Hotspots of Mining-Related Biodiversity Loss in Global Supply Chains and the Potential for Reduction through Renewable Electricity

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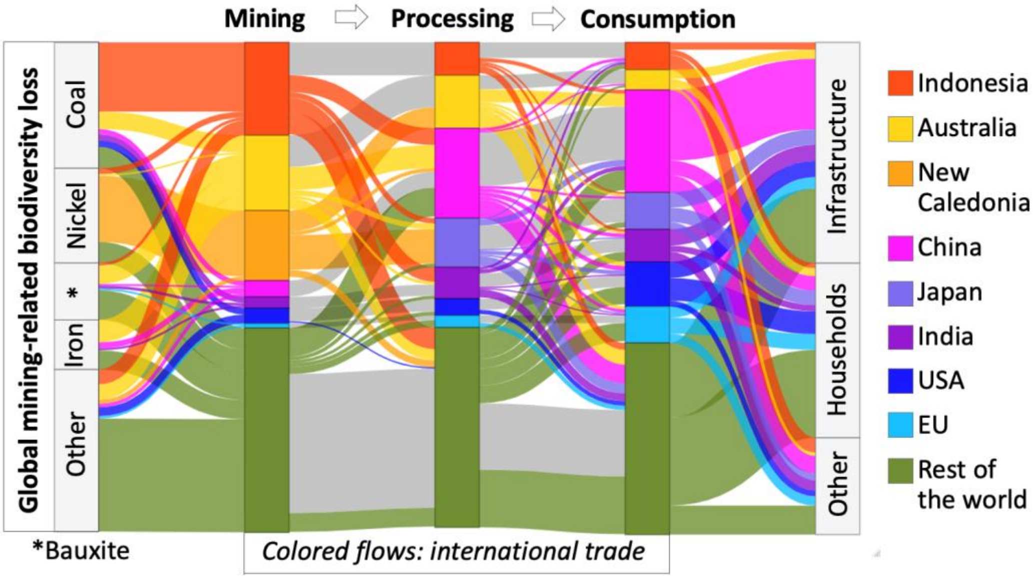
Graphical abstract



Abstract

Anticipated infrastructure growth and energy transition may exacerbate biodiversity loss through increased demand for mining products. This study uses an enhanced multi-regional input-output database (REX, Resolved EXIOBASE) and supply chain impact mapping (SCIM) method to assess global biodiversity loss associated with mining-related land use. We identify hotspots in the supply chain of mining products, compare the impact of fossil and renewable electricity, and estimate the share of mining in total global impacts. We found that half of the global mining-related biodiversity loss occurs 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 bauxite exports to China. Key end-consumers include China's growing infrastructure and the EU's and USA's households-consumption. Electricity generation accounted for 10% of global mining-related biodiversity loss in 2014. The impact of coal-fired electricity was ten times higher than renewables per unit of electricity generated. Globally, mining contributes to less than 1% of total land-use related biodiversity loss, which is dominated by agriculture. Our results provide transparency in sourcing more sustainable mining products and underline synergies in fostering renewables to meet local biodiversity and global climate targets.

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

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

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 causes many environmental and social impacts. Several studies have documented the harmful consequences for the environment and the link to social conflicts[1-8]. This involves the Global South in particular, 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, many mining products are exported to another country for further processing and final consumption. However, 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 regional, sectoral and temporal resolution of the underlying MRIO-database[21-27]. By merging the two global MRIO databases EXIOBASE3[21] (163 sectors and 49 regions) and Eora26[22] (26 sectors and 189 countries), Cabernard & Pfister[28] have created a global MRIO database (REX, Resolved EXIOBASE) with a high regional, sectoral and temporal resolution (163 sectors and 189 countries, from 1995–2015). However, the quality of that database is limited for the mining and metal processing sectors[28]. In addition, a global-scale dataset of biodiversity loss associated with mining-related land use is lacking in all databases, 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[28] to create REX with improved data quality for all mining and metals processing sectors, including a regionalized impact assessment. In this context, we compile and integrate a global-scale data set of biodiversity loss associated with mining-related land use into the database. This regionalized impact assessment is based on the mining area data set of Maus et al[29], ecoregion[30]-specific global species loss factors from UNEP-SETAC[31], and geographic data of the Saving and Loan (SNL) Metals & Mining Database[32]. In contrast to the global mining area data set of Werner et al[33] and Liang et al[34], the dataset of Maus et al[29] includes not only the area-specific mining features of land use (open cuts, tailings dams, waste rock dumps, etc.), but also the patches in-between. However, in contrast to the case study of Sonter et al[35] on the Amazonas, the dataset of Maus et al[29] does not include indirect land use for mining, such as roads, trains and the port built to support the mine, or new settlements that had to be established (except if they are located within the area where mining features predominate). Thus, the mining-related biodiversity loss analyzed in this study refers to the biodiversity impacts related to mining-related land use features, including the patches in-between but excluding the infrastructure outside these features. Finally, we apply the supply chain impact mapping (SCIM) method of Cabernard et al[36] to REX for assessing the global supply-chain impacts of the metals industry and the power sector. Based on this, we address the following research questions (RQ):

RQ 1) Where are the 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 (REX) with Regionalized Biodiversity Impact Assessment

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 the 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 since 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 a time series.

Due to the high sectoral resolution, we used EXIOBASE3[21] as a starting point and followed the procedure of Cabernard & Pfister[28] to compile a highly-resolved MRIO database with a regionalized impact assessment called REX (Resolved EXIOBASE). REX distinguishes 163 sectors for 189 countries, covering the year 2014. To disaggregate the five "rest of the world" regions of EXIOBASE3 into 145 individual countries, we integrated data not only from Eora26[22] and FAOSTAT[37], as done in ref[28], but also from GTAP10[24] and the British Geological Survey (BGS)[38] (SI Methods, Paragraph S1). The latter allowed us to improve, in particular, the data quality for the mining and metals processing sectors. In accordance with ref[28], the resulting transaction and final demand matrices of REX are equal to the original ones of the EXIOBASE3 database when aggregated back to the original regional resolution (±2% because of numeric errors). However, other than ref[28], we used the newest EXIOBASE3 version 3.8.2[39], which provides significant improvements in data quality for the metals mining and processing sectors compared to version 3.4 used in Cabernard & Pfister[28].

We incorporated three environmental extensions into REX for all mining sectors, namely mining quantity (in kg of refined mining product), mining-related land use areas (in m^2) and related biodiversity loss impacts (in global potentially disappeared fraction of species). This means that mining quantity, mining-related land use and related biodiversity loss differ from EXIOBASE3[21]. Mining quantities were directly adopted from BGS[38] by allocating the different commodities to the mining and processing sectors of EXIOBASE3. Mining-related land use area was implemented based on the global-scale data set of mining area from Maus et al[29], which includes active mines between 2000 and 2017 indicated by the SNL Metals & Mining Database[32]. We translated this dataset into mining-related biodiversity loss by weighting the area of each mining polygon of Maus et al[29] with the ecoregion[30]-specific global species loss factors from UNEP-SETAC[31]. These characterization factors indicate the global potentially disappeared fraction (pdf) of species per square meter of land use, which refers to the fraction of global species richness that is potentially lost due to land occupation (SI Paragraph S2). An example for the biodiversity loss impact assessment is shown in Figure S2 with the example of Australia.

As REX distinguishes different mining sectors (e.g., coal, copper, bauxite, etc.), we applied the following procedure to allocate both mining area and related biodiversity loss to the different mining sectors of REX: The first step was to link each mining polygon of Maus et al[29] to the active mines indicated by the SNL Metals and Mining Database[32]. This database provides information on the mined commodities, including the main commodity, which refers to the commodity with the highest monetary output, and all by-products. However, the SNL Metals & Mining Database[32] only indicates approximate point coordinates for the mining properties. Moreover, most properties did not overlap with the mining polygons of Maus et al[29], who applied buffer zones of 10 km when interpreting the satellite images of 6021 active mining properties from the SNL Metals & Mining Database[32]. Thus, we allocated the mining polygons to the closest point coordinates of the mining properties using the minimum distance calculation (minimum distance between the point coordinate to the side of a polygon). An example of this link is shown in Figure S3 and S4 of the SI with the example of Australia. Further information on the link between mining polygons and properties are provided in the SI (Paragraph S3, Figures S5–S8).

Based on the established link between the properties and the mining polygons, we compared two allocation schemes: In the *SNL main commodity allocation*, we allocated the mining area (and related biodiversity loss) of each mining polygon to the main commodity of the corresponding mining sector of REX and aggregated the results on a country level. This allocation has the limitations that by-products are not considered and that the SNL Metals & Mining Database[32] covers only a fraction of the total production volumes compared to the BGS[38] national accounts (SI Paragraph S4). Therefore, we evaluated an additional step for all metal mining sectors in the *BGS country-share allocation*: For all mining polygons assigned to metals, we aggregated the mining area (and related biodiversity loss) on a country-level and reallocated the results to the different mining sectors of each country of REX 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[38] with the estimated price of metals in 2014[40] (e.g., if gold contributes to 5% of the total value of metals mined in Australia, 5% of the metals mining-related land use and biodiversity loss was attributed to gold).

2.2 Supply Chain Impact Mapping (SCIM)

We applied the common Leontief model[14-20] to link the country and sector where biodiversity loss is induced by mining (production or mining perspective) to the region and sector of final consumption (consumption or footprint perspective). To analyze the intermediate steps in the supply chain of mining-related biodiversity loss, we applied the supply chain impact mapping (SCIM) method of Cabernard et al[36]. SCIM allows the total impacts of any industries and regions to be assessed along the global supply chain by adopting different perspectives that are connected in a multi-dimensional impact array, and avoids the issue of double counting based on Dente et al[41]. For example, if SCIM is applied to global metals production, where some steel is used for nickel production, the impacts of that steel are either counted in steel or in nickel production (but not in both sectors as done in previous studies[42-44] to prevent double counting), and the link between the steel and nickel sector is stored in a multi-dimensional impact array that maps the entire upstream and downstream chain of the global metals industry (see ref[36] for further explanation).

Following the procedure of Cabernard et al[36], we defined all metals-related 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 combined the mining perspective (production perspective), the processing perspective (target perspective), the end-sector perspective (final supply perspective), and the consumption perspective (final demand perspective) in a multi-dimensional impact array[36]. To analyze the intermediate step in the supply chain of coal, we implemented an additional perspective, called the "combustion perspective". In this perspective, the biodiversity loss of coal mining is linked to the region where coal was combusted, as done in Cabernard et al[45] for climate impacts of global plastics production due to coal combustion.

To assess the mining-related biodiversity loss of global electricity generation, we chose 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 Cabernard et al[36]. In this context, mining-related biodiversity loss impacts were allocated to the respective electricity sector from a target perspective[36]. 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 unit of generated electricity, we divided the mining-related biodiversity loss of each electricity sector through the respective amount of final electricity generated in 2014. The latter was estimated by dividing the total output of final electricity generated in 2014 (in million Euro) by the price vector (million Euro/ terajoules; see SI Figure S11 for a comparison with the Global Electricity Review[46]). The price vector was derived based on the monetary (in million Euro) and physical (terajoules) MRIO tables of EXIOBASE3 for the year 2011, as done in Cabernard et al[45].

This procedure relies on the simplified assumption that prices of electricity have not changed from 2011 to 2014. In reality, wind and solar electricity experienced a decrease in price between 2011 and 2014 (-17% for wind, -22% for solar thermal, and -49% for solar PV based on ref[47, 48]). Additionally, our procedure assumes that infrastructure build-up of renewable energy remained constant over time. However, renewables have experienced an increase over the past decade in reality. Thus, the installed capacity generates more electricity over a lifetime than was actually generated in 2014. This means that this study's approach tends to overestimate the mining-related impacts of renewables compared to fossil electricity per unit of electricity generated. To estimate the extent of overestimation, we have assessed the biodiversity loss per final electricity generated when both price changes and the installed capacity are taken into account (SI Paragraph S5).

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[29] (57,277 km^2) colored by main commodity based on the active mines indicated by the SNL Metals & Mining Database[32]. Additionally, Figure 1 illustrates the ecoregions[30] colored by the biodiversity loss in global species loss per square meter[31] on a logarithmic scale. Mining areas in ecoregions with a particularly high ecosystem value include coal mines in Indonesia, nickel mines in New Caledonia, gold mines in Ghana, bauxite mines in Australia, iron mines in Brazil, copper and lithium mines in Chile, and diamond mines in South Africa (Figure 1b–h). Detailed maps for mining-related biodiversity loss hotpots in Indonesia, New Caledonia, and Australia are shown in Figures S12–S14 of the SI.

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 owing to 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 the 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 higher in the *SNL main commodity allocation* (20% instead of 13% in global mining-related biodiversity loss), while the share of iron and bauxite mining is higher in the *BGS country-share allocation* (12% and 10% respectively, instead of 6% and 5%, respectively, Figure 2a). One reason is that the *SNL main commodity allocation* is based on the SNL Metals & Mining Database[32], which significantly underestimates extraction volumes for most commodities compared to the BGS (SI Figures S9 and S10). This includes, for example, bauxite and iron mining in Suriname and Venezuela, which is not covered in the SNL Metals & Mining Database[32] (Figure 2). Another reason for this is that the *BGS country-share allocation* does not account for the ecoregion-specific impact assessment of the individual metals. This includes, for example, gold mined in Australia's ecoregions with a high ecosystem value and iron mined in Australia's ecoregions with a low ecosystem value (SI Figure S14). Despite this limitation, we rely on the *BGS country-share allocation* in the following and point to future work to improve the allocation in the conclusion and outlook sections.

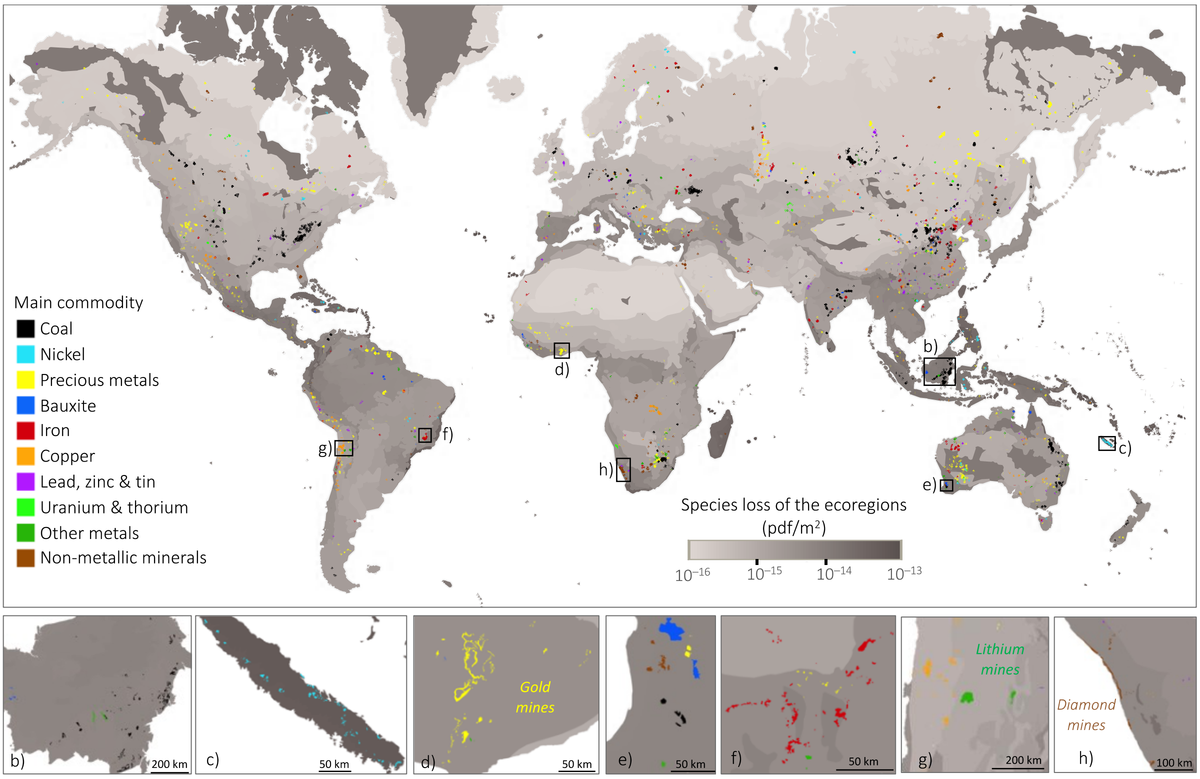


Figure 1. a) Mining area data set from Maus et al[29] (total 57,277 km^2) colored by main commodity based on the active mines of the SNL Metals & Mining Database[32] and their location in ecoregions[30]. The ecoregions are colored by the global species loss in potentially disappeared fraction (pdf) per square meter based on UNEP-SETAC[31]. b–h) Hotspots of mining-related biodiversity loss are shown for those countries and commodities where most of the related impacts are caused in both allocation schemes (see Figure 2).

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 2b). Coal mining in Indonesia and nickel mining in New Caledonia each accounted for 14% of global mining-related biodiversity loss, while Australia's iron, bauxite and coal mining contributed together to 13% of global mining-related biodiversity loss. Further biodiversity loss hotspots involve the mining of nickel in the Philippines, Cuba and Indonesia, bauxite 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, the biodiversity loss associated with non-metallic minerals was mainly attributed to diamond mines in South Africa and Namibia (Figure 2b).

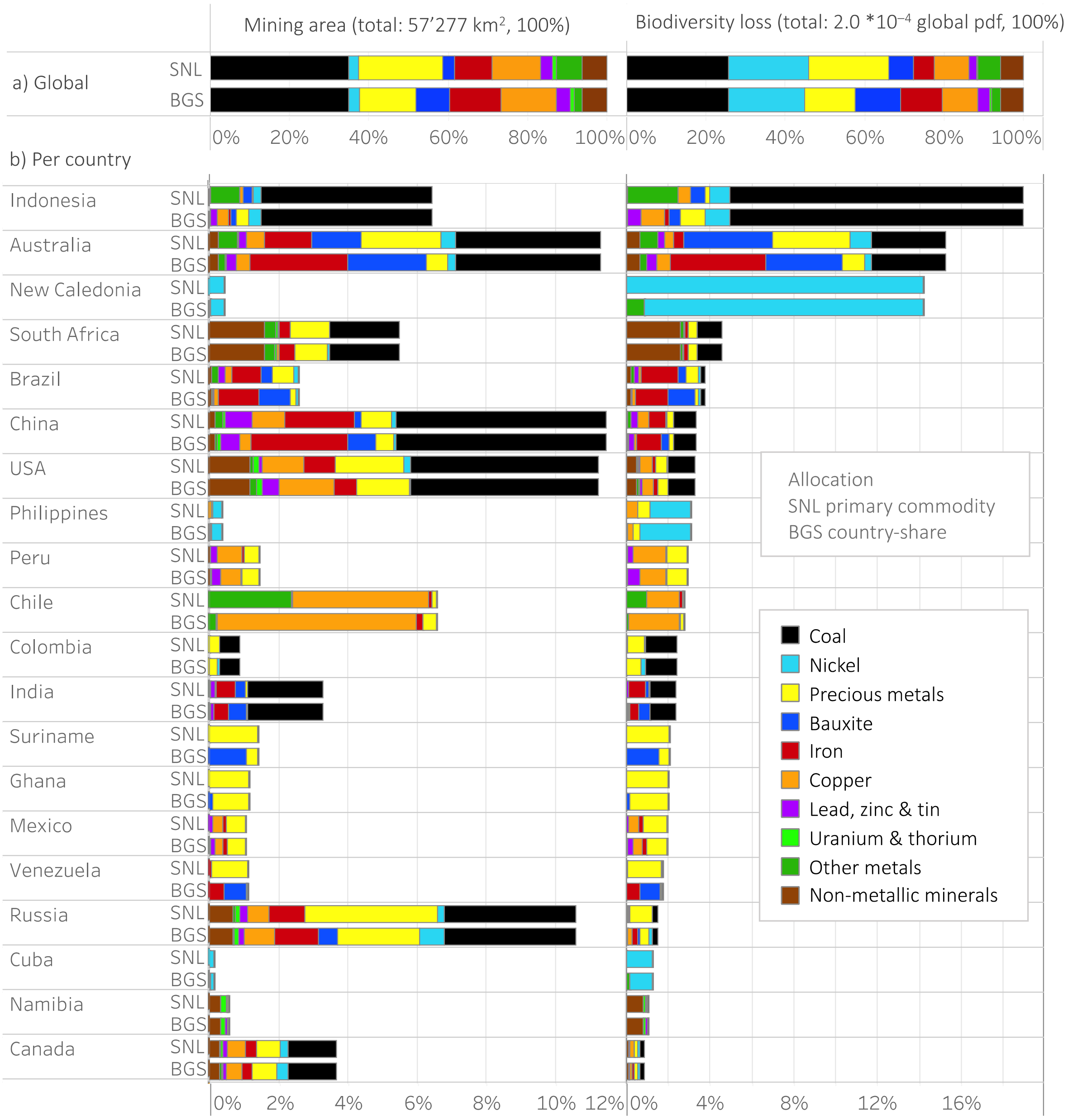


Figure 2: Global mining area (total 57,277 km^2, 100%)[29] and related biodiversity loss impacts (total: 2.0 $*10^{-4}$ global pdf, 100%) divided by mining sector for the two allocation schemes globally (a) and per country (b). The figure shows all countries representing at least 1% of global mining-related biodiversity loss. Together, these countries represent more than 90% of global mining-related biodiversity loss. Results for all countries are listed in the SI (*SI_REX.xlsx*, sheet: *Figure 2 complete).*

Our results point to strong imbalances between refined mining quantity, mining area, and related biodiversity loss per country and mined commodity (Figure 2b, see Figures S15–S18 of the SI for a comparison of refined mining quantity, area, and related biodiversity loss for coal, nickel, bauxite, and iron mining based on the *BGS country-share allocation*). For example, Indonesia accounted for 6% of global coal extraction (year 2014) and 14% of global coal mining area (SI Figure S15). 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 the 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, SI Figure S16). 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 bauxite-mining related biodiversity loss was induced in Suriname and Venezuela, although only 1% of global bauxite was mined in these countries (year 2014, SI Figure S17).

Imbalances between land use and biodiversity loss do not only exist on a country level, but also on an ecoregion level and a polygon level (SI Figure S19). While Werner et al[33] found that bulk mine production amounts (including bulk ore milled) is a reasonable proxy for mining area (based on a mining dataset of 3633 km^2 of 295 large-scale mines), our results indicate that mining area is not appropriate to estimate biodiversity loss. This is attributed to strong differences in local biodiversity impacts considered in this study's regionalized impact assessment based on UNEP-SETAC[31]. The same imbalances between land use area and biodiversity loss were also found for other land use activities such as agriculture and forestry[36, 49]. 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[50]. This highlights the importance of taking the local biodiversity loss of land use into consideration to promote sustainable practices in the mining and metals industry.

The importance of this study's regionalized biodiversity impact assessment is also evident when comparing the results to previous estimates (SI Figure S20). The land use area of mining in the dataset of Maus et al[29] 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[36] ($6.5 * 10^{-6}$ global pdf), which is based on the land use data for mining of EXIOBASE3[21] and the country-average characterization factors from UNEP-SETAC[31]. The reason for this discrepancy is that we applied ecoregion[30]-specific species loss factors, while Cabernard et al[36] is based on country-average species loss factors[31]. When dividing the mining-related biodiversity loss by 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[36] ($3.4 * 10^{-15}$ global pdf/m^2 mining area compared to $4.3 * 10^{-16}$ global pdf/m^2). This underscores the fact that many mines are located in regions with a particularly high ecosystem value, which is consistent with previous literature[3, 9, 51]. For example, Indonesia[52], Australia[53] and New Caledonia[54] are widely recognized biodiversity hotspots with mining activities of global importance.

Other than previous studies on mining in vulnerable ecosystems[3, 9, 51], this study provides a quantitative assessment of global mining-related biodiversity loss that allows the contribution of mining activities in total global land-use-related biodiversity loss to be estimated, taking crops cultivation, pastures, agriculture, industries and housing all into account. Based on the same UNEP-SETAC impact method[31] applied here, global land-use related biodiversity loss has been estimated to range from 0.08–0.14 global pdf[12, 36, 55-57]. 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, 58-60], we find that mining activities contribute to less than 0.25% of global land-use related biodiversity loss, whose losses are in fact dominated by agriculture (75%) and forestry (15%)[12, 36]. This is in accordance with two case studies on biodiversity loss in Australia[61] and forestry loss in Indonesia[62], which found that mining had by far the lowest impact compared to other land use types such as agriculture, other industries, and urbanization.

In contrast to the dataset of Maus et al[29] used here (57'277 km^2), the use of the global mining area dataset of Liang et al[34] (31,396 km^2) or Werner et al (3633 km^2)[33] would further decrease the total impact of mining and might also change the relative contribution on a country level, shown in Figure 2. One reason for this is that these studies[33, 34] applied a stricter delineation method than Maus et al[29] to distinguish the different mining features (open cuts, tailings dams, waste rock dumps, etc.), but excluded the patches in-between. Another reason is that these datasets are based on different satellite data sources acquired at different times with distinct spatial resolutions, covering a different subset of mining locations. Therefore, previous datasets are not comparable, which points to the need for standardized methodologies to monitor mining areas.

As subnational mining activities are considerably underreported compared to national accounts of the BGS[38] (SI Figures S9–S10), the share of mining in total global land-use related biodiversity loss might be underestimated in this study. Moreover, biodiversity loss impacts would be considerably higher if indirect impacts were taken into account. Indirect impacts can result from the mining infrastructure facilities, urban expansion to support a growing workforce, and the development of mineral commodity supply chains. For example, Sonter et al[35] found that mining was responsible for 11,670 km^2 of deforestation in the Amazon if such indirect effects are taken into account. This is almost five times higher than mining-related land use in the Amazon considered here. In addition to these indirect impacts, cumulative impacts driven by mining in combination with other pressures (e.g., agriculture), acid mine drainage, soil erosion, environmental disasters due to dam failures of tailings, and other potential long-term impacts are substantial and need to be assessed by future research on a global scale[5-7, 35, 54, 58-61, 63].

3.2 Supply Chain Analysis and Reduction Potentials through 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 3a–b). For example, although half of global mining-related biodiversity loss was induced in Australia, Indonesia and New Caledonia, less than 10% of global impacts were attributed to their consumption. This means that the vast majority of the biodiversity loss caused in Australia (91%), Indonesia (75%), and New Caledonia (99%) was attributed to exports. Conversely, less than 10% of global mining-related biodiversity loss was induced in China, the USA, the EU, Japan or India, although more than half of global mining-related biodiversity was related to their consumption. 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 3b). This includes real estate (construction) and equipment (such as machinery, electronics, transport equipment) that are acquired by local residents to be used in the production process for more than one year (Figure 3c). In contrast, household consumption contributes most substantially to the EU's and USA's mining-related biodiversity loss footprint. This includes, for example, private electronics (e.g., mobile phones and television), private transport (e.g., cars and bicycles), direct energy use (e.g., coal electricity used by households) as well as food, textiles and furniture (due to metals and coal used in the supply chain to produce these commodities).

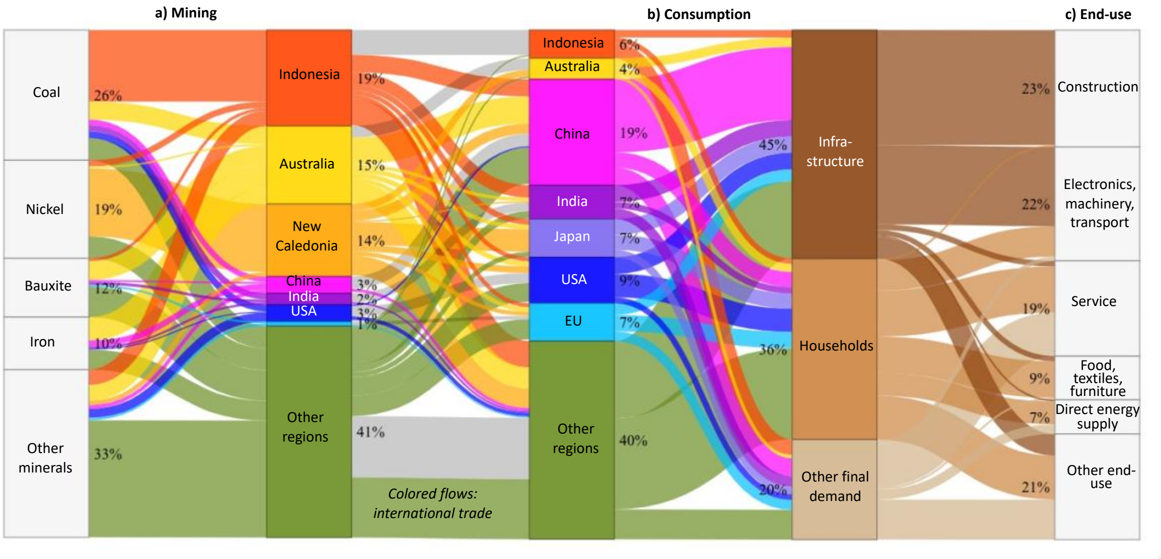


Figure 3. Supply chain analysis of global mining-related biodiversity loss in 2014 (total: 2.0 $*10^{-4}$ global pdf, 100%). "Other final demand" includes changes in inventories (9%), final expenditures by the government (8%) and by non-profit organizations (3%). The intermediate steps in the global supply chain of the metals industry, coal combusting industry, and power sector are shown in Figure 4 and Figure S24–S27 of the SI.

On a per-capita level, the 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 to or below the global per-capita average, respectively (see Figure S21 of the SI for a comparison on a per-capita basis). 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 3a–b). The supply chain analysis of mining-related biodiversity loss split by income (per-capita GDP)[64] and by the Global North and South is shown in Figures S22 and S23 of the SI.

Metals supply chain: The supply chain of mining-related biodiversity loss impacts of total global metals production is shown in Figure 4 and Figure S24 of the SI. Overall, 76% of total global mining-related biodiversity loss is 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 4c–d). This also involves 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 S24a–b). Overall, a quarter of global metals-related biodiversity loss is attributed to steel. This fraction is significantly lower than for the climate impacts of metals, which are dominated by steel production (>80%), mostly because of coal combustion[50].

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 4a–b). Similarly, most metals are processed in another country than where they are finally consumed (Figure 4b–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 was 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 bauxite mined in Australia and further processed in China, and nickel mined in New Caledonia and further processed in Japan and Australia. As nickel processed in Japan is used mostly for domestic consumption, Japan's consumption contributes to almost a quarter of global nickel-mining related biodiversity loss (see SI Figure S25 and Paragraph S6 for an in-depth analysis of biodiversity loss related to nickel mining). This is similar to the results of Nakajima et al[65], who found that 19% of the land use related to Nickel mining in New Caledonia is attributed to Japan's final consumption. However, the estimated global mining area of nickel was more than five hundred times lower in Nakajima et al [65] (1.9 km^2) compared to this study (>10,000 km^2 in both allocation schemes, Figure 2). The reason for this is that Nakajima et al[65] applied nickel land use intensities based on Ecobalance[66], while this study used satellite data from Maus et al[29].

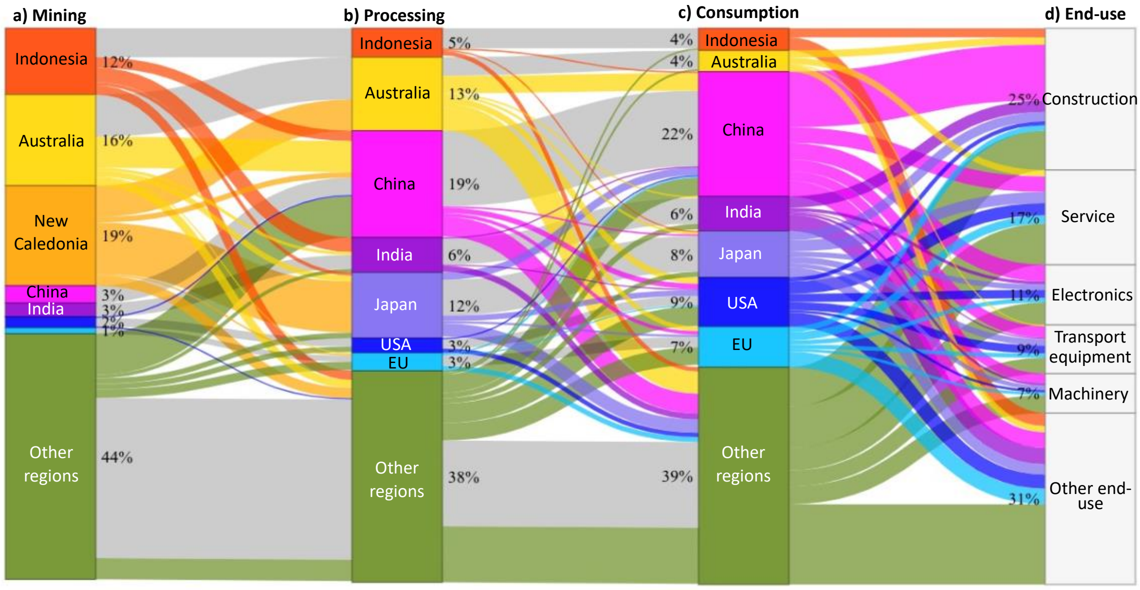


Figure 4. Supply chain analysis of global mining-related biodiversity loss for metals production in 2014 (total: 1.5 $*10^{-4}$ global pdf, 100%). Colored flows between the regions of mining, processing, and consumption refer to international trade. An in-depth analysis for the type of metals processed in the respective regions is shown in Figure S25 of the SI.

Coal supply chain: The intermediate steps in the global supply chain of coal mining are illustrated in Figure S26 of the SI, including the country where coal is combusted (combustion or processing perspective). While most coal-mining related biodiversity loss was induced in Indonesia (55%), the majority of this coal was exported for combustion abroad, especially to China and India. Due to unreported illegal coal mining in Indonesia (50-80 million tons, 0.3% of Indonesia's total coal exports)[67, 68], Indonesia's coal exports might be even higher. In January 2022, Indonesia imposed a month-long coal export ban due to local blackout issues. Thus, the results might look different if current time trends were considered[32].

As most of Indonesia's coal exports were combusted in China and India, 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 (SI Figure S26). 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 with previous studies showing that many climate and particulate-matter related health impacts of coal combustion are induced in China and India[50, 69], 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 S27) and per terajoules (Figure 5), 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 S27). Renewable electricity accounted for 3.5% of mining-related biodiversity loss associated with global electricity generation. While coal electricity relies on a 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 six times higher for coal electricity than for any type of renewable electricity when calculated per terajoules (Figure 5). On average, the biodiversity impact of fossil electricity is ten times higher compared to that of renewables, although this study's approach tends to overestimate the mining-related impacts of renewable energy compared to fossil electricity (Figure 5). Taking price changes and the installed capacity into account would decrease the biodiversity impact of renewables by at least 50% for all renewables except hydro-electricity (SI Figure S28).

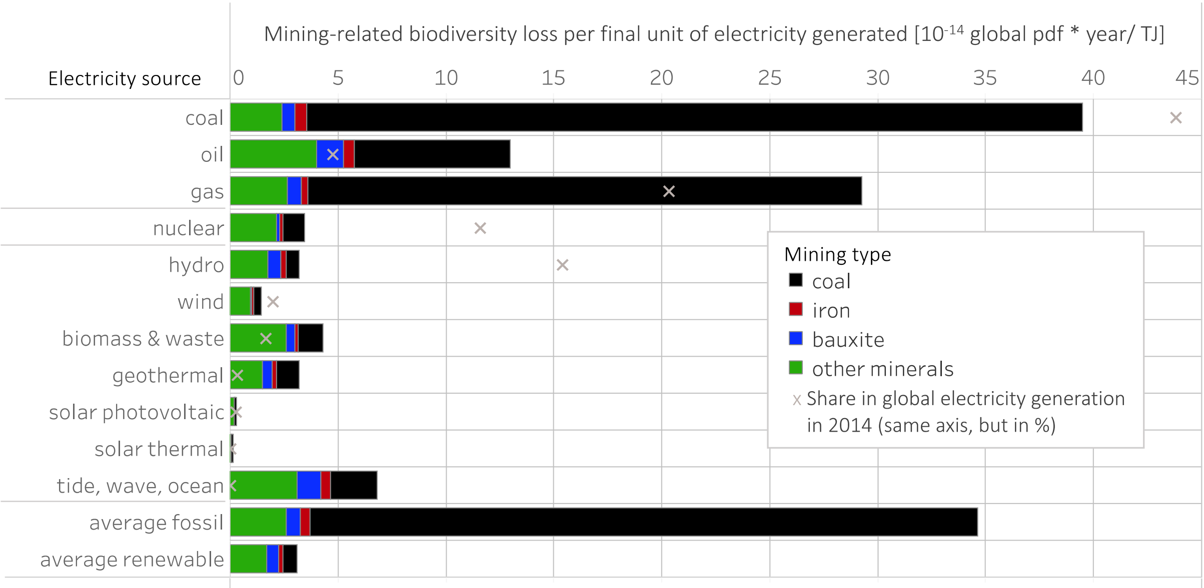


Figure 5. Mining-related biodiversity loss per final unit of electricity generated in 2014. The unit refers to global species loss in potentially disappeared fraction (pdf*year) per final electricity unit generated in terajoules (TJ). Average impacts for fossil and renewable electricity are calculated based on the estimated global electricity generation in 2014.

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, the mining-related biodiversity impacts of renewables might decrease in the future (per electricity generated), as shown by Harpprecht et al[70] for other environmental impacts in the supply chain of renewables such as climate impacts and acidification. One reason for such a reduction is the reduced impact of coal mining in the supply chain of renewables due to a shift from coal to renewables (Figure 5). Another reason might be the rising share of secondary metals projected for the future[71]. Nevertheless, the 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 standards[3, 9, 51]. As some of these countries permit the release of tailings into river systems and marine environments, this points to another uncertainty concerning the interpretation of the satellite data, namely, that mine areas are not fully visible in satellite imagery for mapping[29, 34].

4. Limitations and Outlook

This study provides a quantitative assessment of the land-use related biodiversity loss of mining in global supply chains (based on the global-scale mining areas of Maus et al[29] and MRIO data for the year 2014) to provide decision-making support for industry and policy makers aiming to improve 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 enhance the model by providing time series for the past, present and future. To analyze the supply chain effects of future scenarios, further work is needed to couple MRIO analysis with Integrated Assessment Models by integrating the shared socioeconomic pathways[72-79]. Furthermore, this study's approach (based on Cabernard & Pfister[28]) can be used to integrate further MRIO databases, both monetary (e.g., GLORIA[27]) and physical (e.g., FABIO[80]), as well as other data sources (e.g., bilateral trade data) to improve data quality.

One limitation of this study is that MRIO data are from 2014 and SNL data[32] are based on active mines between 2000–2017. Thus, this study only provides a snapshot for the year 2014 with uncertainties with respect to the spatial distribution of mining-related biodiversity loss. Therefore, future work is needed to integrate more recent datasets on mining-related land use area into the MRIO database. This includes, in particular, the integration of the updated global mining area dataset of Maus et al[81]. Compared to the previous dataset[29] used here (21,060 polygons extending over 57,277 km^2 based on 6021 mining properties from the SNL Metals & Mining Database[32]), the updated dataset contains 44,929 polygons covering 101,583 km^2 of large-scale as well as small-scale and artisanal mining (based on 34,820 mining properties from the SNL Metals & Mining Database[32]). In this latter dataset, mining areas are several times higher in Myanmar, Guyana, Peru, Argentina, Brazil, Indonesia, Canada, Suriname, Ghana and Venezuela (see Figure 3 in Maus et al[81]). Thus, the use of this more recent dataset might increase findings pertaining to the related biodiversity loss in these countries considerably.

As data in the SNL Metals & Mining Database[32] are incomplete, future work should also consider the national statistics in the BGS[38]. The consideration of more recent time trends on metals extraction based on the BGS[38] might increase, in particular findings on biodiversity loss impacts of bauxite mining in Guinea as well as bauxite and nickel mining in Indonesia as these metals showed a strong increase between 2014–2022 (SI Figure S29–31). Complete national statistics based on the BGS[38] have been taken into account in this study to some extent in the *BGS country-share allocation*. However, as this allocation has the limitation that it conceals the ecoregion-specific impact assessment of the individual metals on a country level, future work is needed to improve the allocation of mining areas and biodiversity loss to the different mining commodities on a mine-level.

Moreover, further work is needed to incorporate other drivers of biodiversity loss into MRIO analysis, including the 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, 58-60]. Moreover, other environmental aspects such as mining-related local water scarcity[82-84] as well as the socioeconomic dimension of mining should be tackled. Given the socioeconomic importance of mining as driver of additional developments in local communities that could prevent biodiversity loss impacts in the long-term, future work is needed to align social, economic and biodiversity conservation goals[85, 86].

In addition to extraction data from the BGS[38], mining-related land use[29] and resultant biodiversity loss[30, 31], REX covers further key indicators that tackle the sustainable development goals. These include the total material footprint (including bulk ore milled for all metals in mining sectors), climate impacts, health impacts due to particulate matter emissions[87], blue water consumption, water stress[88], total land use, and related biodiversity loss[89] (based on the UNEP-SETAC methodologies[31] in accordance with ref[28]). REX is provided open-access (*https://doi.org/10.5281/zenodo.6609852*) and can be applied by researchers, industries and policy makers for purposes of obtaining a more detailed supply chain analysis and impact assessment not only of mining products, but of any industries and nations.

Supporting Information

The Resolved EXIOBASE (REX) database is provided open access at:

https://doi.org/10.5281/zenodo.6609852

The Supporting Information is provided open access at:
https://pubs.acs.org/doi/10.1021/acs.est.2c04003

(Paragraph S1) Resolved EXIOBASE (REX), (Paragraph S2) regionalized biodiversity loss impact assess- ment, (Paragraph S3) linking mining properties to mining polygons, (Paragraph S4) limitations of the SNL main commodity allocation, (Paragraph S5) effect of price changes and installed capacity, and (Paragraph S6) results on the nickel supply chain; additional information provided as supporting figures (Figures S1−S31). (PDF)

Classification countries and sectors (classification of sectors and regions in REX based on EXIOBASE3, Eora26, and GTAP10), complete Figure 2 (results of Figure 2 for all countries covered by REX), and country results (mining-related biodiversity loss from a production and consumption perspective per country in total and on a per capita basis). (XLSX)

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