Title: Hotspots of mining-related biodiversity loss in global supply chains and the potential for reduction by renewable electricity

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

Affiliations:

[1]Swiss Federal Institute of Technology, ETH Zurich
Department of Civil, Environmental and Geomatic Engineering
Institute of Environmental Engineering
Ecological Systems Design
John-von-Neumann-Weg 9
8093 Zurich, Switzerland
[2]Swiss Federal Institute of Technology, ETH Zurich
Department of Humanities, Social, and Political Sciences
Institute of Science, Technology, and Policy (ISTP)
Universitätstrasse 41
8092 Zurich, Switzerland

Corresponding author:

*Dr. Livia Cabernard
livia.cabernard@istp.ethz.ch

Contacts of co-author:

Dr. Stephan Pfister
stephan.pfister@ifu.baug.ethz.ch

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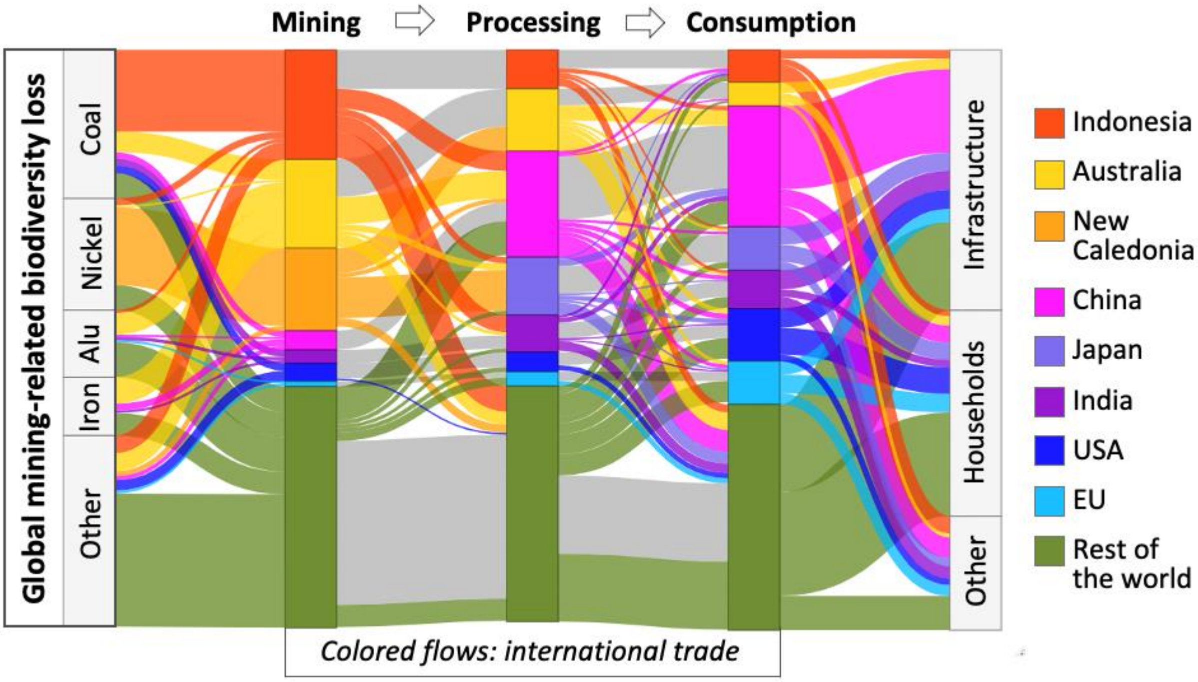
Graphical abstract



Abstract

The expected growth in infrastructure and energy transition may exacerbate biodiversity loss by the rising demand for mining products. Many mining products are extracted in the Global South and exported to the global North for further processing and final consumption, where a link to the devastating environmental effects is often missing. Based on an enhanced multi-regional input-output database, this study assesses global biodiversity loss associated with land use of mining (mining-related) to identify hotspots, key processing industries, and final consumers of mining products. Our study reveals that half of global mining-related biodiversity loss occur in Indonesia, Australia, and New Caledonia. Major international trade flows of embodied biodiversity loss involve Indonesia's coal exports to China and India, New Caledonia's nickel exports to Japan and Australia, and Australia's iron and aluminum exports to China. Key consumers include China's growing infrastructure and households in the EU and USA. Electricity generation accounted for 10% of global mining-related biodiversity loss in 2014. The impact of coal-fired electricity is far higher compared to renewables, both overall and per electricity generated. Our results underline synergies in fostering renewables while reducing global biodiversity loss, and provide transparency for industry and policy to source more sustainable mining products.

Synopsis: This study's regionalized impact assessment coupled with enhanced multi-regional input-output analysis highlights the importance for considering local biodiversity impacts in the supply chain of mining products and highlights the potential to mitigate them by a shift from coal electricity to renewables.

Keywords: multi-regional input-output (MRIO) analysis, metals, coal, biodiversity loss footprint, land use, regionalized impact assessment, sustainable mining, international trade

1. Introduction

The rising global demand for mining products, including metals, other minerals, and coal, poses a challenge to sustainable development. On the one hand, mining products are inextricably linked to economic growth currently pursued in industrialized societies. On the other hand, mining is also one of the most environmentally and socially dangerous human activities. Several studies have documented the harmful consequences for the environment and the link to social conflicts[1-8]. This involves especially the Global South, where most mining activities take place, but where governments often fail to enforce environmental regulations. In this context, previous studies have also pointed to the trade-off in view of metal-intensive renewable energy production that is crucial to limit global warming below 1.5°C, but likely to exacerbate mining threats to biodiversity[9-11]. This and the projected growth in demand for mining products in the future[12, 13] are alarming signs that related impacts will continue to intensify, highlighting the need for improved sustainability strategies in the mining and metals industry.

Once extracted in the Global South, many mining products are exported to the global North, where a link to the devastating environmental effects of mining is often missing. To foster sustainable mining, it is thus essential to fill the information gap from the local scale where mining takes place and impacts are caused to the international scale of further processing and final consumption. Environmentally-extended multi-regional-input-output (MRIO) analysis is one form of life-cycle assessment that can provide such information[14-20]. However, the level of detail is limited by the spatial, sectoral, and temporal resolution of the underlying MRIO-database[21-27]. Recently, an MRIO database with high spatial, sectoral, and temporal resolution has been created[28, 29] by using the synergies of two MRIO databases with high sectoral[21] and regional resolution[22]. However, the quality of that database is limited for mining and metal processing sectors[29]. Moreover, a global-scale dataset of biodiversity loss associated with land use of mining is missing in any database, although this is crucial to foster sustainable practices in the mining and metals industry.

To address these research gaps, we follow the approach of Cabernard & Pfister[29] to create a highly-resolved MRIO database with improved data quality for all mining and metals processing sectors and regionalized impact assessment. In this context, we compile and integrate a global-scale data set of biodiversity loss associated with land use of mining into the database. This regionalized impact assessment is based on the mining area data set of Maus et al[30], ecoregion[31]-specific global species loss factors from UNEP-SETAC[32], and geographic data of the SNL metal & mining database[33]. By mapping the intermediate steps in the global supply chain of mining, processing, and final consumption, we address the following research questions (RQ) concerning biodiversity loss associated with land use of mining, called mining-related biodiversity loss in this study:

RQ 1) Where are hotspots of global mining-related biodiversity loss impacts and how does mining contribute to global land-use related biodiversity loss (Section 3.1)?

RQ 2) Which countries are key processing industries and final consumers of mining products and what is the role of (fossil and renewable) electricity generation (Section 3.2)?

2. Methods

2.1 Resolved EXIOBASE with regionalized biodiversity Impact Assessment (REXIA)

In a global MRIO database, the global economy is split into a specific number of sectors and regions, whose transactional flows and environmental accounts (e.g., GHG emissions) are captured for a specific time frame[21, 22, 24]. Currently, several global MRIO databases exist, including EXIOBASE3[21], Eora26[22], and GTAP[24], which differ in their sectoral, regional and temporal resolution. EXIOBASE3 has the highest sectoral resolution (163 sectors, including 29 mining and metals sectors) but lowest regional resolution (44 countries and 5 Rest of the World regions). In contrast, Eora26 has the lowest sectoral resolution (26 sectors, including two mining and metals sectors) but the highest regional resolution (189 countries). The sectoral and regional resolution of GTAP falls somewhere in between, as the newest version of GTAP (GTAP10) distinguishes 65 sectors (including 8 mining and metals sectors) for 121 countries. However, GTAP10 only covers the year 2014, while EXIOBASE3 and Eora26 are available as time series.

Due to the high sectoral resolution, we used EXIOBASE3[21] as a starting point and followed the procedure of Cabernard & Pfister[29] to compile a highly-resolved MRIO database with regionalized impact assessment called REXIA (Resolved EXIOBASE with regionalized Impact Assessment). REXIA distinguishes 163 sectors for 189 countries, covering the year 2014. In contrast to ref[29], we integrated data not only from Eora26[22] and FAOSTAT[34], but also from GTAP10[24] and the British Geological Survey (BGS)[35] (SI Methods, Paragraph S1). The latter allowed us to improve especially the data quality for mining and metals processing sectors. In accordance to ref[29], the resulting transaction and final demand matrices of REXIA equals the original ones of the EXIOBASE3 database when aggregated back to the original regional resolution (±2% because of numeric errors). However, other than ref[29], we used the newest EXIOBASE3 version 3.8.2[36], which provides significant improvements in data quality for metals mining and processing sectors compared to version 3.4 used in ref[29].

We implemented three environmental extensions into REXIA for all mining sectors, namely mining quantity (in kg), land use of mining areas (in m2) and related biodiversity loss impacts (in global potentially disappeared fraction, pdf). This means that mining quantity, land use of mining and related biodiversity loss differ from EXIOBASE3[21]. Mining quantities were directly adopted from BGS[35] by allocating the different commodities to the mining and processing sectors of EXIOBASE3. Land use of mining area was implemented based on the global-scale data set of mining area from Maus et al[30], which includes active mines between 2000 and 2007 indicated by the SNL metals and mining database[33]. We translated this dataset into mining-related biodiversity loss by weighting the area of each mining polygon of Maus et al[30] with the ecoregion[31]-specific global species loss factors from UNEP-SETAC[32]. These factors indicate the global potentially disappeared fraction (pdf) per square meter of land use. As Maus et al[30] did not indicate the type of mine (e.g., coal, copper, aluminum, etc.), we applied the following procedure to allocate both mining area and related biodiversity loss to the different mining sectors of REXIA:

The first step was to identify the primary commodity for each mining polygon indicated by Maus et al[30]. This was done by linking each mining polygon to the active mines indicated by the SNL metals and mining database[33]. This database provides information on the mined commodities, such as the primary commodity, but only indicates approximate point coordinate for the mines. If the mining polygons did not overlap with the point coordinates (which was the case for most mines), we allocated the mining polygons to the closest point coordinates using the minimum distance calculation (minimum distance between the point coordinate to the side of a polygon). This procedure allowed to identify the primary commodity for each mining polygon. For the different metals mining sectors of REXIA, we compared two allocation schemes. In the *primary commodity allocation*, we allocated the mining area (and related biodiversity loss) of the identified primary commodity to the corresponding mining sector of REXIA and aggregated the results on a country level. In the *monetary allocation*, we allocated the mining area (and related biodiversity loss) of metals to the different mining sectors of each country of REXIA based on the monetary value of the respective extracted metal quantities in these countries in 2014. This value was calculated for each metal and country by weighting the extracted metal quantity indicated by BGS[35] with the estimated price of metals in 2014[37].

2.2 Supply chain analysis of mining-related biodiversity loss

We applied the common Leontief model[14-20] to link the country and sector where biodiversity loss are induced by mining (production or mining perspective) to the region and sector of final consumption (consumption or footprint perspective). To assess mining-related biodiversity of the global metals industry, we applied the method of Cabernard et al[38, 39], which prevents the issue of double counting based on Dente et al[40] (see ref[39] for an explanation of the issue of double counting and how it is prevented). Following the procedure of ref[39], we set all metals mining and processing sectors as target-sectors (21 target-sectors) and all countries as target regions (189 countries), resulting in 3969 target-sector-regions. To analyze the intermediate steps in the global metals supply chain, we followed the procedure of ref[39] to adopt different perspectives, namely the mining perspective (production perspective), the processing perspective (target perspective), and the end-use/final consumption perspective. To analyze the intermediate step in the supply chain of coal, we implemented an additional perspective, called "combustion perspective". In this perspective, biodiversity loss of coal mining is linked to the region where coal was combusted, as done in ref[38] for climate impacts of global plastics production due to coal combustion.

To assess mining-related biodiversity loss of global electricity generation, we have set all electricity sectors as target-sectors (10 target-sectors including fossil-based, nuclear, and renewable electricity) and all countries as target-regions (189 countries), following the method of ref[39]. In this context, mining-related biodiversity loss impacts were allocated to the respective electricity sector from a target perspective[39]. This means e.g., that if coal electricity was needed to build infrastructure for renewable electricity, the related biodiversity loss (e.g., due to coal mining) is allocated to renewable electricity generation and not accounted for in coal electricity. To calculate mining-related biodiversity loss per generated electricity, we divided the mining-related biodiversity loss of each electricity sector through the respective amount of electricity generated in 2014. The latter was estimated by multiplying the total output of generated electricity in 2014 (in Mio. Euro) with the inverted price vector (Mio.

Euro/ terajoules). The inverted price vector was derived based on the monetary (in Mio. Euro) and physical (terajoules) MRIO tables of EXIOBASE3 for the year 2011, as done in ref[38]. This procedure relies on the simplified assumption that prices of electricity have not changed from 2011 to 2014. Additionally, this assumes that infrastructure build-up of renewable energy remained constant over time. However, renewables experienced an increase over the past decade in reality. Thus, the installed capacity is expected to generate more electricity over life time than was actually generated in 2014. This means that this study's approach tends to overestimate mining-related impacts of renewable energy compared to fossil electricity.

3. Results and Discussion

3.1 Hotspots of global mining-related biodiversity loss

Figure 1a shows the mining area data set from Maus et al[30] (57'277 km^2) colored by primary commodity based on the active mines indicated by the SNL metals and mining database[33]. Also, Figure 1 illustrates the ecoregions[31] colored by the biodiversity loss in global species loss per square meter[32] on a logarithmic scale. Mining areas in ecoregions with particular high ecosystem value include Nickel mines in New Caledonia, coal mines in Indonesia, aluminum mines in Australia, iron mines in Brazil, gold mines in Ghana, and diamond mines in South Africa (Figure 1b–f).

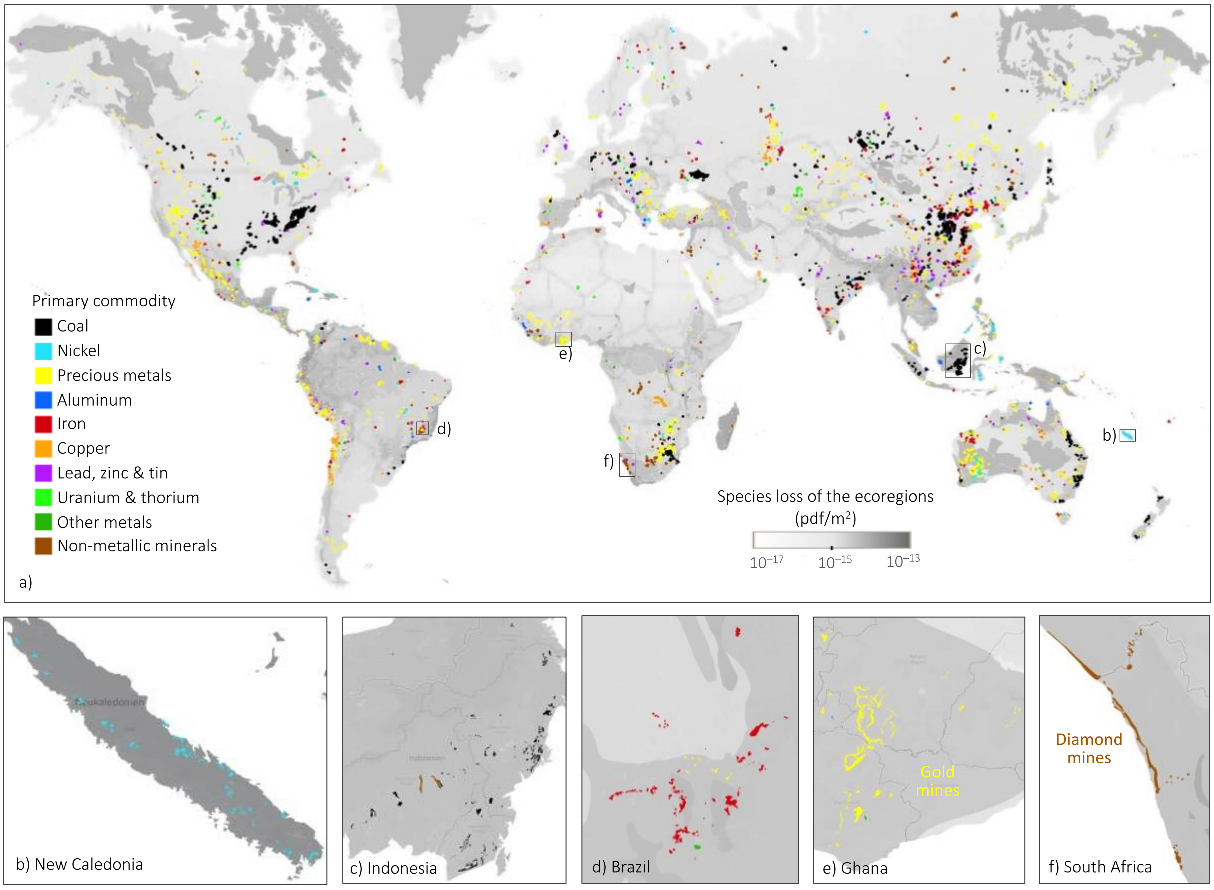


Figure 1. Mining area data set from Maus et al[30] (total 57'277 km^2) colored by primary commodity based on the active mines on the SNL metals and mining database[33] and their location in ecoregions[31]. The ecoregions are colored by the global species loss in potentially disappeared fraction (pdf) per square meter based on UNEP-SETAC[32].

Weighting all mining areas with the ecoregion-specific species loss per square meter results in a global mining-related biodiversity loss of $2.0 * 10^{-4}$ global pdf, meaning that almost 0.02% of global species went extinct by mining activities. This is shown for the two allocation schemes in Figure 2a on a global level. In both allocation schemes, more than half of global mining-related biodiversity loss was attributed to mining of coal (26%), nickel (>19%), and precious metals (>12%). The major difference in the two allocation schemes is that the contribution of precious metals is lower in the monetary allocation (13% instead of 20% in global mining-related biodiversity loss), while the share of iron and aluminum mining is higher in the monetary allocation (12% and 10% respectively, instead of 6% and 5%, respectively, Figure 2a). The main reason is that gold, aluminum, and iron are often extracted from the same mine, but gold is indicated as the primary commodity in most cases. This applies particularly for Australia, Suriname and Venezuela, where the contribution of iron (Australia and Venezuela) and aluminum (Suriname and Venezuela) significantly increases in the monetary-based allocation (see SI Figure S2 for a comparison of the allocation schemes on a country level). To account for the extraction of metals other than those indicated as primary commodity, we rely on the monetary allocation in the following.

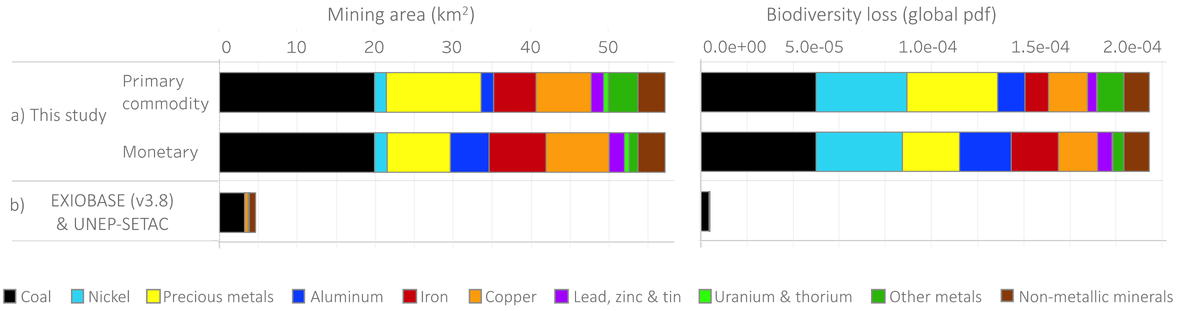


Figure 2. Global mining area (total 57'277 km^2, 100%)[30] and related biodiversity loss (total: $1.95 * 10^{-4}$ global pdf, 100%) divided by country and mining sector for a) the two allocation schemes for metals applied in this study and b) compared to EXIOBASE version 3.8[21] (mining area) combined with the country-average global species loss factors from UNEP-SETAC (biodiversity loss) as done in ref[39].

The breakdown by country reveals that half of global mining-related biodiversity loss occurred in Indonesia, Australia, and New Caledonia, although these countries accounted for less than 20% of global mining area (Figure 3). Coal mining in Indonesia and nickel mining in New Caledonia each accounted for 14% of global-mining related biodiversity loss, while Australia's iron, aluminum, and coal mining contributed together to 13% of global mining-related biodiversity loss. Further biodiversity loss hotspots involve mining of nickel in the Philippines, Cuba, and Indonesia, aluminum in Suriname, Brazil and Venezuela, as well as iron in Brazil, China, and Venezuela. Biodiversity loss related to precious metals mining were mostly attributed to gold mining in Ghana, Indonesia, Australia, Peru, Mexico, Colombia, and Papua New Guinea, while most impacts associated with copper mining occurred in Chile, followed by Peru and Indonesia. In contrast, biodiversity loss of non-metallic minerals was mainly attributed to diamond mines in South Africa and Namibia (Figure 3).

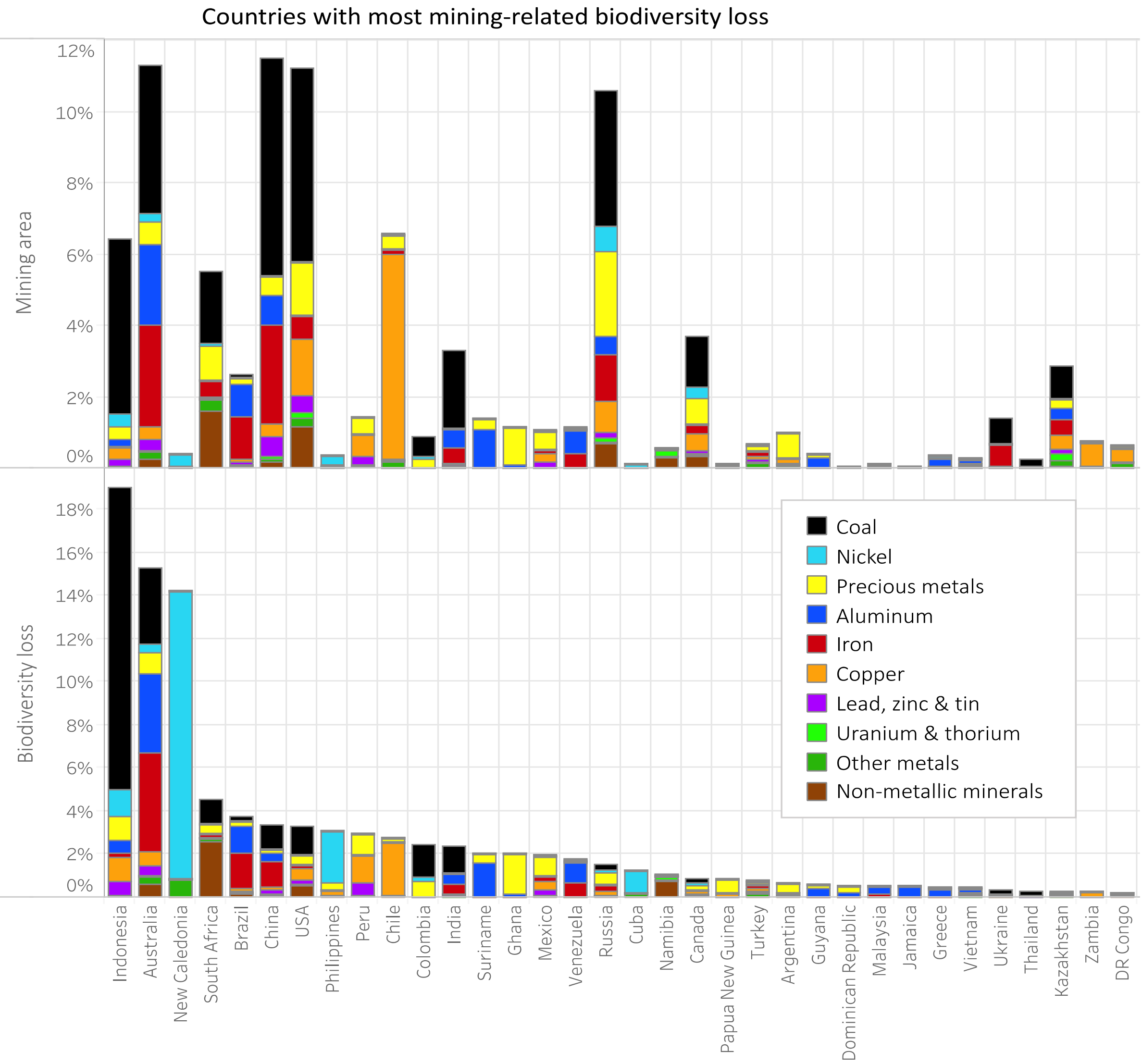


Figure 3: Global mining area (total 57’277 km^2, 100%)[30] and related biodiversity loss impacts (total: 2.0 *10^{-4} global pdf, 100%) divided by country and mining sector based on the monetary allocation. The figure shows all countries representing at least 0.2% of global mining-related biodiversity loss. Together, these countries represent 95% of global mining-related biodiversity loss.

Our results point to strong imbalances between quantity, mining area, and related biodiversity loss per country and mined commodity (Figure 3, see Figure S3–S6 of the SI for a comparison of quantity, area, and related biodiversity loss for coal, nickel, aluminum, and iron mining). For example, Indonesia accounted for 6% of global coal extraction (year 2014) and 14% of global coal mining area (SI Figure S3). However, as Indonesia’s coal mines are situated in vulnerable ecosystems (Figure 1b), more than half of coal-related biodiversity loss occurred in Indonesia. The opposite pattern holds for China, where almost half of global coal was extracted (year 2014), accounting for 18% of global coal mining area. Nevertheless, only 4% of coal-related biodiversity loss was caused in China. Similarly, Russia accounted for 25% of global nickel mining area, but only 1% of the related biodiversity loss. In contrast, more than 70% of the world’s biodiversity loss of nickel mining was induced in New Caledonia, even though only 13% of the world’s nickel mining areas are in New Caledonia (with less than 10% of total global nickel production). Mining in New Caledonia’s vulnerable ecosystem is also the reason why nickel accounts for less than 3% of the world's mining area, but more than 10% of the related biodiversity loss (Figure 2a). Similarly, more than 20% of aluminum-mining related biodiversity loss was induced in Suriname and Venezuela, although only 1% of global aluminum was mined in these countries (year 2014, SI Figure S5). While Werner et al[41] found that mining quantity is a reasonable proxy for mining area (based on a mining dataset of 3'633 km^2), our results indicate that for most countries and mining products, neither quantity is suitable to predict mining area, nor is mining area appropriate to estimate biodiversity loss. Furthermore, our results show that hotspots of biodiversity loss differ from other environmental impacts of mining products, such as climate and particulate-matter related health impacts, dominated by China's steel and cement production[42]. This highlights the importance of considering local biodiversity loss of land use to promote sustainable practices in the mining and metals industry.

The importance of this study's regionalized biodiversity impact assessment is also reflected when comparing the results to previous estimates (Figure 2a–b). The land use area of mining in the dataset of Maus et al applied here (57'277 km^2) is four times higher compared to EXIOBASE3[21] (15'000 km^2). However, the mining-related biodiversity loss of this study ($2.0 * 10^{-4}$ global pdf) is thirty times higher compared to the results of Cabernard et al[39] ($6.5 * 10^{-6}$ global pdf) which is based on land use data for mining of EXIOBASE3[21] and the country-average characterization factors from UNEP-SETAC[32]. The reason is that we applied ecoregion[31]-specific species loss factors, while Cabernard et al[39] is based on country-average species loss factors[32]. When dividing the mining-related biodiversity loss through the related land use area, this study results in an eight times higher average biodiversity loss impact per square meter mining area compared to ref[39] ($3.4 * 10^{-15}$ global pdf/m^2 mining area compared to $4.3 * 10^{-16}$ global pdf/m^2). This underscores that many mines are located in regions with particular high ecosystem value (e.g., Nickel mines in New Caledonia or coal mines in Indonesia), which is consistent with previous literature[3, 9, 43].

Other than previous studies on mining in vulnerable ecosystems[3, 9, 43], this study provides the first quantitative assessment on global mining-related biodiversity loss. This allowed us to estimate the contribution of mining activities in total global land-use related biodiversity loss, including crops cultivation, pastures, agriculture, industries, and housing. Based on the same UNEP-SETAC impact method[32] applied here, global land-use related biodiversity has been estimated to range from 0.08–0.14 global pdf[12, 39, 44-46]. This is 400-700 times higher than the biodiversity loss related to mining found in this study ($2.0 * 10^{-4}$ global pdf). Although mining activities can lead to severe local ecosystem damage and environmental disasters[5-8, 47-49], we find that mining activities contribute to less than 0.25% of global land-use related biodiversity loss, which is dominated by agriculture (75%) and forestry (15%)[12, 39]. However, as mining areas are concentrated on a small area compared to agriculture and forestry, local impacts are still significant and potential long-term impacts need to be considered in future research.

3.2 Supply chain analysis and reduction potentials by renewable electricity

This section analyzes the role of international trade by linking the country where mining activities take place and biodiversity loss is induced (production or mining perspective) to the country of further processing (processing perspective for metals, combustion perspective for coal) and final consumption (consumption or footprint perspective). Due to international trade, more than 75% of global mining-related biodiversity loss was induced in a country other than that of final consumption in 2014 (Figure 4a–b). For example, more than half of global mining-related biodiversity was related to consumption by China, the USA, the EU, Japan, and India, although less than 10% of the related impacts were caused in these regions. Thus, the vast majority of the biodiversity loss footprint of China (88%), the USA (80%), the EU (90%), Japan (99%), and India (75%) was induced abroad. Key international flows of embodied biodiversity loss involve Australia's iron and steel exports for China's consumption, Indonesia's coal exports for China's and India's consumption, and New Caledonia's nickel exports for Japan's consumption. For example, more than two-thirds of Japan's mining-related biodiversity loss footprint was induced by nickel mining in New Caledonia.

From a consumption perspective, almost 20% of global mining-related biodiversity loss impacts were related to China's and India's infrastructure build-up, which dominates the mining-related biodiversity footprint of these countries (Figure 4b). In contrast, households (e.g., electronics, cars, etc.) contribute strongest to the EU's and USA's mining-related biodiversity loss footprint. On a per-capita level, mining-related biodiversity loss footprints of Japan, the USA ,and most European countries exceed the global average, while those of China and India are similar and below the global capita average, respectively (see Figure S7 of the SI for a comparison on a per-capita level). Australia stands out with per-capita footprints ten times above the global average, although the vast majority of Australia's domestic mining-related biodiversity loss is attributed to exports (Figure 4a–b).

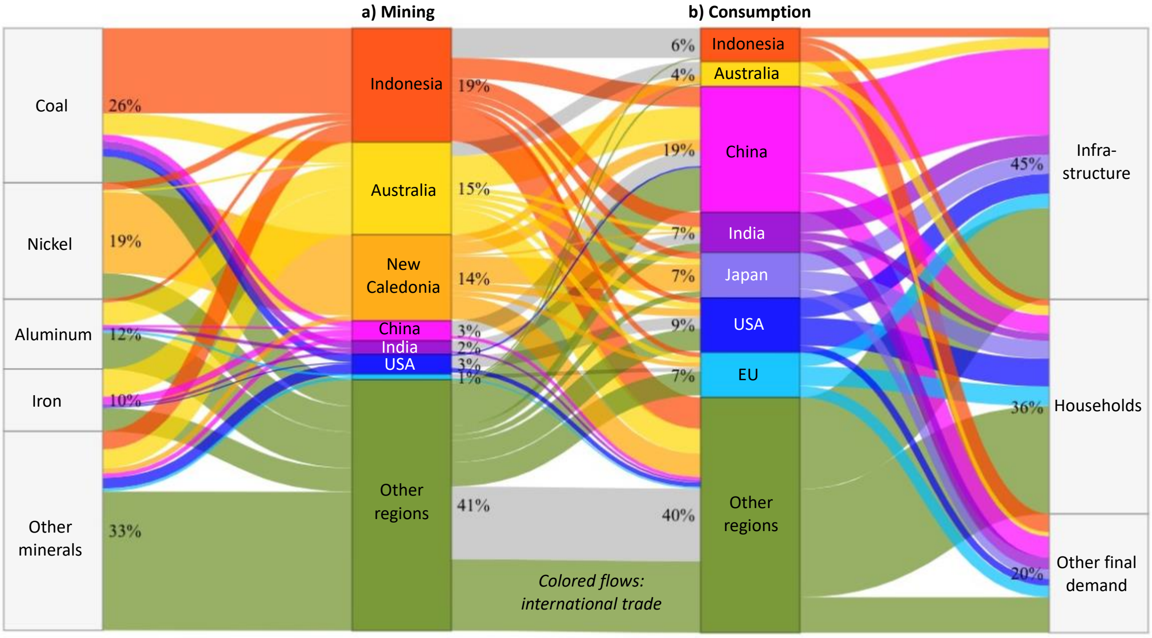


Figure 4. Supply chain analysis of global mining-related biodiversity loss in 2014 (total: 2.0 $*10^{-4}$ global pdf, 100%).

Metals supply chain: The supply chain of mining-related biodiversity loss impacts of total global metals production is shown in Figure 5 and Figure S8 of the SI. Overall, 76% of total global mining-related biodiversity loss are attributed to metals production (5.1 $*10^{-5}$ global pdf). This includes biodiversity loss not only related to metals mining, but also coal mining to supply heat and electricity for metals production, mostly steel. The link to the end-use sector shows that a quarter of the biodiversity loss is because of metals used for construction, mostly steel for China's infrastructure (Figure 5c–d). This involves also impacts in the supply chain of steel production due to coal mining in Indonesia, as well as nickel mining in New Caledonia and the Philippines (as both coal and nickel are used for steel production, SI Figure S8a–b). Overall, a quarter of global metals-related biodiversity loss is attributed to steel. This fraction is significantly lower than for climate impacts of metals, which are dominated by steel production (>80%), mostly because of coal combustion[42].

The link between metals mining and processing countries shows that most biodiversity loss is induced in another country than where metals are further processed (Figure 5a–b). Similarly, most metals are processed in another country than finally consumed (Figure 5b–c). Thus, almost half of metals-related biodiversity loss impacts were caused in New Caledonia, Australia, and Indonesia, but only 18% and 8% were related to their processing and consumption, respectively. In contrast, only 4% of the global metals-related biodiversity loss were induced in China and Japan, but a third was attributed to China's and Japan's metals processing industry. Major international trade flows involve iron and aluminum mined in Australia and further processed in China, and nickel mined in New Caledonia's and further processed in Japan and Australia. An in-depth analysis for biodiversity loss related to nickel mining shown in Figure S9 and discussed in Paragraph S2 of the SI.

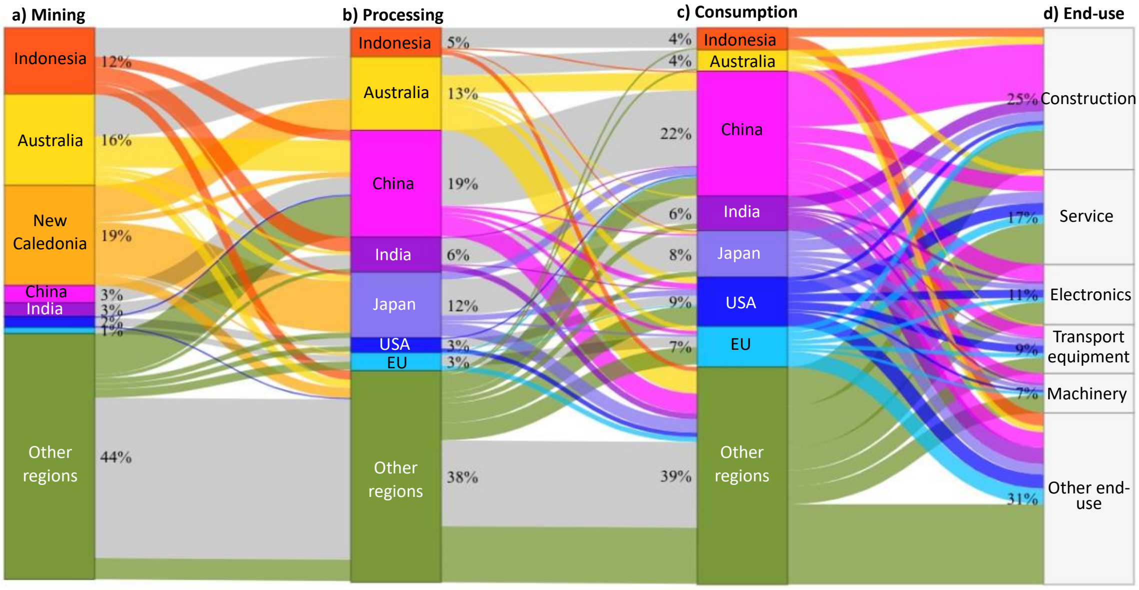


Figure 5. Supply chain analysis of global mining-related biodiversity loss for metals production in 2014 (total: 1.5 $*10^{-4}$ global pdf, 100%). Colored flows between the region of mining, processing, and consumption refer to international trade. An in-depth analysis for the type of metals processed in the respective regions is shown in Figure S8 of the SI.

Coal supply chain: The intermediate steps in the global supply chain of coal mining are illustrated in Figure S10 of the SI, including the country where coal is combusted (combustion or processing perspective). While most of coal-mining related biodiversity loss was induced in Indonesia (55%), the majority of this coal was exported for combustion abroad, especially in China and India. Thus, China and India contribute to more than 40% of global coal-mining related biodiversity loss from a combustion perspective, although less than 10% of global coal-mining related impacts were induced in these countries. The majority of that coal was combusted to manufacture materials, mostly for construction, electronics, machinery and transport equipment, including also coal combusted to manufacture materials and commodities for exports. Overall, more than half of global coal-mining related biodiversity loss is related to heat and electricity supply to manufacture metals (29%), cement (10%), chemicals (10%), and plastics (5%). This is in accordance to previous studies showing that many climate and particulate-matter related health impacts of coal combustion are induced in China and India[42, 50], with a rising fraction related to material production (mostly cement, steel and plastics for building their infrastructure and supplying the global market).

Electricity supply chain: To compare mining-related biodiversity loss of fossil and renewable electricity, we assessed the related impacts of global electricity generation in total (SI Figure S11) and per terajoules (Figure 6), respectively, in 2014. Overall, 10% of global mining-related biodiversity loss was attributed to electricity generation in 2014 ($2.0 * 10^{-5}$ global pdf). Thereof, the vast majority was related to coal mining for fossil electricity (95%). Hotspots include coal mined and exported by Indonesia and Australia for electricity generation abroad, mainly in China and India (SI Figure S11). Renewable electricity accounted for 3.5% of mining-related biodiversity loss of global electricity generation. While coal electricity relies on the constant supply of coal, renewable electricity only relies on mining products for building the facilities. This includes for example coal and minerals to produce steel and cement to build the infrastructure. Thus, mining impacts on biodiversity are also more than ten times higher for coal electricity than any type of renewable electricity when calculated per terajoules (Figure 7), although this study's approach tends to overestimate mining-related impacts of renewable energy compared to fossil electricity (see Section 2.2).

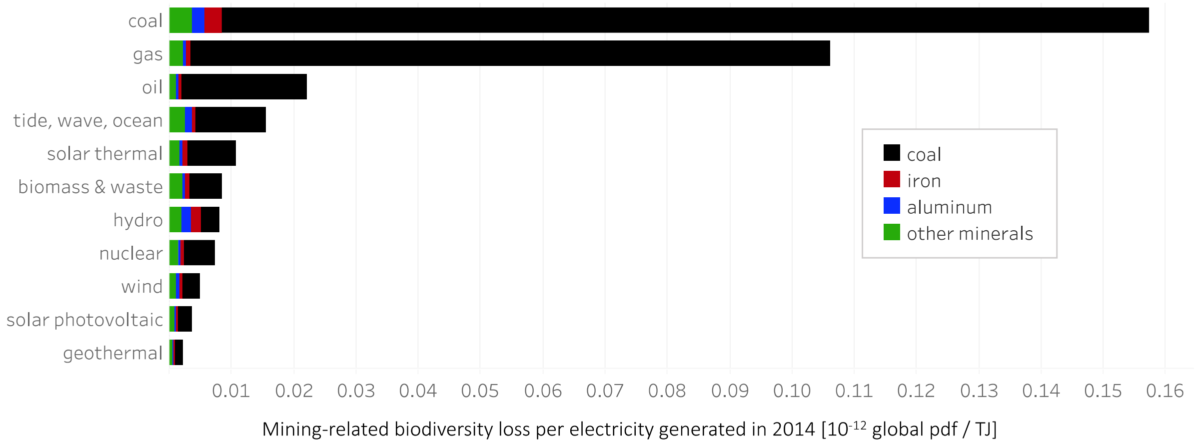


Figure 6. Mining-related biodiversity loss per electricity generated in 2014. The unit refers to global species loss in pdf (potentially disappeared fraction) per generated electricity in terajoules (TJ).

While previous studies concluded that the energy transition will exacerbate biodiversity threats from mining[9-11], our results point to synergies in promoting renewables to comply with the Paris Agreement while reducing biodiversity impacts. This is attributed to the avoided impact of coal electricity, which is about ten times higher compared to the impact of renewables. Moreover, mining-related biodiversity impacts of renewables might decrease in the future (per electricity generated), as shown by Harpprecht et al[51] for other environmental impacts in the supply chain of renewables, such as climate impacts and acidification. One reason is the reduced impact of coal mining in the supply chain of renewables due to a shift from coal to renewables (Figure 7). Another reason might be the rising share of secondary metals projected for the future[52]. Nevertheless, mining of metals used for renewable electricity, including rare earth metals, might also result in the exploitation of new ecosystems, especially in countries with low environmental regulations[3, 9, 43].

4. Limitations and Outlook

This study provides a quantitative assessment of land-use related biodiversity loss of mining in global supply chains (based on the global-scale mining areas of ref[30] and MRIO data for the year 2014) to provide decision support for industry and policy for improved supply chain management. However, future work is needed to improve resolution both spatially (e.g., on company level) and sectorally (e.g., higher differentiation of metal sectors), as well as to provide time series for the past, present, and future. To analyze supply chain effects of future scenarios, further work is needed to couple MRIO analysis with Integrated Assessment Models, such as the shared socioeconomic pathways[53-60]. Also, this study's approach (based on ref[29]) can be used to integrate further MRIO databases, both monetary (e.g., GLORIA[27]) and physical (e.g., FABIO[61]), as well as other data sources (e.g., bilateral trade data) to improve data quality. Moreover, further work is needed to implement other drivers of biodiversity loss into MRIO analysis, including biodiversity impacts of oil and gas mining (especially shale gas and oil sands), acid mine drainage, and environmental disasters due to dam failures of tailings[5-7, 47-49]. Also, other environmental aspects such as local water scarcity of mining[62-64] should be tackled.

In addition to extraction data from the BGS[35], land use of mining[30], and related biodiversity loss[31, 32], this study's database called REXIA covers further key indicators that tackle the sustainable development goals. These include the total material footprint, climate impacts, health impacts due to particulate matter emissions[65], blue water consumption, water stress[66], total land use, and related biodiversity loss[67] (based on the UNEP-SETAC methodologies[32] in accordance to ref[29]). REXIA is provided open-access (*https://doi.org/10.5281/zenodo.6609852*) and can be applied by researchers, industries, and policy makers for a more detailed supply chain analysis and impact assessment not only of mining products, but any industries and nations.

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Competing interests. The authors declare no competing interests.

Supporting Information

Link to REXIA (open access once the paper is accepted):
https://doi.org/10.5281/zenodo.6609852

PDF document with figures supporting the results of the research article:
Supporting_Information.pdf

Excel file for classification of sectors and regions of EXIOBASE3, Eora26, and GTAP10:
SI_Classification.xlsx

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