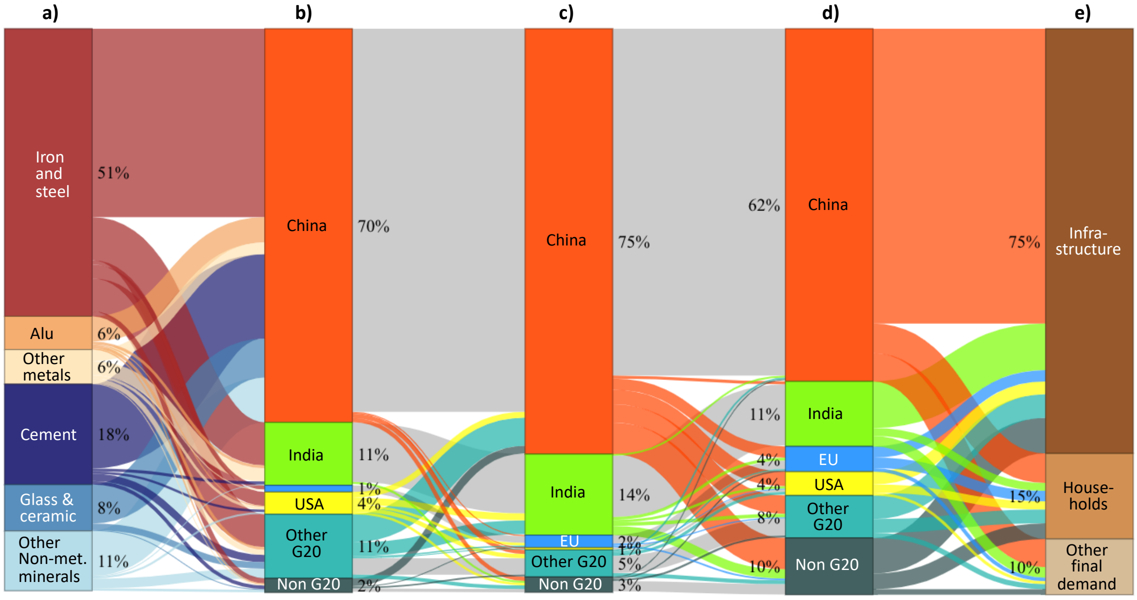


Figure C.4: Value chain analysis of the coal footprint of global minerals production in 2015 (3.9 Gt coal, 100%). Each bar sums up to 100% and shows the coal footprint of global minerals production from different perspectives (a–e), such as the mineral product (a), and the region where coal was extracted (b), minerals were processed (c), and minerals were consumed (d) by the respective final demand category (e).

Paragraph C.9. The G20’s rising impacts

From 1995 to 2015, the G20’s GHG emissions, PM health impacts, and water stress have increased by more than 44%, 18%, and 39%, respectively, both from a production and consumption (footprint) perspective (Figure C.5). The G20’s workforce increased by more than 15%, while the G20’s value added more than doubled from both perspectives. The reason why impacts increased at a similar speed from both perspectives is that the G20 include both high-income countries, who tend to consume more materials than they produce (net importers), as well as emerging economies, who tend to produce more materials than they consume (net exporters), and these two effects cancel each other out (Figure C.6). On a per-capita level, the G20’s GHG emissions have increased by more than 20% since 1995, reaching 8 t CO_2-equivalents per capita in 2015. Thus, the G20’s per-capita GHG emissions were by a factor of 2.5 higher compared to non-G20 members, while for the other environmental impacts, the G20’s per-capita impacts were only 40-70% higher (year 2015, Figure C.6).

Paragraph C.10. Split in material production and downstream chain

Overall, the G20’s consumption accounted for 82% of global GHG emissions (37 Gt CO_2-equivalents), more than 70% of global PM health impacts, water stress, land-use related biodiversity loss, workforce, and 86% of global value added (GDP) in 2015. Additionally, 4–5% of the global impacts were related to the G20’s exports to non-G20 members (Figure 4.2a of Chapter 4, Figure C.13b and C.14b). The production of material resources, including upstream and midstream impacts of material resource extraction and processing (scope 3), caused almost 60% of the G20’s GHG emissions, half of the G20’s PM health impacts, and more than 90% of the G20’s water stress and land-use related biodiversity loss (from both perspectives, Figure C.5b–e). The remaining fraction of all impacts was caused in the downstream chain of material production by the downstream economy (e.g., further manufacturing, construction, service) and households (e.g., heating and private transport). The G20’s GHG emissions released in the downstream chain of material production were almost exclusively (98%) attributed to fossil fuels burning. Including downstream impacts, fossil resources were thus the strongest contributor to the G20’s GHG emissions (Figure 4.2c–d of Chapter 4). In contrast, biomass production drove the G20’s water stress and land-use related biodiversity loss, mainly due to agriculture and farming for food and textiles production, and forestry for wood and paper production (Figure C.13 and C.14, Paragraph S11). Despite the high environmental impacts, material resource production contributed to only 22% of the G20’s total value added, but occupied more than half of the G20’s workforce due to low-paid jobs in agriculture (SI Figure C.5f–g, Figure C.15 and C.16).

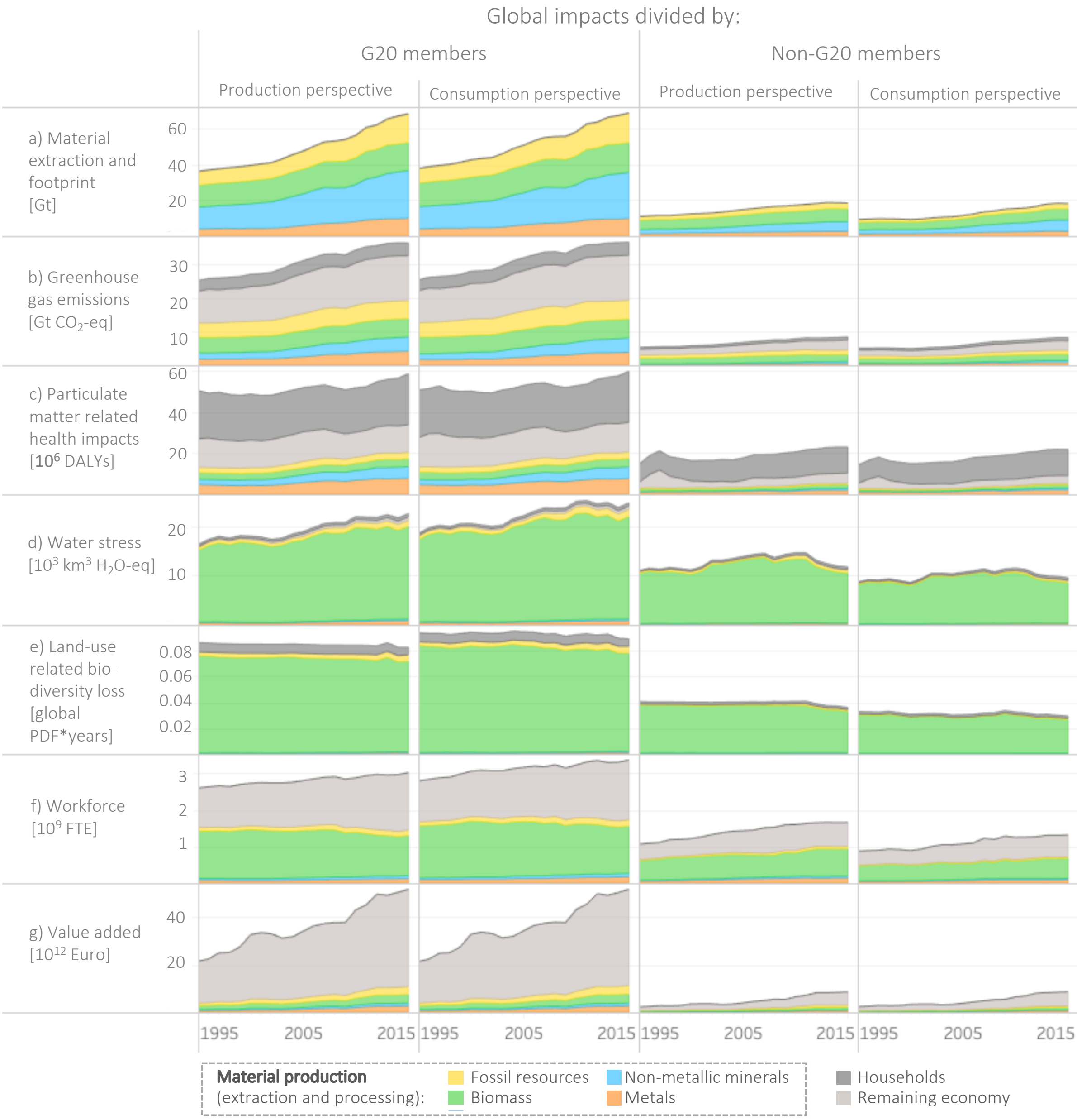


Figure C.5. Temporal development of the environmental and socioeconomic impacts of the G20 and non-G20 members from a production and consumption (footprint) perspective from 1995 to 2015. While the production perspective indicates the domestic impacts, the consumption perspective indicates the impacts related to final consumption, including the impacts related to imports, but excluding those of the exports. Results on a per-capita level are shown in Figure C.6. Note global land-use related biodiversity loss shows a decreasing trend that in EXIOBASE3[5, 41], which is in contrast to other studies[14].

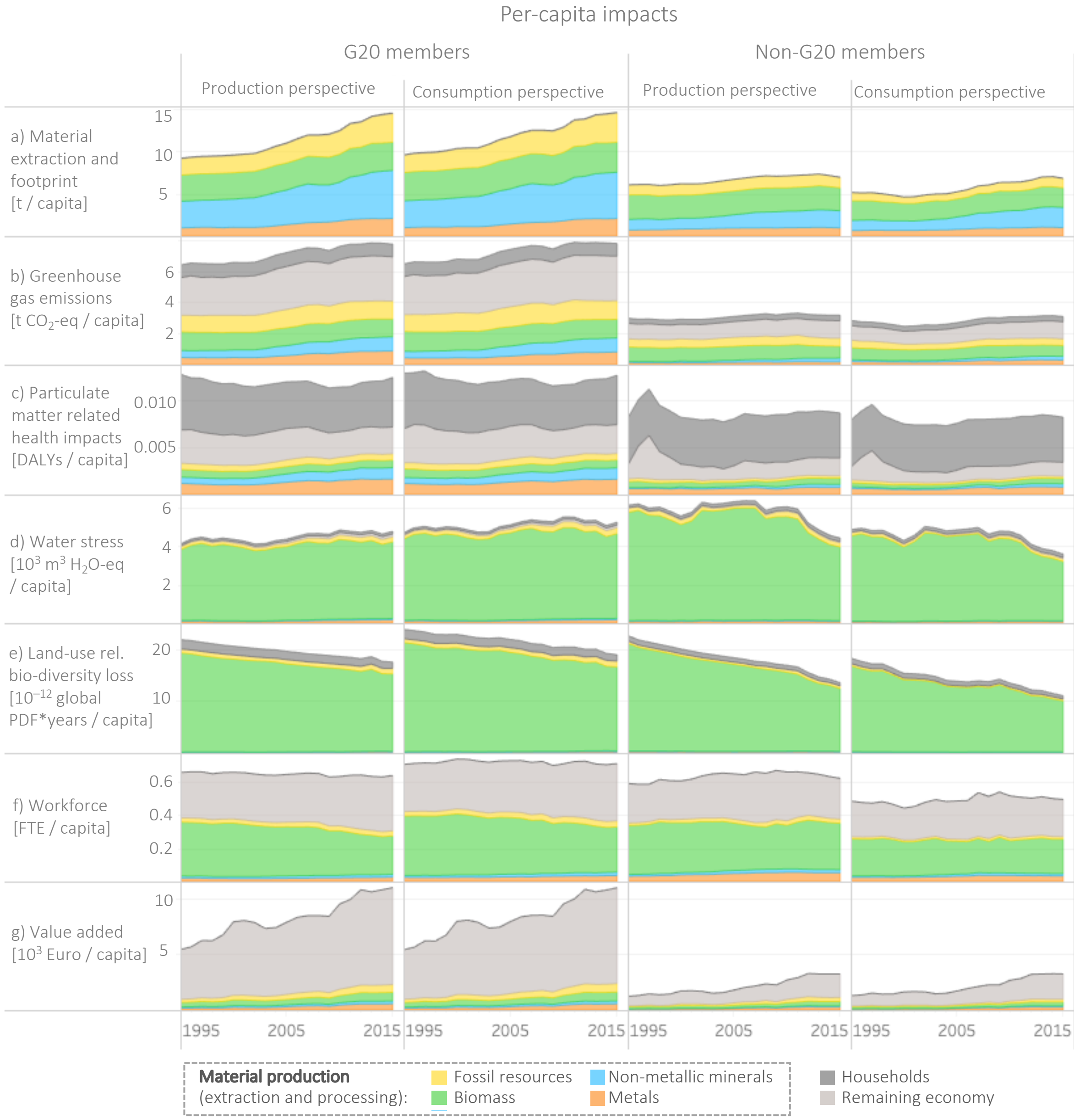


Figure C.6. Temporal development of the environmental and socioeconomic impacts of the G20 and non-G20 members from a production and consumption (footprint) perspective from 1995 to 2015 on a per-capita level. While the production perspective indicates the domestic impacts, the consumption perspective indicates the impacts related to final consumption, including the impacts related to imports, but excluding those of the exports. Note global land-use related biodiversity loss shows a decreasing trend that in EXIOBASE3[5, 41], which is in contrast to other studies[14].

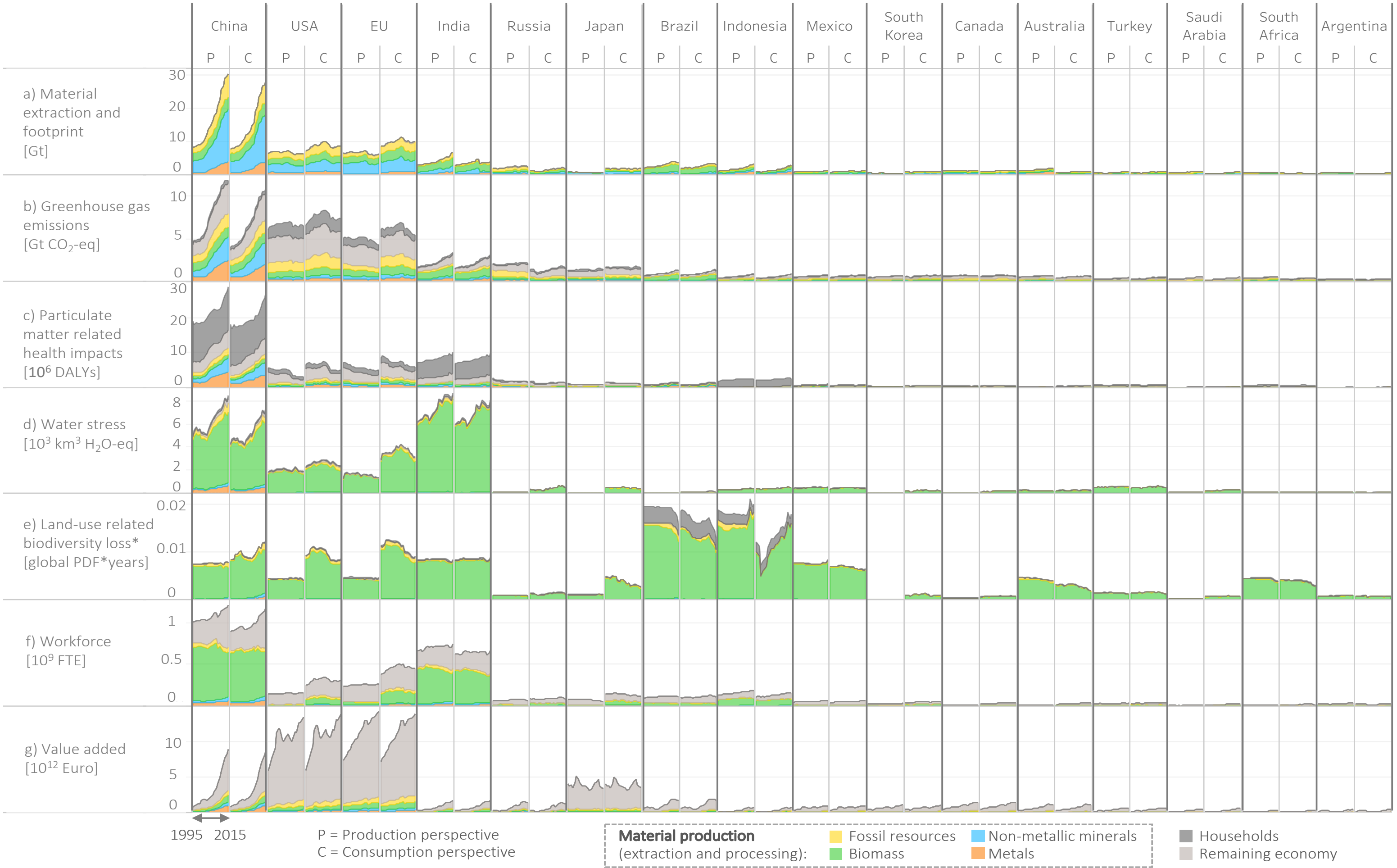


Figure C.7. Temporal development of the total environmental and socioeconomic impacts of the G20 members split by material resource production (metals, non-metallic minerals, biomass, fossil resources) and material resource use in the downstream economy and by households (mainly fossil fuels, see Figure 4.2 of Chapter 4) from 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. The same results are shown on a per-capita level in Figure 4.7 of Chapter 4. Note global land-use related biodiversity loss shows a decreasing trend that in EXIOBASE3[5, 41], which is in contrast to other studies[14].

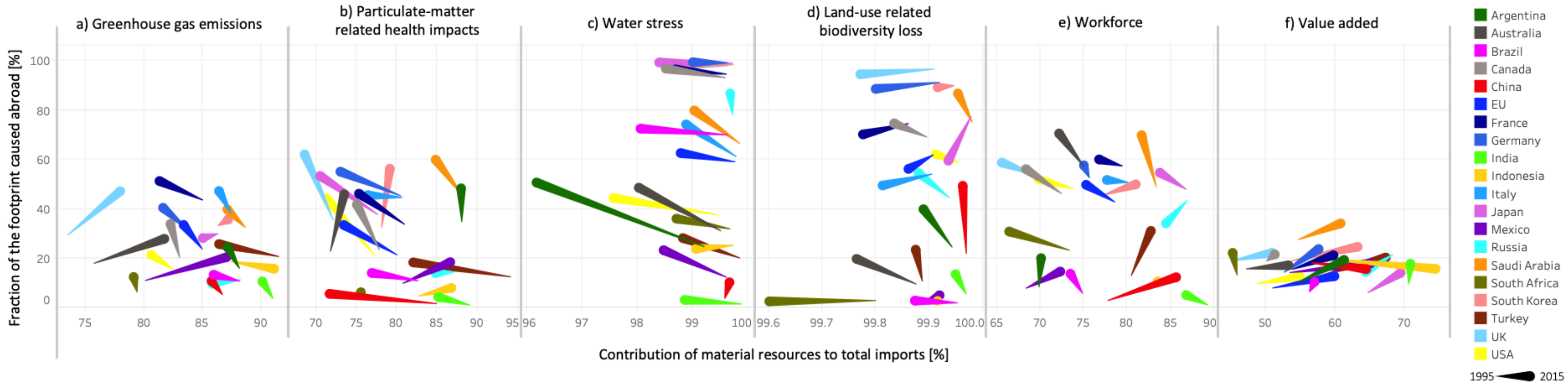


Figure C.8. Change in the fraction of the G20 members' footprints caused abroad due to imports plotted against the contribution of material resources to total imports between 1995 and 2015.

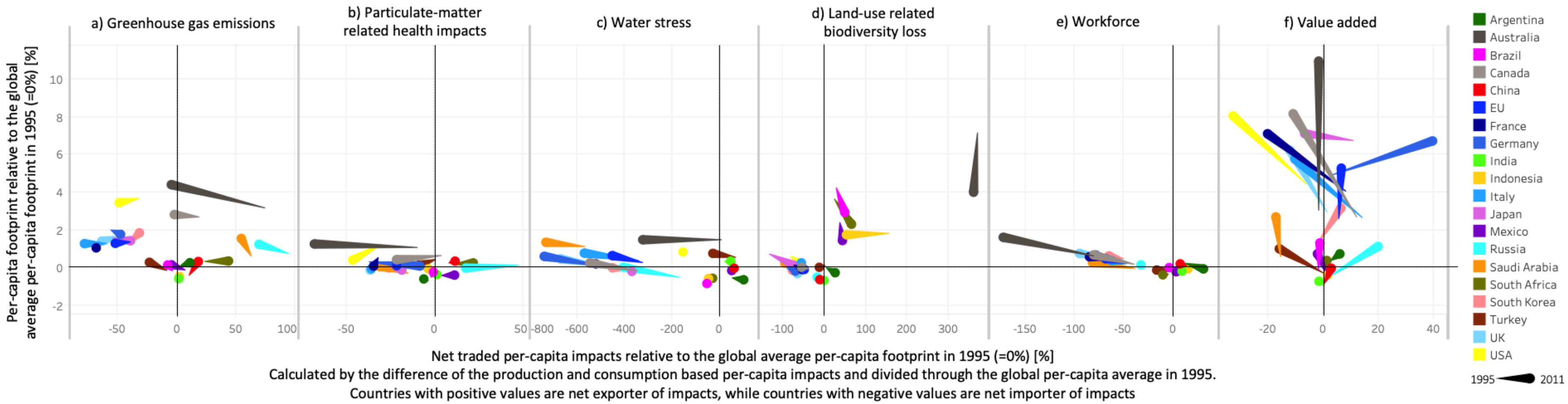


Figure C.9. Change in the G20 members' per-capita footprints plotted against the net traded impacts between 1995 and 2011. The Figure is shown for the time span until 2011 because the data afterwards are now-casted and thus subject to high uncertainty[5, 41]. The results for the time span from 1995 to 2015 are shown in Figure C.11 for EXIOBASE3 (used in this study) and Figure C.12 for a comparison of net traded greenhouse gas emissions in EXIOBASE3 and Eora26.

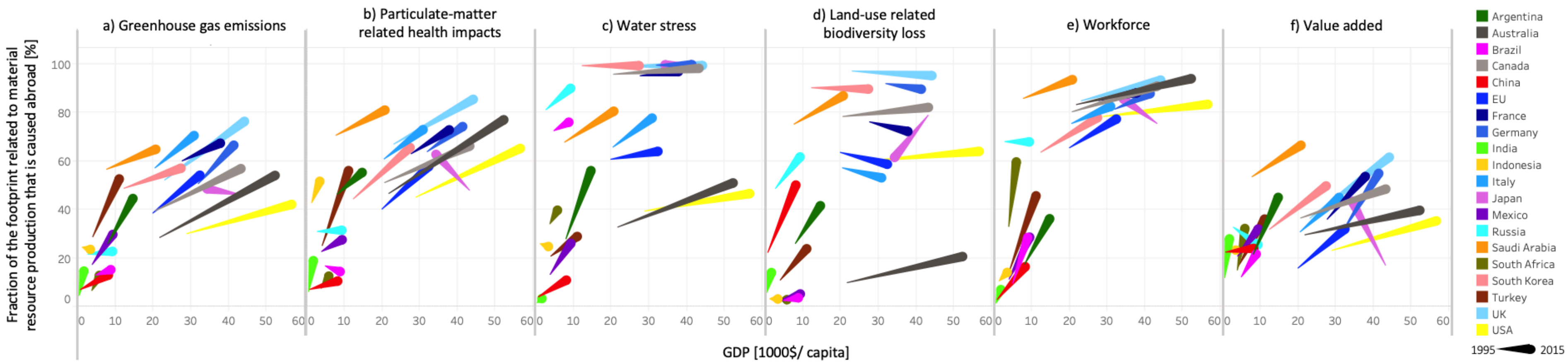


Figure C.10. Change in the fraction of the G20's footprints related to material resource production that is caused abroad due to material resource imports from 1995 to 2015 plotted against the GDP. The footprint due to material resource production includes the impacts related to the extraction and processing of material resources to ready-to-be used materials, foods and fuels, but excludes the impacts related to the use of material resources in the downstream economy and by households.

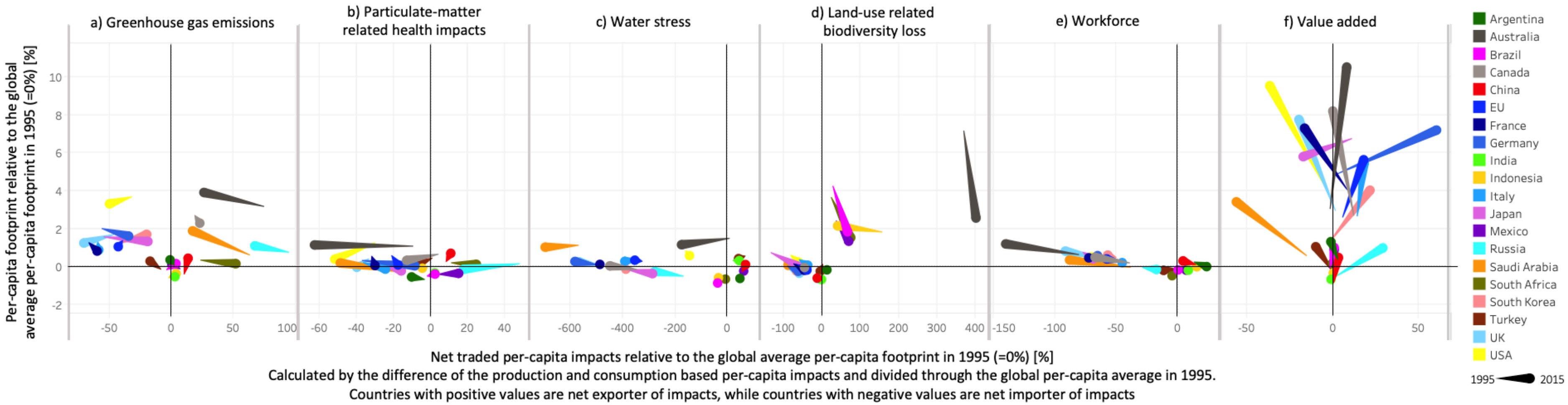


Figure C.11. Same as Figure C.10, but shown for the time span from 1995 to 2015, where the increasing net imported impacts of high-income regions like the EU and USA are less visible than for the time span from 1995 to 2011. Since data after 2011 are now-casted in EXIOBASE3[5, 41], these results are subject to higher uncertainty and need to be considered critically. A comparison of the change in net traded greenhouse gas emissions during the two time periods is shown for EXIOBASE3 and Eora26 in Figure C.12.

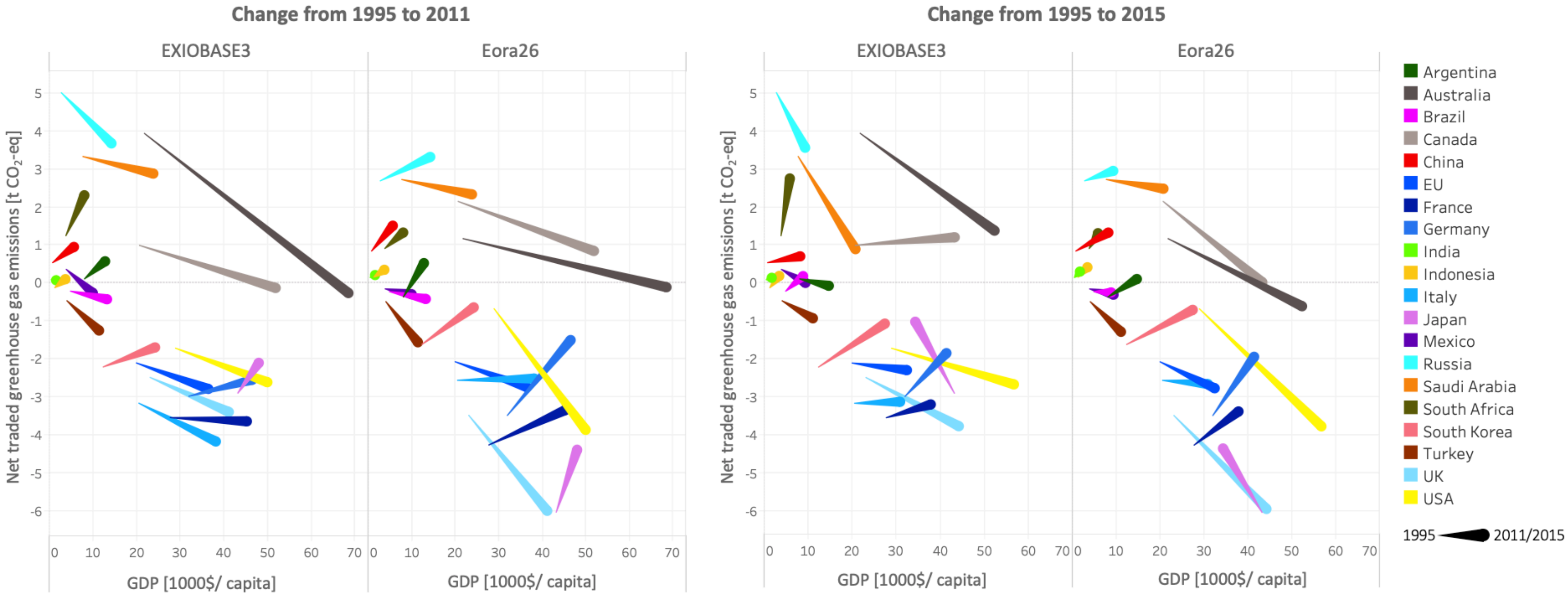


Figure C.12. Change in net traded greenhouse gas emissions from 1995 to 2011 and from 1995 to 2015 in EXIOBASE3 (used in this study) and Eora26 plotted against the GDP. For the time period from 1995 to 2015, high-income regions like the EU and the USA show a stronger increase in the net imported greenhouse gas emissions in Eora26, where data are not now-casted.

Paragraph C.11. The G20's water stress and biodiversity loss impacts

The value chain of the G20's water stress and land-use related biodiversity loss is shown in Figure C.13 and C.14 from a consumption (b1) and production perspective (c1), including the role of trade with non-G20 members (b2 and c2), in 2015. In contrast to previous studies on the G20's footprints[58, 59], Figure C.13a and C.14a illustrate the scope 3 impacts of those biomass products which contribute strongest to the G20's water stress and biodiversity loss impacts (note that in standard consumption-based accounting the impacts of these materials are allocated to the sector of end-use instead of the materials). It reveals that meat and dairy products account for 10% of the G20's water stress footprint and a third of the G20's land-use related biodiversity loss. Textiles account for 7% of the G20's water stress and 4% of the G20's land-use related biodiversity loss. The G20's water stress footprint of textiles has more than doubled over since 1995, both from a production and consumption perspective. This was mainly attributed to China's increasing textile production and demand from other regions.

Figure C.13 and C.14 show that more than 10% of the G20's water stress and land-use related biodiversity loss footprint were caused in non-G20 members, mostly due to food imports by the EU, USA and China. From a consumption perspective, almost 80% of the G20's water stress was related to food consumption by China, India, the EU and the USA. The cultivation of crops accounted for 85% of the G20's water stress and one third of the G20's land-use related biodiversity loss (production perspective, Figure C.13d and C.14d). Cattle farming and forestry each contributed to 29% of the G20's land-use related biodiversity loss. Almost half of the biodiversity loss due to cattle farming was caused in Brazil and Mexico, while most forestry-related biodiversity loss was caused in Indonesia (Figure C.14c–d). Despite the high environmental footprints, agriculture contributed to only 3% of the G20's value added, but occupied 35% of the G20's total workforce due to low-paid agricultural work.

China and India contributed strongest to the G20's increasing water stress from both a production and consumption perspective (Figure C.13b–c). In 2015, more than 70% of the G20's domestic water stress occurred in China and India (production perspective, Figure C.13c–d). The main reasons were the increased cultivation of wheat, rice, and other crops due to China and India's growing population and China's increased per-capita consumption of food. The low-pay associated with agricultural work explains why China and India employed 80% of the people working in the G20's material resource sector, but generated only one-third of the related value added (Figure C.13c–d and C.14c–d). A similar imbalance between impacts and benefits was also observed for Brazil, Indonesia, and Mexico, where half of the G20's domestic land-use related biodiversity loss was induced by agriculture and forestry (Figure C.13c–d), while generating only 7% of the G20's value added (Figure C.7g).

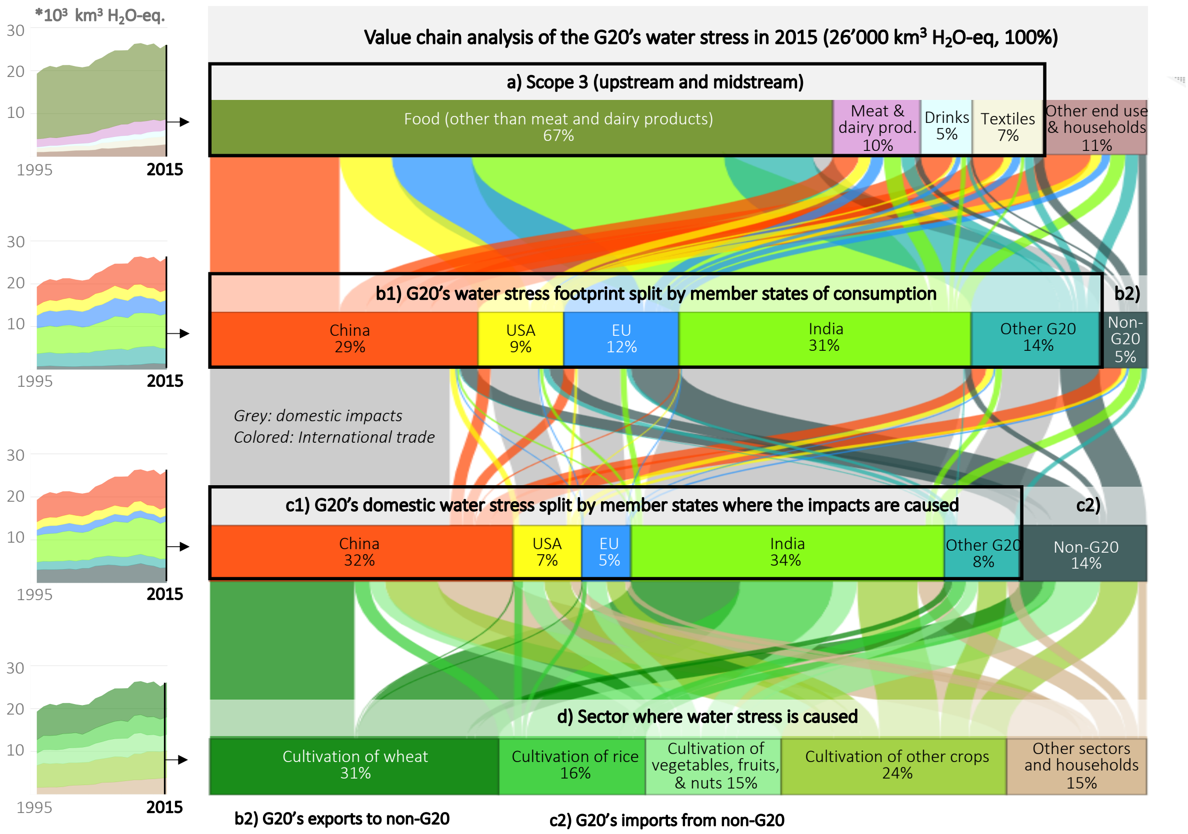


Figure C.13. Value chain analysis of the G20's consumption-based water stress (b1, water stress footprint) and the G20's exports to non-G20 members (b2) in 2015 (totally 26'000 km^3 H_2O-equivalents, 100%). Each bar sums up to 100% and allocates the G20's water stress to the different perspectives in the global value chain, such as a) those biomass products which contribute strongest to the G20's water stress, b) the region of final consumption, c) the regions where water stress is caused, and d) the industrial sector where water stress is caused. The small graphs to the left show the temporal development from 1995 to 2015.

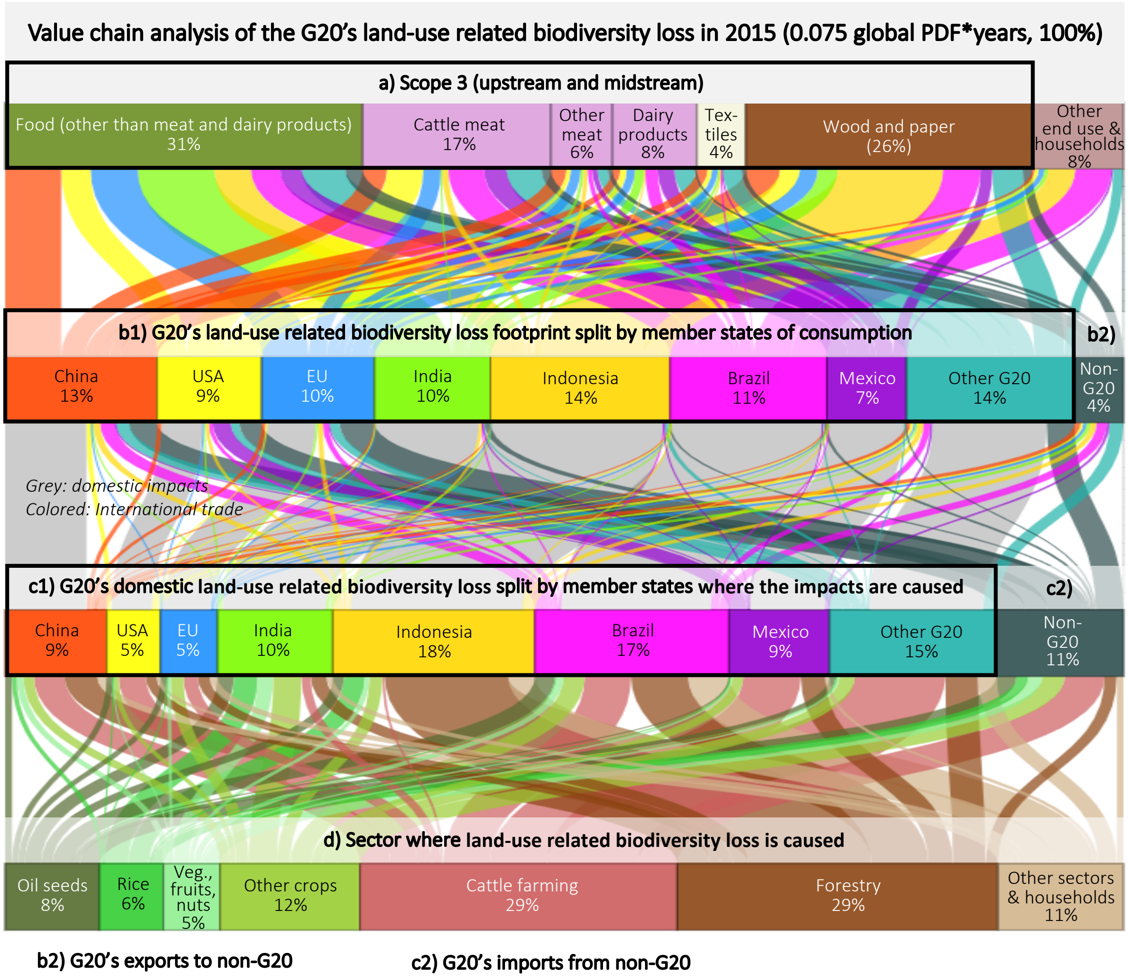


Figure C.14. Value chain analysis of the land-use related biodiversity loss of the G20's consumption (b1) and exports to non-G20 members (b2) in 2015. Each bar sums up to 100% and allocates the G20's land-use related biodiversity loss to the different perspectives in the global value chain, such as a) those biomass products which contribute strongest to the G20's land-use related biodiversity loss impacts, b) the regions of final consumption, c) the regions where biodiversity loss is caused and d) the industrial sector where biodiversity loss is caused. The 100% correspond to 0.075 global PDF*years, which means that due to the G20's consumption and exports, 7.5% of world's species were extinct in 2015.

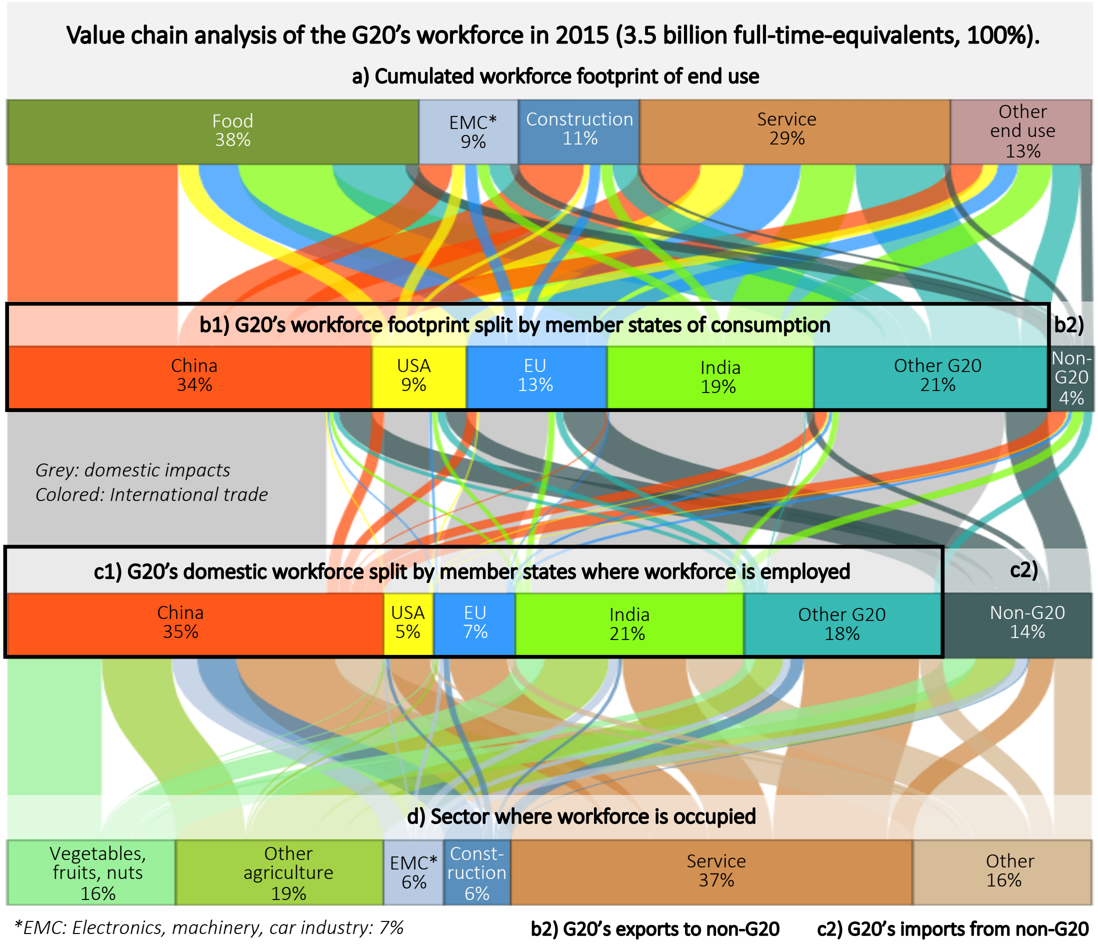


Figure C.15. Value chain analysis of the workforce occupied for the G20's consumption (b1) and exports to non-G20 members (b2) in 2015 (totally 3.5 billion full-time-equivalents, 100%). Each bar sums up to 100% and allocates the workforce to the different perspectives in the global value chain, such as a) the product or sector where material resources are finally used b) the regions where material resources are finally used, c) the regions where the workforce is occupied and d) the industrial sector where the workforce is occupied.

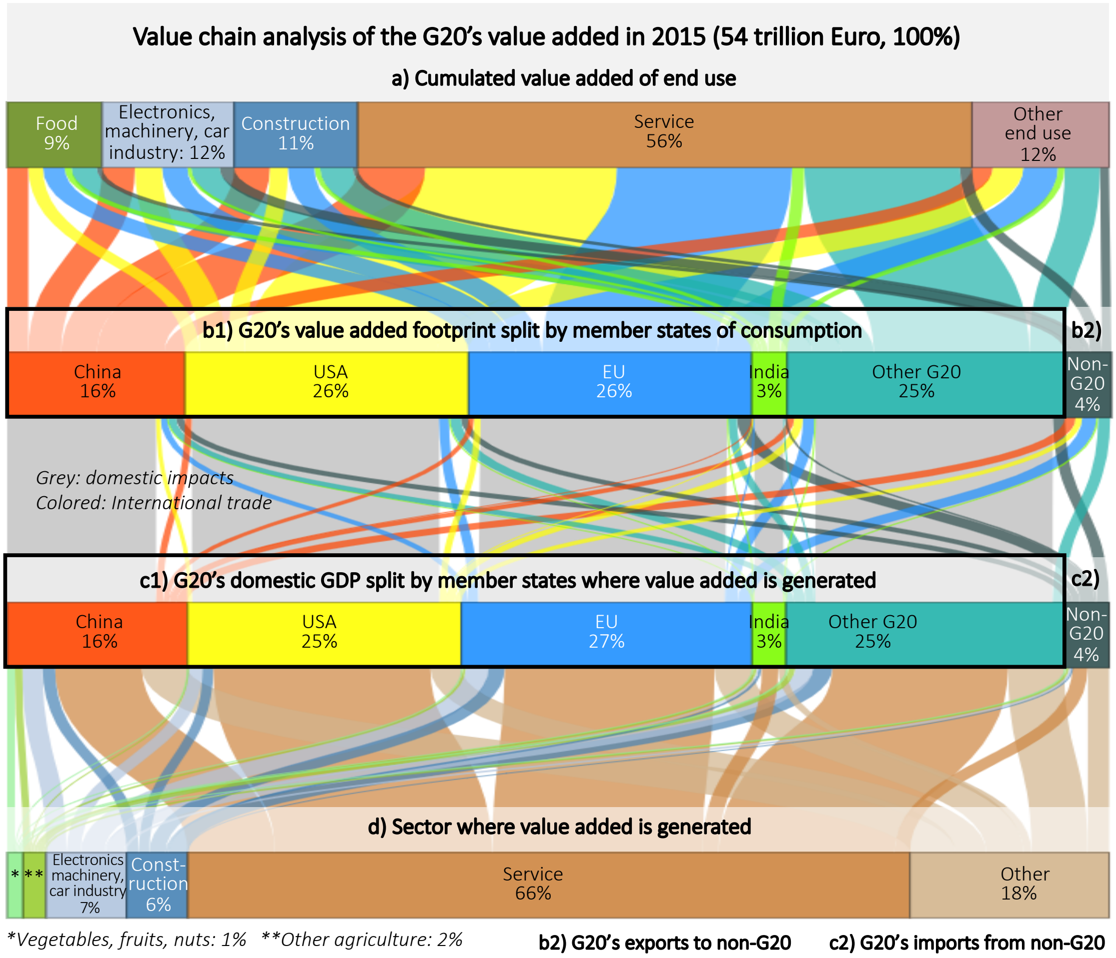


Figure C.16. Value chain analysis of the value added related to the G20's consumption (b1) and exports to non-G20 members (b2) in 2015 (totally 54 trillion Euro, 100%). Each bar sums up to 100% and allocates the value added to the different perspectives in the global value chain, such as a) the product or sector where material resources are finally used b) the regions where material resources are finally used, c) the regions where the value added is generated and d) the industrial sector where the value added is generated.

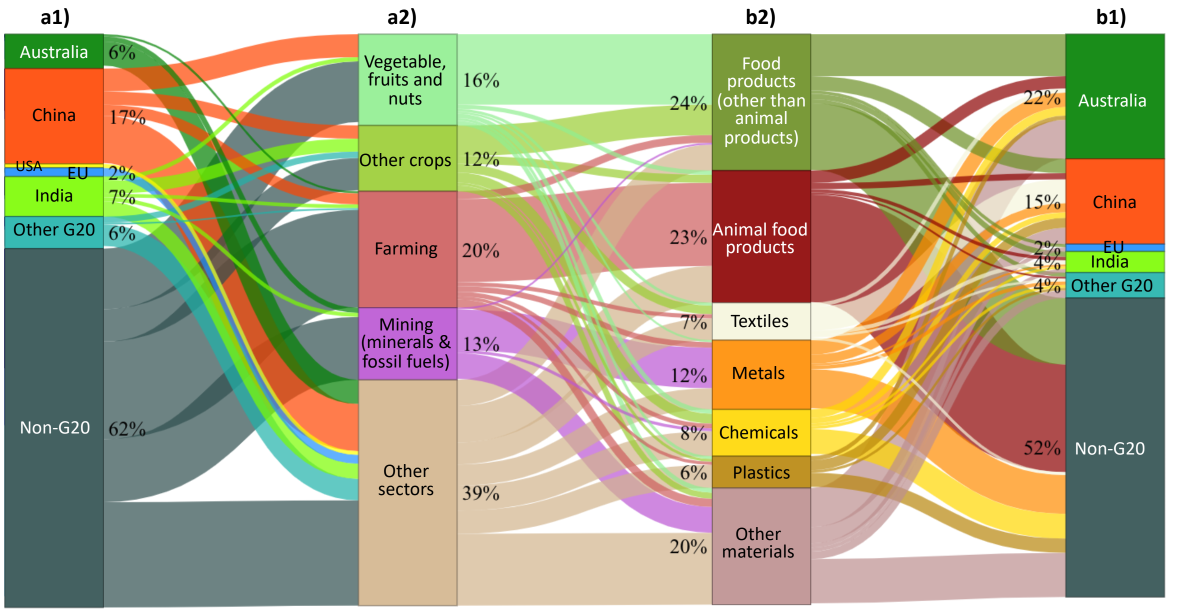


Figure C.17: In-depth analysis of the workforce employed to supply Australia's material consumption in 2015 (totally 15'500 full-time equivalents, 100%). Each bar sums up to 100% and shows the workforce required to supply Australia's material consumption from different perspectives to map the intermediate steps in the value chain, such as the region (a1) and sector (a2) where the workforce was occupied and the link to the region (b1) where they were processed into ready-to-be used materials (b2). Note that half of these materials were directly imported and consumed by Australia (mainly food) and the other half was further manufactured, either abroad or in Australia, before consumed by Australia (e.g., metals, chemicals, and plastics into electronics, machinery, and transport equipment).

C.4 Conclusion

Paragraph C.12

Our results supports earlier findings on the unprecedented displacement of environmental[1-4, 6, 9] and socioeconomic[4] impacts due to international trade, particularly from higher to lower income regions. However, other than previous work[58-60], this study evaluates the geographical and sectoral relationships in the G20's material resource value chain and shows that trade in material resources is the major cause of the impact displacement for all indicators (70–100%, Figure 4.7 of Chapter 4, Figure C.8–C.11). In contrast to this study, Xu et al[61] found a positive effect of international trade on many sustainable development goals. This is because they measured progress towards the sustainable development goals relative to the GDP. The positive trade effect found by Xu et al[61] implies that international trade increases GDP more than environmental impacts. This trend is referred to as the relative decoupling of environmental impacts from GDP. In the same way that international trade increases GDP by using comparative cost benefits, it could also reduce environmental impacts by using local advantages in water and land resources, such as shifting agriculture to water-abundant and land-abundant regions[62, 63]. However, this study supports previous findings[1, 2] that many high-income regions strongly rely on biomass products from regions with high water stress and biodiversity loss (Figure 4.7d–e of Chapter 4, Figure C.10c–d, C.13, and C.14). One reason is that, unlike comparative cost benefits, environmental impacts are not reflected in the price, which is a major incentive for consumers. A potential countermeasure would be internalizing supply chain impacts in the price, which requires impact transparency. This study's method and database allows mapping the environmental and socioeconomic impacts of international trade in material resources and identifying its sustainable development potential.

Although growing GDP can sometimes contribute to more carbon equality[64] (Figure 4.6a) and decrease emissions through technology improvements[65] (Figure 4.6a, e.g. for the EU), it is also the key driver of the increasing global environmental impacts[66]. This is because rising affluence leads to an increase in consumption, which ultimately outpaces the emission reductions achieved through technology improvements[67-72]. Thus, it is crucial to tackle the overwhelming power of consumption and the economic growth paradigm[73]. This also underlines the importance of measuring progress towards sustainable development in relation to planetary boundaries[74, 75] instead of GDP[61], by specifying science-based targets, such as carbon budgets. Although the Paris Agreement sets specific emissions targets for the most important economies, it is restricted to domestic emissions. This explains why Roelfsema et al[60] found an emission gap in meeting the Paris Agreement for several G20 members that are major exporters of material resources, such as China and Russia. In contrast, the EU and USA were projected to meet their targets[60] despite their higher carbon footprints (Figure 4.6a). As shown here, these reductions are realized through outsourcing of the environmental impacts due to increased material resource imports. Extending the national contributions of the Paris Agreement to a consumption perspective and creating transparency on the G20's material resource value chains is thus crucial to address supply chain management in policy making.

C.5 References

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Appendix D

Growing environmental footprint of plastics driven by coal combustion

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D.1 Methods

Methods D.1. Carbon intensities of plastics resin production

The carbon intensity of resin production indicates the cumulative GHG emissions related to the production of one kg of plastics resin. To estimate the carbon intensity of resin production (in kg CO_2-eq / kg resin) per region and year, we calculated the cumulative GHG emissions of resin production based on Eq. 5.1 of Chapter 5 and divided it by the resin production amounts per region and year. Since resin production data from 1995 to 2015 were not available for most regions, we estimated the approximate amount of plastics resin produced per region for this time span by multiplying the monetary total output vector of plastics resin production per country and year (x_{resin}^{mon}, in Euro) with the country-specific inverted resin price vector for the year 2011 ($p_{resin}^{phy/mon}$, in kg / Euro). Similar to the inverted fuel price vector (Eq. 5.6 of Chapter 5), we calculated the inverted resin price vector ($p_{resin}^{phy/mon}$, in kg / Euro) from the quotient of the physical (x_{resin}^{phy}, in kg) and monetary (x_{resin}^{mon}, in Euro) total output vector of resin production in 2011 (from EXIOBASE3). Although this approach neglects temporal price fluctuations, it provides an estimate on the resin production amounts, which are in the range of available resin production data (Figure D7).

D.2 Results and Discussion

Results D.1. The EU and the USA induce half of the plastics-related GHGs in the Middle East

Over the past two decades, the EU and USA's plastics-related carbon footprint induced abroad has quadrupled in China and tripled in the Middle East (Figure D.5 and D.6). Plastics-related GHG emissions in the Middle East have tripled from a production perspective since 1995 (Figure 5.1 of Chapter 5). This increase was mostly driven by foreign plastics demand. In 2015, 90% of the plastics-related GHG emissions in the Middle East were attributed to foreign plastics demand, and more than half were attributed to the EU and USA. Plastics-related GHG emissions in the Middle East were induced by domestic plastics production and oil and gas extraction and processing for foreign plastics production. In contrast to China, Indonesia, Other Asia, and South Africa, which mined almost 90% of the plastics-related coal, the Middle East extracted more than a third of the oil and more than half of the gas used for global plastics production in 2015 (Figure 5.2a–b of Chapter 5). Only 5% of the plastics-related oil and gas extracted in the Middle East were used for domestic plastic production, and the vast majority (95%) was exported as energy carriers and feedstock for plastics production in other regions, mainly China (40%) and Other Asia (33%, Figure 5.2b–c of Chapter 5).

Results D.2. China's carbon intensity of resin production is twice the global average

From 1995 to 2015, the carbon intensity of global resin production decreased from 6.8 to 4.5 kg CO_2-equivalents per kg resin (Figure D.7b). Decreasing carbon intensity of plastics resin production due to technology improvements explain why domestic GHG emissions from resin production have decreased in the EU and USA (Figure D.5 and D.6), even though their plastics resin production has increased over the past decades (Figure D.7a). Although China's carbon intensity of resin production has decreased by a factor of three, it is still twice the global average in 2015 due to its strong reliance on coal. Similarly, the carbon intensity of resin production in India, Indonesia, and South Africa is distinctly above the global average. Since a plastics production growth is expected for coal-based economies with high carbon intensity of resin production, a fast exit from coal and transition to renewable energy is important to reduce the global carbon and PM health footprint of plastics in the future. Since the EU and USA increasingly consume carbon-intensive plastics from coal-based economies, it is important that they invest in cleaner energy in their plastics supply chain for improving their plastics-related carbon and PM health footprints. However, an increase in domestic plastics production is also expected for the USA in the next decade due to their booming shale gas production[1], which is expected to make the USA's plastics production competitive with China's cheap coal-based plastics. The USA's shale gas extracting industry releases high amounts of methane emissions into the air, which have been underestimated in previous inventories[2]. Therefore, improved environmental practices and standards are also important in the domestic supply chain of the USA's plastics production.

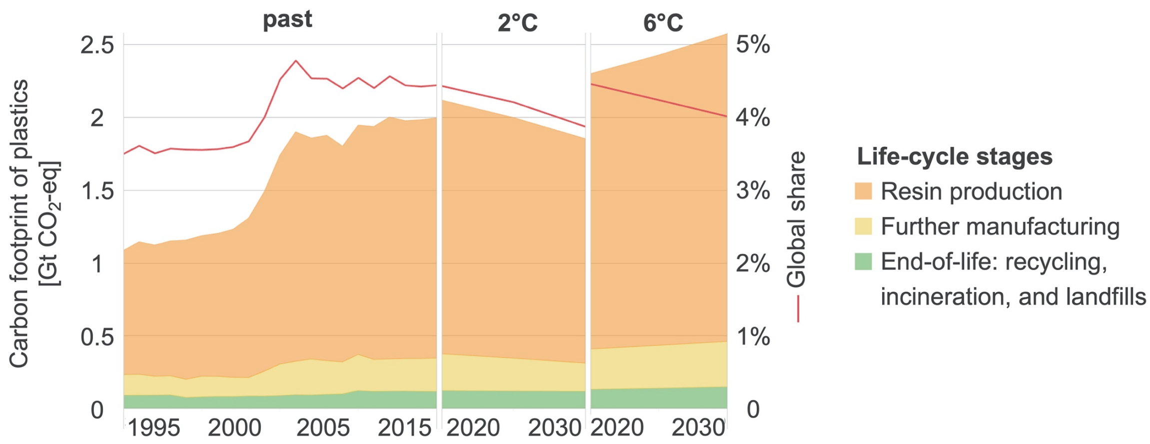


Figure D.1. Temporal development of the global carbon footprint (GHG emissions) of plastics from 1995 to 2015 and from 2020 to 2030 under different scenarios (2-degree and 6-degree scenario until 2100[34,35]) divided by life-cycle stages. The value chain analysis of the carbon footprint of global plastics production (resin production and further manufacturing) is shown in Figure 5.1 of Chapter 5 for the year 2015. The temporal development of the global carbon footprint of plastics recycling, incineration, and landfills is shown separately in Figure D.2.

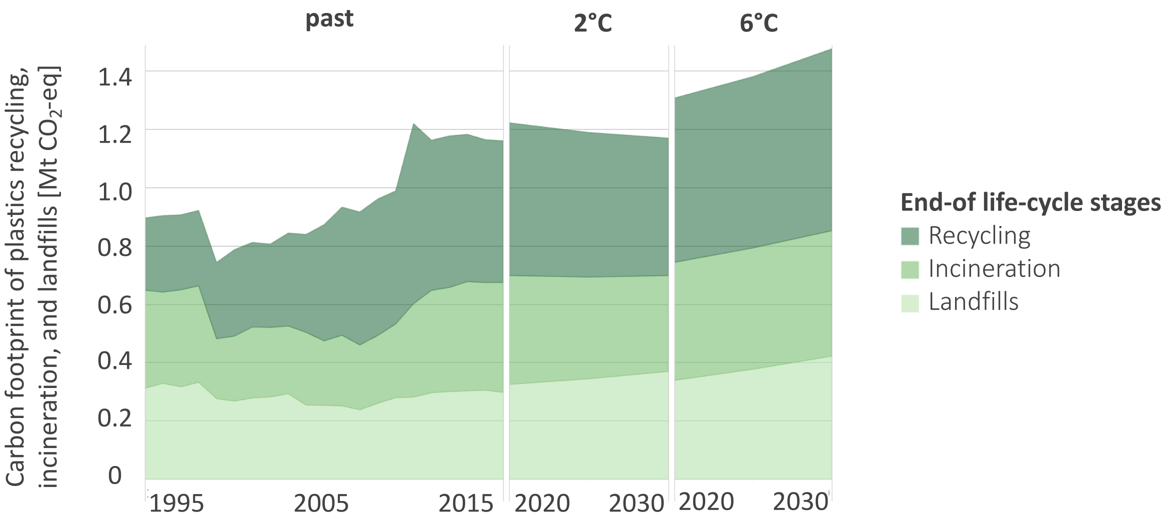


Figure D.2. Temporal development of the global carbon footprint (GHG emissions) of plastics recycling, incineration, and landfills from 1995 to 2015 and from 2020 to 2030 under different scenarios (2° and 6° scenario until 2100[3, 4]). Note that in this figure, no credits were given for the saved primary plastics production. The according savings through primary plastics substitution were accounted for in the decreased impact of (primary) plastics production shown in Figure 5.1 of the main paper and Figure D.1. The value chain analysis of the carbon footprint of global plastics recycling is shown in Figure D.3 for the year 2015.

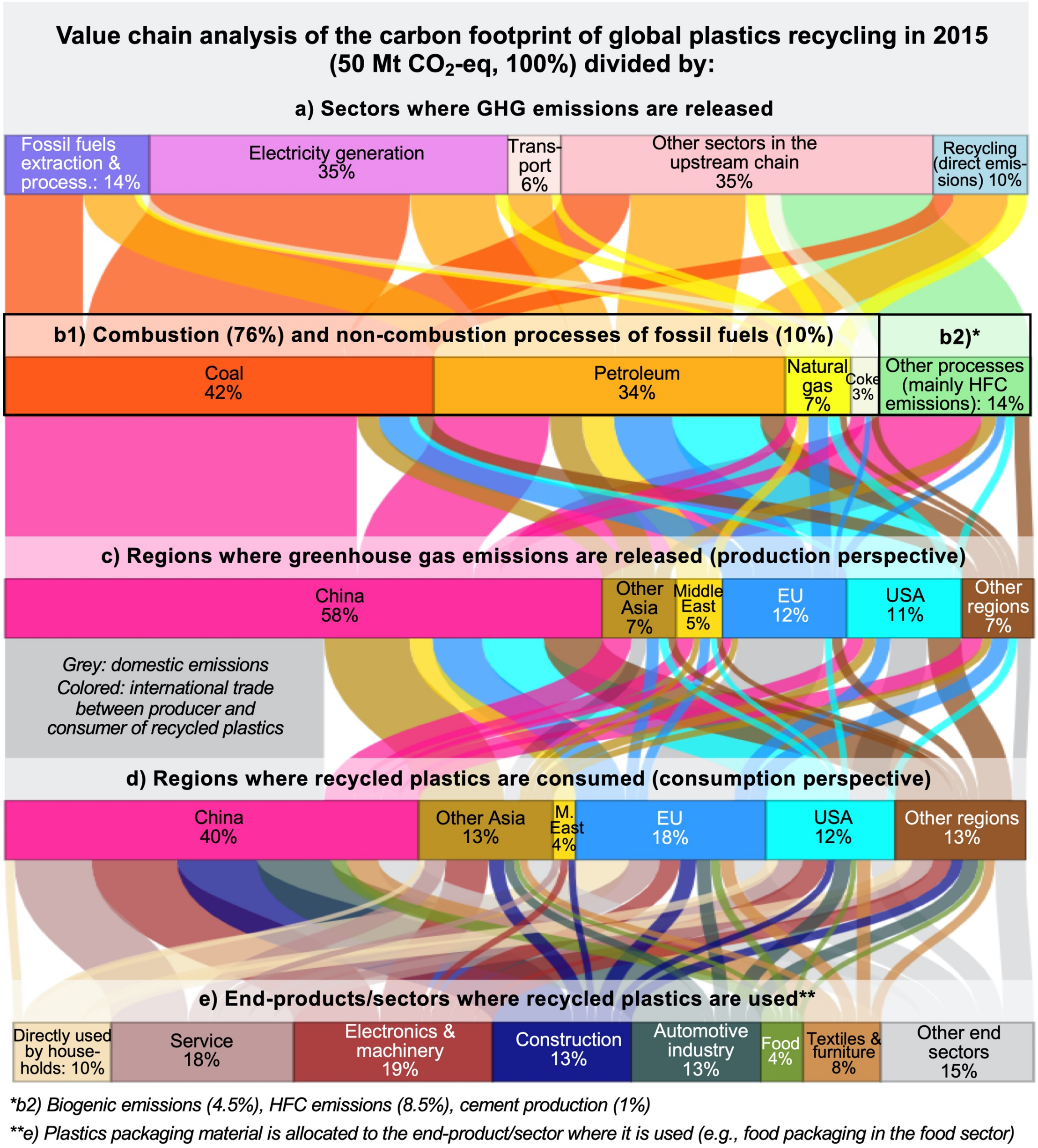


Figure D.3. Global value chain analysis of the carbon footprint of global plastics recycling in 2015 (50 Mt CO_2-equivalents). The format is the same as in Figure 5.1 of Chapter 5, except that Indonesia is part of "Other Asia" and South Africa is part of "Other regions" in this figure. It shows the cradle-to-gate GHG emissions of global plastics recycling, and excludes the GHG emissions of resin production and further manufacturing (which are shown in Figure 5.1 of Chapter 5).

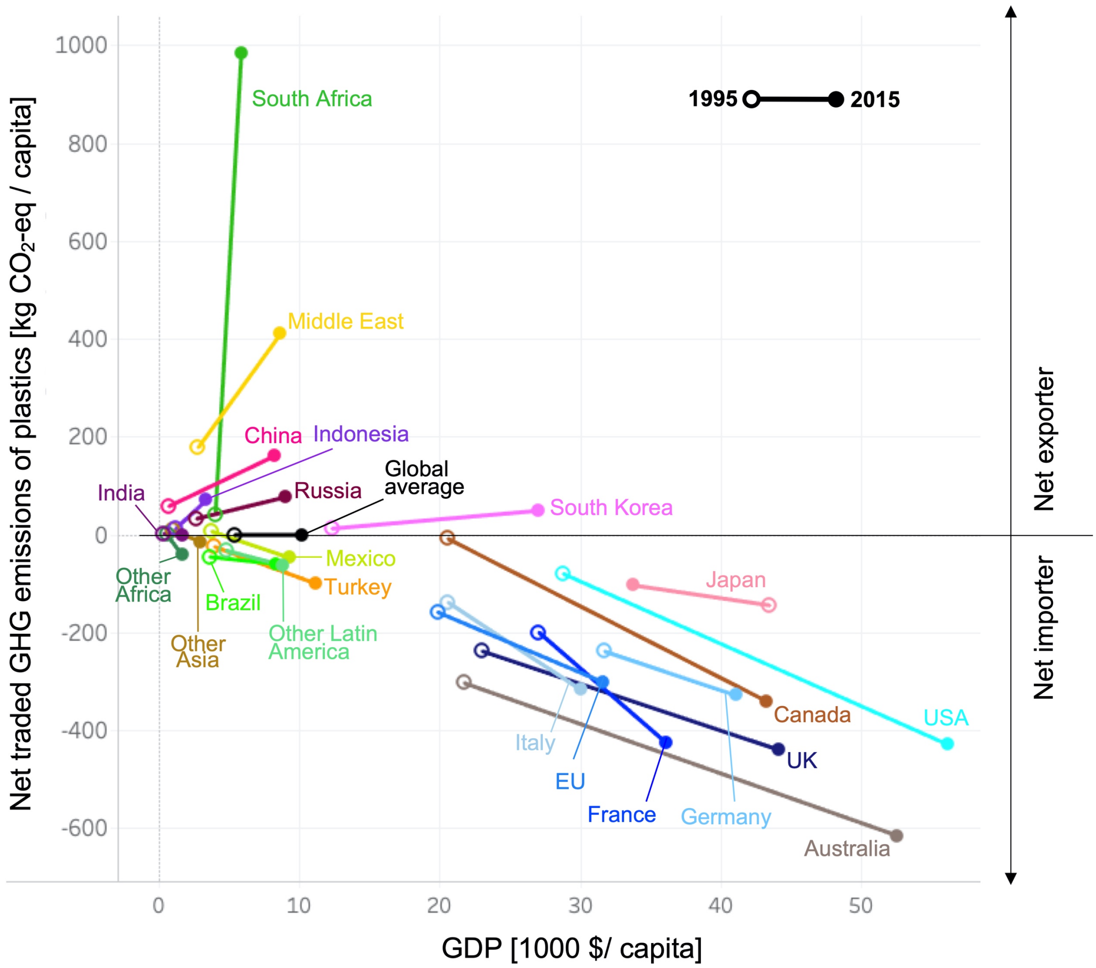


Figure D.4. Net traded GHG emissions of plastics plotted against the GDP from 1995 to 2015. Net traded GHG emissions of plastics were calculated by the difference of the plastics-related GHG emissions from a production and a consumption perspective (which equals the difference of the plastics-related GHG emissions of exports and imports). A positive value means that a region exports more plastics (and GHG emissions related to the production of the exported plastics) than it imports. In contrast, a negative value means that a country imports more plastics (and GHG emissions related to the production of the imported plastics) than it exports. All high-income regions except South Korea are net importer of plastics-related GHG emissions, meaning their plastics-related GHG emissions are higher from a consumption than production perspective. Vice versa, most low- and middle-income regions are net exporter of plastic-related GHG emissions. The same trend can be observed for PM health impacts.

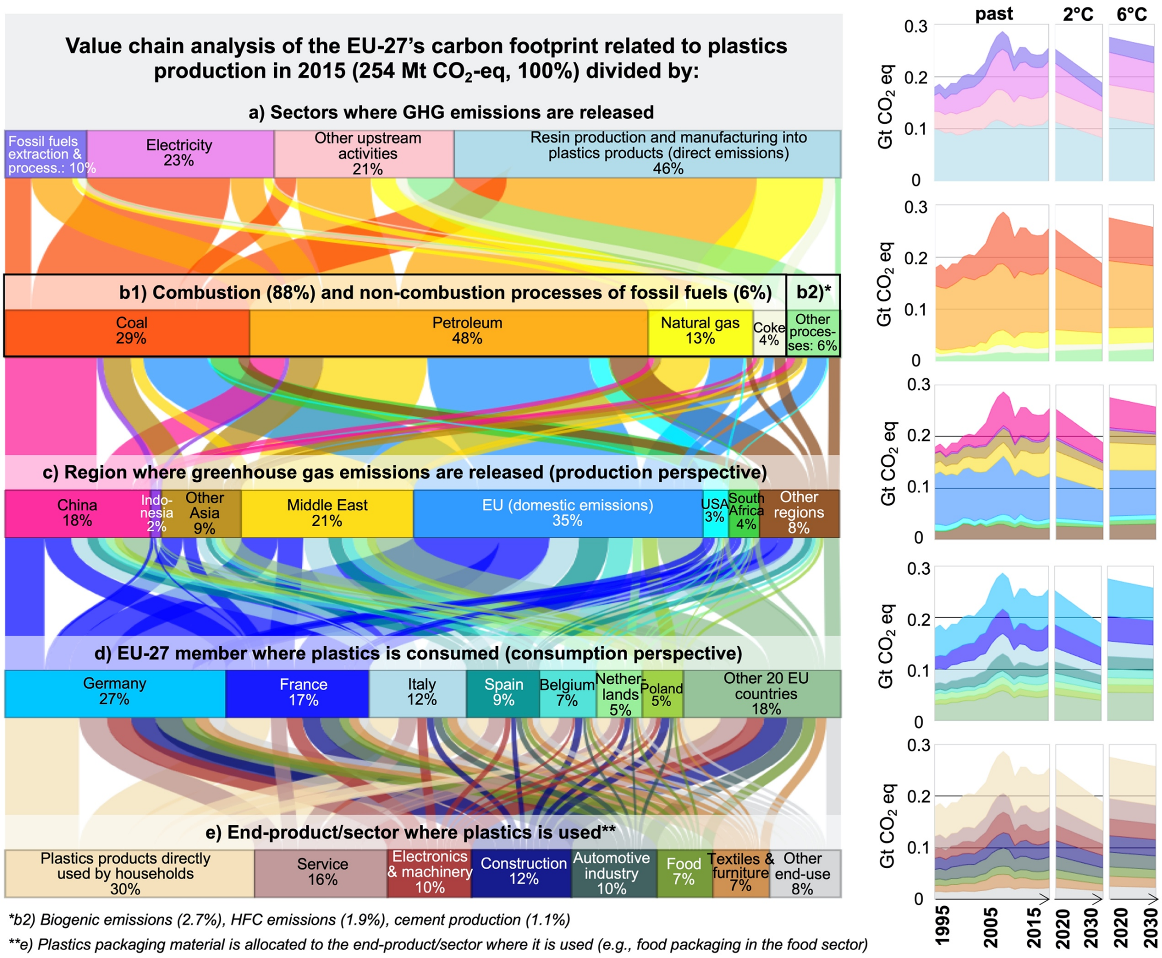


Figure D.5. The flow chart on the left shows the global value chain analysis of the EU's carbon footprint due to plastics production in 2015 (254 Mt CO_2-equivalents, 100%) and the small graphs on the right show the temporal evolution of the EU's carbon footprint due to plastics production from 1995 to 2030 under different scenarios (2-degree and 6-degree scenario until 2100[34,35]), following the format of Figure 5.1 of Chapter 5. The end-of-life stages of plastics (recycling, incineration, and landfills) contributed to another 19 Mt CO_2-equivalents in 2015 (data not shown in this figure).

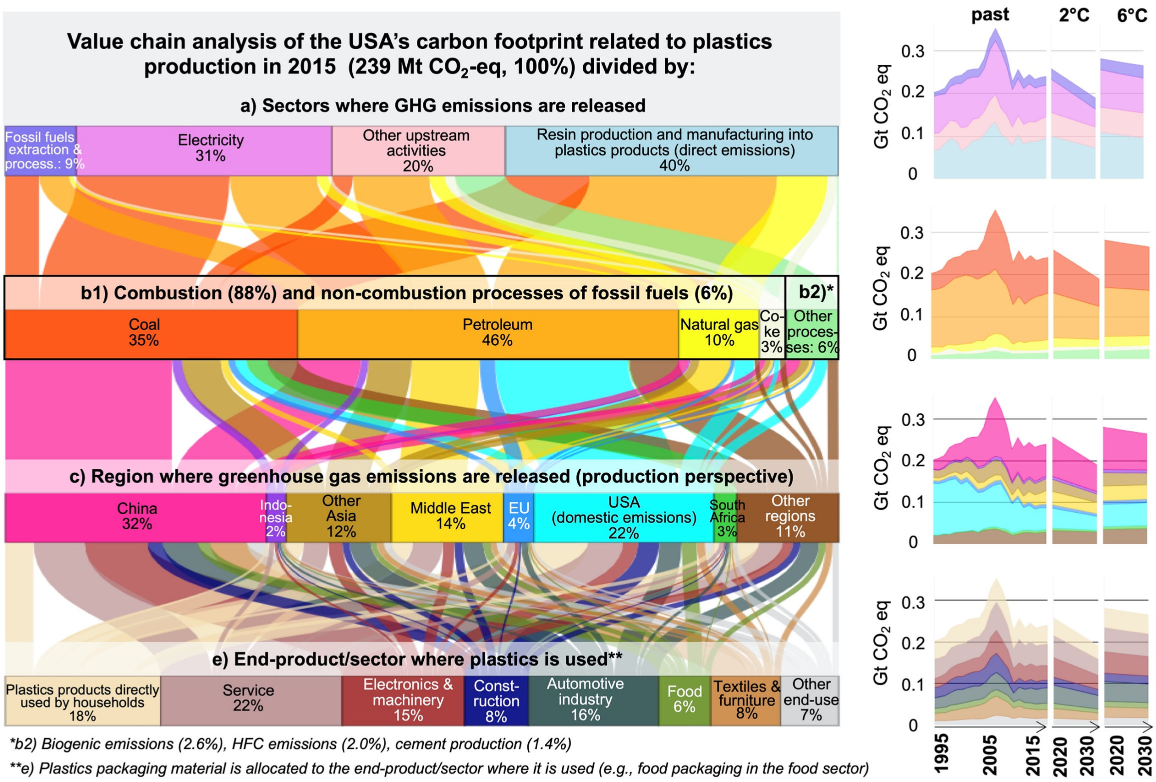


Figure D.6. The flow chart on the left shows the global value chain analysis of the USA's carbon footprint due to plastics production in 2015 (239 Mt CO_2-equivalents, 100%) and the small graphs on the right show the temporal evolution of the EU's carbon footprint due to plastics production from 1995 to 2030 under different scenarios (2-degree and 6-degree scenario until 2100[34,35]), following the format of Figure 5.1 of Chapter 5. The end-of-life stages of plastics (recycling, incineration, and landfills) contributed to another 20 Mt CO_2-equivalents in 2015 (data not shown in this figure).

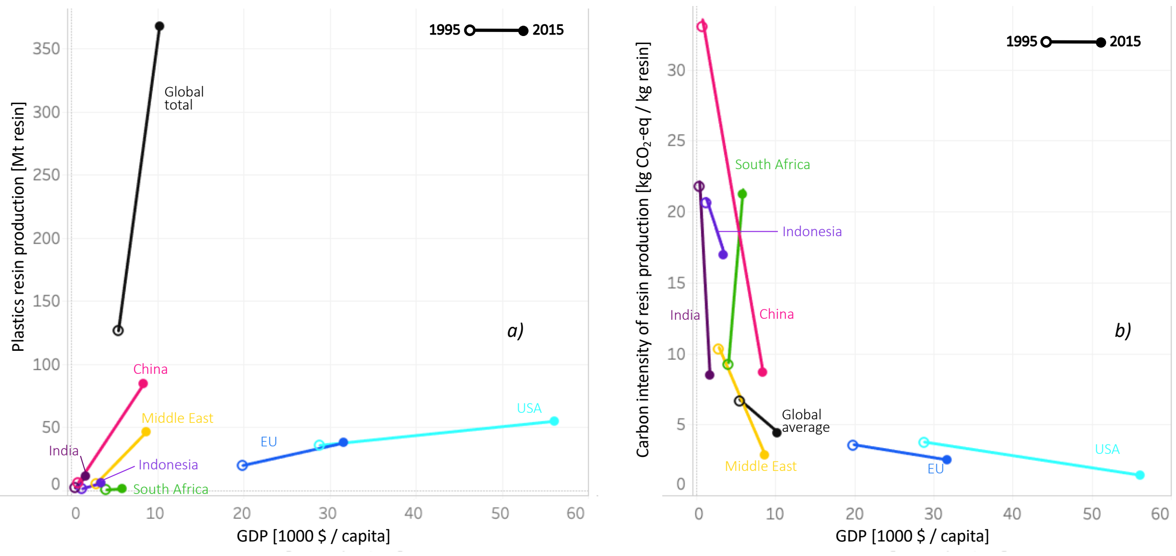


Figure D.7. a) Plastics resin production and b) related carbon intensity globally and for some regions plotted against the GDP from 1995 to 2015. The plastics resin production data calculated in this study are comparable (±20%) to data available for the entire globe, the EU, the USA, China, India, and Indonesia[5, 6]. The carbon intensity of plastic resin production indicates the cumulative GHG emissions related to the production of one kg of plastics resin. The USA's carbon intensity of plastics resin production may have been underestimated for 2015 because the USA's domestic plastics production relies increasingly on shale gas extraction[1], whose methane emissions have been underestimated in previous inventories[2]. The carbon intensities of resin production are discussed above (Results S2).

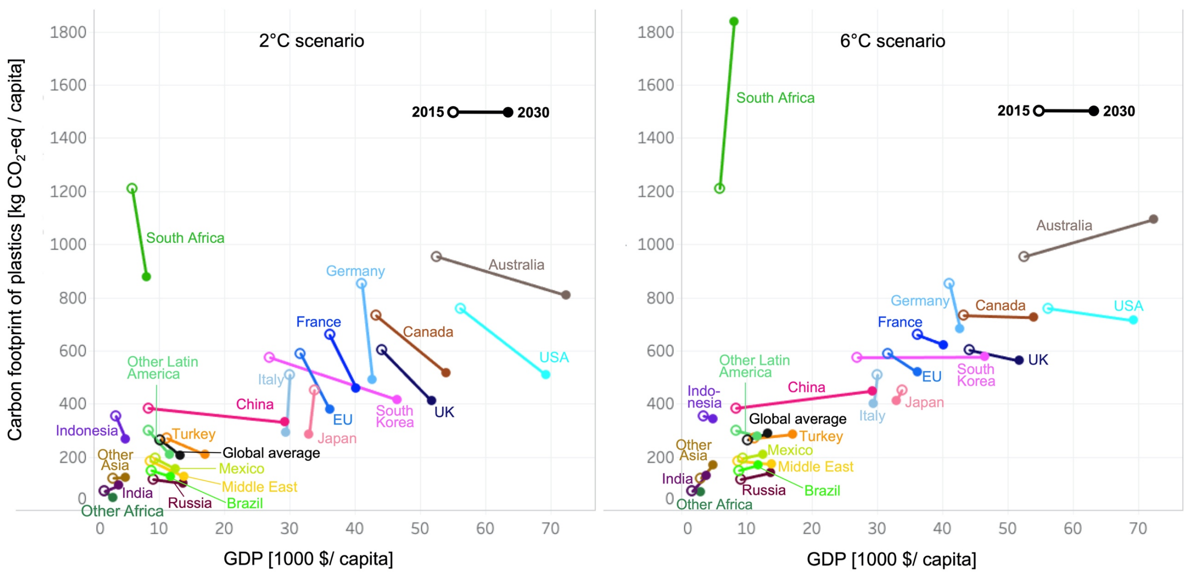


Figure D.8. Change in per-capita carbon footprints of plastics from 2015 until 2030 if the world follows the IEA's projections for a 2-degree or 6-degree scenario[34,35] plotted against the GDP. The carbon footprint of plastics allocates the GHG emissions of plastics to the region where plastics are finally used (consumption perspective). Due to the expected population growth, plastics-related carbon footprints at the per-capita level are expected to increase only slightly for most regions until 2030 if the world follows a 6-degree scenario. If the world follows a 2-degree scenario instead, plastics-related carbon footprints at the per-capita level are expected to decrease for all regions except India and Other Asia. However, their plastics-related carbon footprints are still half the global average in 2030. Note that the USA's current boom in shale gas extraction may increase the USA's domestic plastics production and related GHG emissions in the future,[64,65] which was not accounted for in the scenarios used here[34,35].

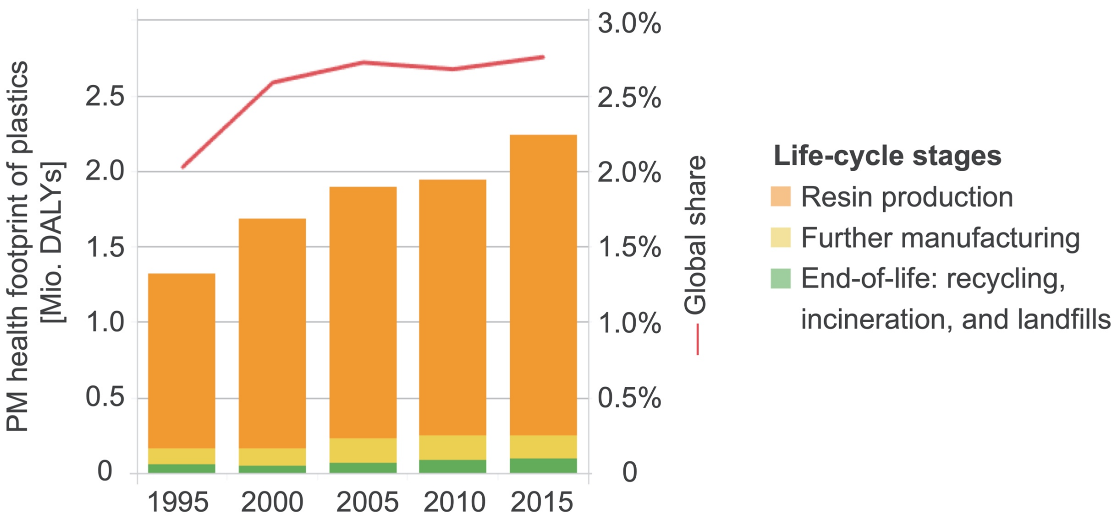


Figure D.9. Temporal development of the global PM health footprint of plastics from 1995 to 2015 divided by life-cycle stages (based on EXIOBASE3[22], the impact assessment recommended by UNEP-SETAC[57] and the methodology of Cabernard et al[31]). The value chain analysis of the PM health footprint of global plastics production (resin production and further manufacturing) in 2015 is shown in Figure 5.4 of Chapter 5.

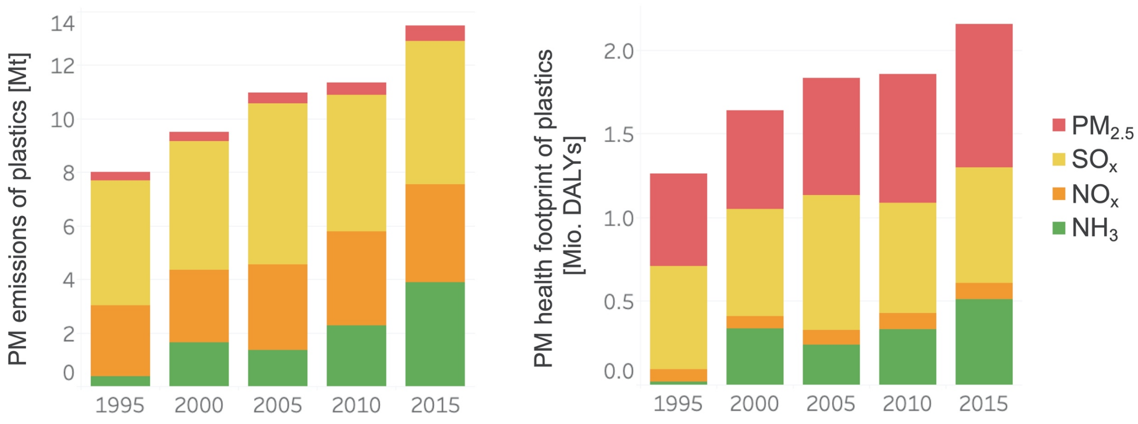


Figure D.10. Temporal development of plastics-related PM emissions and health impacts divided by type of PM emissions (based on EXIOBASE3[22], the impact assessment recommended by UNEP-SETAC[57] and the methodology of Cabernard et al[31]).

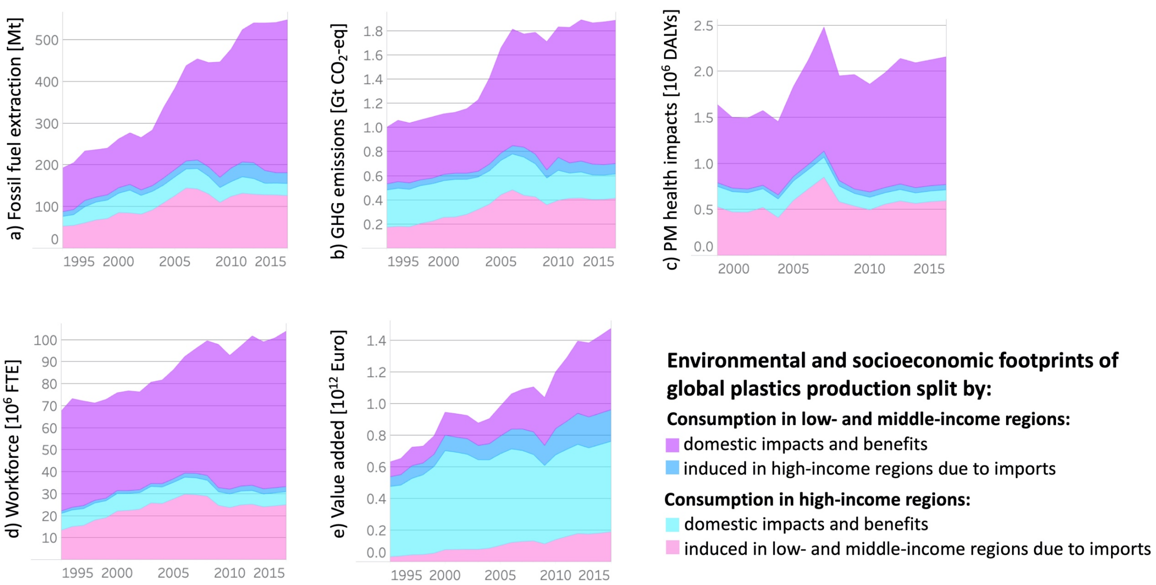
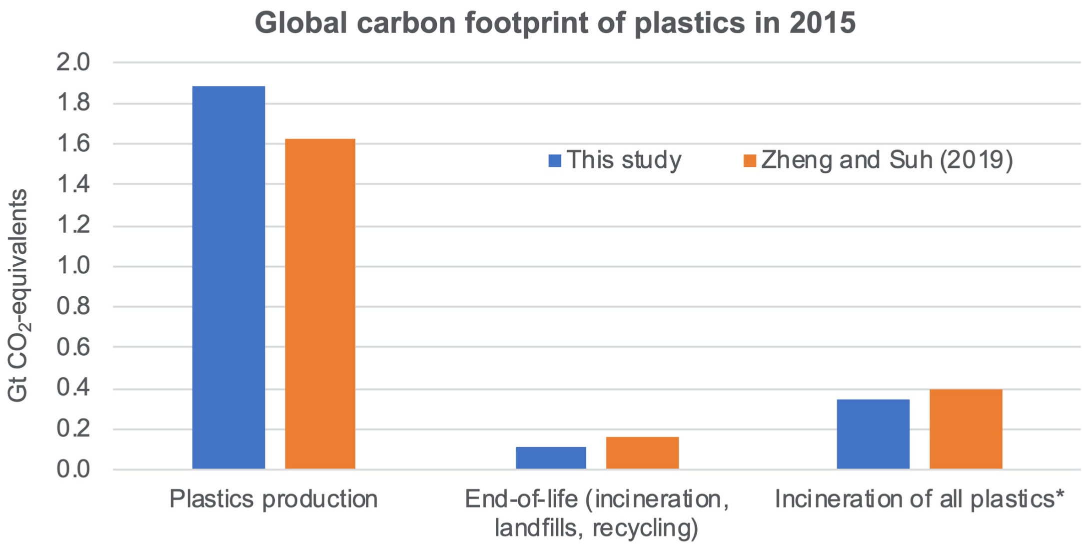


Figure D.11. Temporal evolution of the environmental and socioeconomic footprints of global plastics production over the past two decades split by plastic consumption in different income regions, and split by domestic and foreign import-related impacts.



**Potential GHG emissions if all plastics were incinerated instead of landfilled and recycled*

Figure D.12. Comparison of the global plastics-related carbon footprint in 2015 to the study of Zheng and Suh[17], who applied bottom-up life-cycle analysis to assess the global plastics-related carbon footprint in 2015. This study's global carbon footprint of plastics production is 16% higher compared to Zheng and Suh[17]. The reason for this might be that the MRIO-based approach applied here accounts for the fuel-specific energy mix, such as the increased reliance on coal, while Zheng and Suh[17] calculated with average global energy mixes. The study of Zheng and Suh[17] further assumed that 24% of global plastics produced in 2015 were incinerated, releasing 96 Mt CO_2-equivalents. This means that 400 Mt CO_2-equivalents would have been released if all plastics were incinerated according to Zheng and Suh[17], which is comparable to the 350 Mt CO_2-equivalents calculated in this study.

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Appendix E

Conclusions and Outlook

E.1 Methods

Table E.1. Classification of sectors in EXIOBASE3 into target industries illustrated in Figure 6.1 of Chapter 6.

No.	163 Sectors in EXIOBASE3	target industry
1	Cultivation of paddy rice	food
2	Cultivation of wheat	
3	Cultivation of cereal grains nec	
4	Cultivation of vegetables, fruit, nuts	
5	Cultivation of oil seeds	
6	Cultivation of sugar cane, sugar beet	
7	Cultivation of plant-based fibers	
8	Cultivation of crops nec	
9	Cattle farming	
10	Pigs farming	
11	Poultry farming	
12	Meat animals nec	
13	Animal products nec	
14	Raw milk	
19	Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing	
35	Processing of meat cattle	
36	Processing of meat pigs	
37	Processing of meat poultry	
38	Production of meat products nec	
39	Processing vegetable oils and fats	
40	Processing of dairy products	
41	Processed rice	
42	Sugar refining	
43	Processing of Food products nec	
44	Manufacture of beverages	
45	Manufacture of fish products	
15	Wool, silk-worm cocoons	textiles
47	Manufacture of textiles	
48	Manufacture of wearing apparel; dressing and dyeing of fur	
49	Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear	
18	Forestry, logging and related service activities	

50	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	wood & paper
51	Re-processing of secondary wood material into new wood material	
52	Pulp	
53	Re-processing of secondary paper into new pulp	
54	Paper	
24	Mining of uranium and thorium ores	metals
25	Mining of iron ores	
26	Mining of copper ores and concentrates	
27	Mining of nickel ores and concentrates	
28	Mining of aluminium ores and concentrates	
29	Mining of precious metal ores and concentrates	
30	Mining of lead, zinc and tin ores and concentrates	
31	Mining of other non-ferrous metal ores and concentrates	
72	Manufacture of basic iron and steel and of ferro-alloys and first products thereof	
73	Re-processing of secondary steel into new steel	
74	Precious metals production	
75	Re-processing of secondary preciuos metals into new preciuos metals	
76	Aluminium production	
77	Re-processing of secondary aluminium into new aluminium	
78	Lead, zinc and tin production	
79	Re-processing of secondary lead into new lead	
80	Copper production	
81	Re-processing of secondary copper into new copper	
82	Other non-ferrous metal production	
83	Re-processing of secondary other non-ferrous metals into new other non-ferrous metals	
84	Casting of metals	
32	Quarrying of stone	non-metallic minerals
33	Quarrying of sand and clay	
34	Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying	
65	Manufacture of glass and glass products	
66	Re-processing of secondary glass into new glass	
67	Manufacture of ceramic goods	
68	Manufacture of bricks, tiles and construction products, in baked clay	
69	Manufacture of cement, lime and plaster	
70	Re-processing of ash into clinker	
71	Manufacture of other non-metallic mineral products n.e.c.	
20	Mining of coal and lignite; extraction of peat	fossil resources
21	Extraction of crude petroleum and services related to crude oil extraction, excluding surveying	
22	Extraction of natural gas and services related to natural gas extraction, excluding surveying	
23	Extraction, liquefaction, and regasification of other petroleum and gaseous materials	
56	Manufacture of coke oven products	

57	Petroleum Refinery	
110	Manufacture of gas; distribution of gaseous fuels through mains	
59	Plastics, basic	chemicals
60	Re-processing of secondary plastic into new plastic	
61	N-fertiliser	
62	P- and other fertiliser	
63	Chemicals nec	
64	Manufacture of rubber and plastic products	
86	Manufacture of machinery and equipment n.e.c.	electronics and machinery
87	Manufacture of office machinery and computers	
88	Manufacture of electrical machinery and apparatus n.e.c.	
89	Manufacture of radio, television and communication equipment and apparatus	
90	Manufacture of medical, precision and optical instruments, watches and clocks	
96	Production of electricity by coal	electricity
97	Production of electricity by gas	
98	Production of electricity by nuclear	
99	Production of electricity by hydro	
100	Production of electricity by wind	
101	Production of electricity by petroleum and other oil derivatives	
102	Production of electricity by biomass and waste	
103	Production of electricity by solar photovoltaic	
104	Production of electricity by solar thermal	
105	Production of electricity by tide, wave, ocean	
106	Production of electricity by Geothermal	
107	Production of electricity nec	
108	Transmission of electricity	
109	Distribution and trade of electricity	
120	Transport via railways	public transport
121	Other land transport	
122	Transport via pipelines	
123	Sea and coastal water transport	
124	Inland water transport	
125	Air transport	
119	Hotels and restaurants	service
126	Supporting and auxiliary transport activities; activities of travel agencies	
127	Post and telecommunications	
128	Financial intermediation, except insurance and pension funding	
129	Insurance and pension funding, except compulsory social security	
130	Activities auxiliary to financial intermediation	
131	Real estate activities	
132	Renting of machinery and equipment without operator and of personal and household goods	
133	Computer and related activities	

134	Research and development	
135	Other business activities	
136	Public administration and defence; compulsory social security	
137	Education	
138	Health and social work	
159	Activities of membership organisation n.e.c.	
160	Recreational, cultural and sporting activities	
161	Other service activities	
162	Private households with employed persons	
163	Extra-territorial organizations and bodies	
94	Recycling of waste and scrap	waste
95	Recycling of bottles by direct reuse	
139	Incineration of waste: Food	
140	Incineration of waste: Paper	
141	Incineration of waste: Plastic	
142	Incineration of waste: Metals and Inert materials	
143	Incineration of waste: Textiles	
144	Incineration of waste: Wood	
145	Incineration of waste: Oil/Hazardous waste	
146	Biogasification of food waste, incl. land application	
147	Biogasification of paper, incl. land application	
148	Biogasification of sewage slugde, incl. land application	
149	Composting of food waste, incl. land application	
150	Composting of paper and wood, incl. land application	
151	Waste water treatment, food	
152	Waste water treatment, other	
153	Landfill of waste: Food	
154	Landfill of waste: Paper	
155	Landfill of waste: Plastic	
156	Landfill of waste: Inert/metal/hazardous	
157	Landfill of waste: Textiles	
158	Landfill of waste: Wood	
16	Manure treatment (conventional), storage and land application	not analyzed
17	Manure treatment (biogas), storage and land application	
46	Manufacture of tobacco products	
55	Publishing, printing and reproduction of recorded media	
58	Processing of nuclear fuel	
85	Manufacture of fabricated metal products, except machinery and equipment	
91	Manufacture of motor vehicles, trailers and semi-trailers	
92	Manufacture of other transport equipment	
93	Manufacture of furniture; manufacturing n.e.c.	
111	Steam and hot water supply	
112	Collection, purification and distribution of water	

113	Construction	
114	Re-processing of secondary construction material into aggregates	
115	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries	
116	Retail sale of automotive fuel	
117	Wholesale trade and commission trade, except of motor vehicles and motorcycles	
118	Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods	

E.2 Results

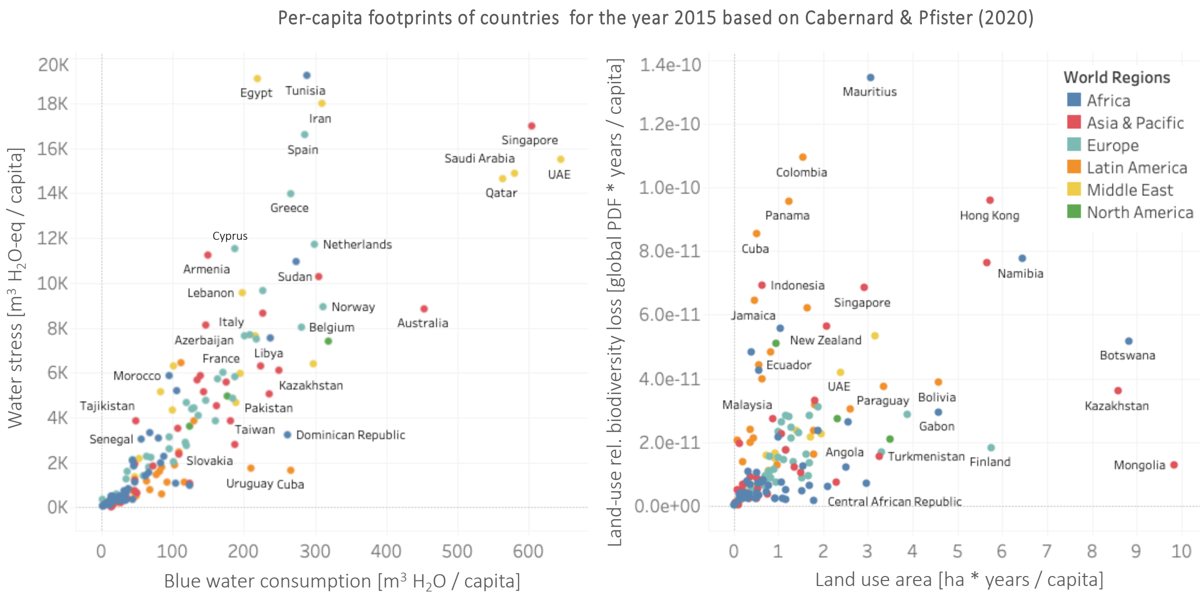

Figure E.1. Comparison of per-capita footprints of countries for water and land impacts if local conditions on water scarcity and ecosystem value have been taken into account (based on Chapter 3).

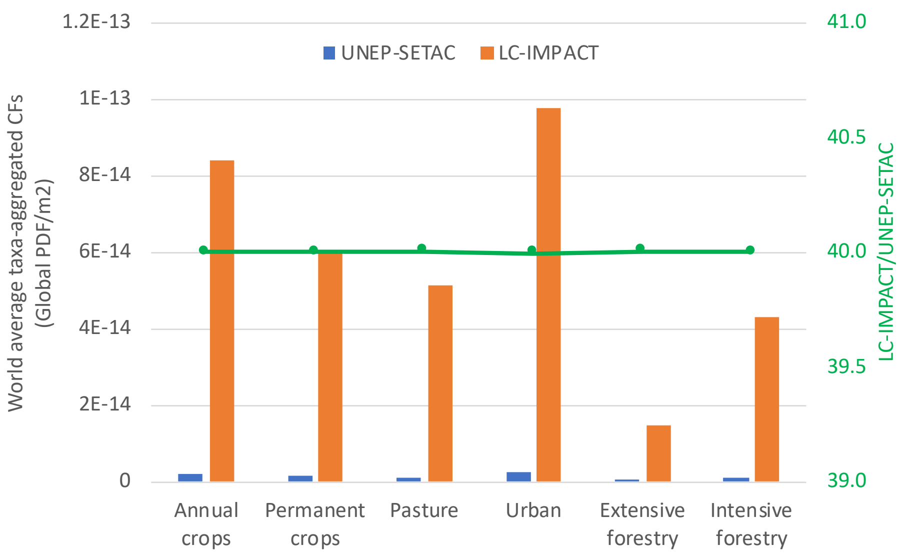

Figure E.2. Comparison of average characterization factors (CFs) for assessing global land-use related biodiversity loss from UNEP-SETAC[1] and LC-IMPACT[2].

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2015 – 2017	Master in Environmental Sciences at ETH Zurich (Major course: Biogeochemical cycles and pollutant dynamics)
2011 – 2015	Bachelor in Environmental Sciences at ETH Zurich
2007 – 2011	Highschool in Muttenz (Focus: Artistic Design), Switzerland

Practical experience

Oct 2016 – Mar 2017	Master thesis at the Alfred Wegener Institute at Helgoland, Germany Topic: Evaluation and optimization of an automated technique based on Raman spectroscopy for microplastics analysis in the North Sea
Mar 2015 – Jan 2016	Internship at the Cantonal Office for the Environment in Zurich, Topic: Developing and implementing a standard technique for microplastics analysis in Zurich's sewage plants and natural waters

Selected presentations

- 78th LCA Discussion Forum in Wädenswil. Topic: Life Cycle Thinking = Lower Environmental Footprint? Title: A new method for analyzing sustainability performance of global supply chains to effectively address big and relevant issues. Sept 14, 2021. Link presentation.
- Online SETAC conference. Topic: How Life Cycle Assessment Can Serve Effectively Environmental Footprinting and Policy Making. Title: A highly resolved MRIO database with LCIA extensions for sustainable policies. May 4, 2021. Link presentation.
- NEO Panel at ETH Zurich. Topic: Corporate Responsibility in the commodity sector. Title: Switzerland's role in global commodity trade. Mar 4, 2020. Link event.
- 73rd LCA Discussion Forum in Wädenswil. Topic: Life-cycle assessment of digital transformation. Title: Environmental impacts of materials in ICT. Nov 21, 2019. Link presentation.
- SETAC Conference in Helsinki. Topic: Natural Resources in LCA. Title: Regionalized Global LCA of Natural Resource Extraction and Processing. May 27, 2019.

Publication List

Articles included in this dissertation

Chapter 2 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.

Chapter 3 Cabernard, L.; Pfister, S., A highly resolved MRIO database for analyzing environmental footprints and Green Economy Progress. *Science of The Total Environment* **2020**, 755, 142587. https://doi.org/10.1016/j.scitotenv.2020.142587.

Chapter 4 Cabernard, L.; Pfister, S.; Hellweg, S., Improved sustainability assessment of the G20's supply chains of materials, fuels, and food. *Environmental Research Letters* **2022**, https://doi.org/10.1088/1748-9326/ac52c7.

Chapter 5 Cabernard, L.; Pfister, S.; Oberschelp, C.; Hellweg, S., Growing environmental footprint of plastics driven by coal combustion. *Nature Sustainability* **2021**. https://doi.org/10.1038/s41893-021-00807-2.

Further publications

Van der Merwe, A.; Cabernard, L.; Günther, I., Viability of Urban Mining: the relevance of information, transaction costs and externalities. Under review by *Ecological Economics.*

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. https://doi.org/10.1007/s11367-020-01801-0.

IRP, Natural resource use in the group of G20. Cabernard, L.; Pfister, S.; Hellweg, S.; Baptista, M. J.; **2019**. Link G20 factsheets.

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Cabernard, L.; Roscher, L.; Lorenz, C.; Gerdts, G.; Primpke, S. Comparison of Raman & Fourier transform infrared spectroscopy for the quantification of microplastics in the aquatic environment. *Environmental Science & Technology* **2018**, 52(22), 13279-13288. https://doi.org/10.1021/acs.est.8b03438.

Cabernard, L.; Durisch-Kaiser, E.; Vogel, J. C.; Rensch, D.; Niederhauser, P. Mikroplastik in Abwasser und Gewässer. *Aqua & Gas* **2016**, vol. 96: no. 7/8, pp. 78-85, Zürich: SVGW.