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Full Length Article

Mining-related tree cover loss embodied in EU consumption

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ABSTRACT

Global supply chains for mined materials generate environmental pressures that often occur far from final consumption. To address these distant effects, emerging legal frameworks require companies to exercise due diligence across their supply chains. However, accurately quantifying local mining impacts and tracing them from production to consumption remains challenging. This study analyses global tree cover loss within mine sites from 2001 to 2019, focusing on final demand in the European Union (EU) – a major importer of raw materials and a leading actor in shaping supply chain regulation. Combining satellite imagery with a multi-region input–output framework, we estimate that 1.5 million hectares of global tree cover loss were directly associated with the expansion of mining areas. Of the 1.2 million hectares traceable through supply chains, 12% were associated with EU consumption. Notably, 85% of this EU-related share occurred outside its territorial borders. Although modest compared to other drivers of deforestation, these losses are ecologically significant, as mining expands particularly in vulnerable ecosystems. The results highlight pronounced spatial and commodity-specific variations, offering insights for implementing and refining European due diligence initiatives aimed at more responsible global sourcing.

1. Introduction

The global economy depends on an expanding supply of mined materials, with extraction now at historically unprecedented levels and projected to increase further in the coming decades (JRC, 2023; UNEP, 2024; Giljum et al., 2025). Coal continues to underpin energy systems in many regions (IEA, 2025) and remains an essential energy product for industries such as plastics manufacturing (Cabernard et al., 2022). At the same time, the accelerating shift towards renewable energy systems is driving a steep rise in the demand for metals and minerals critical to low-carbon technologies (Ali et al., 2017; Sovacool et al., 2020; Xu et al., 2020). For instance, constructing an electric vehicle requires six times more minerals than a conventional car, and building an onshore wind power plant needs nine times the mineral resources compared to a gas-fired power plant (IEA, 2021). Therefore, even as the transition to low-carbon energy systems delivers substantial environmental co-benefits (Luderer et al., 2019), it also highlights the need for responsible mining practices to prevent further degradation of vulnerable ecosystems affected by the extraction of materials essential for renewables (Sonter et al., 2020, 2023; Luckeneder et al., 2021).

Mined materials enter global supply chains and end up in industrial production and final consumption distant from extraction sites (Giljum et al., 2025; Fu et al., 2023). Earlier research has demonstrated that European consumption contributes to environmental pressures that are disproportionately borne outside Europe (Steen-Olsen et al., 2012; Lutter et al., 2016; Tukker et al., 2016; Koslowski et al., 2020; Bruckner et al., 2023). For mined materials, import reliance in the European Union (EU) is particularly pronounced (European Commission, EIP on Raw Materials, 2022). This not only raises concerns about the reliable and unhindered access to critical raw materials (Hool et al., 2023), but also highlights the risk that mining activities linked to European demand may be associated with environmental damage and social harms at extraction sites abroad, including cases of unsafe working conditions, health risks, and community displacement (Sovacool et al.,

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2020). To secure mineral resources while safeguarding human rights and achieving global environmental goals, comprehensive initiatives and binding legal frameworks are essential. These should address social and environmental risks throughout the entire supply chain, incorporating Scope-3 reporting and stringent law enforcement to assess, mitigate and disclose pressures and impacts linked to EU consumption (Ventura, 2023).

To promote corporate accountability along global supply chains, the European Council has adopted the Corporate Sustainability Due Diligence Directive (CSDDD). First proposed by the European Commission in 2022, the directive was agreed in 2024 in a significantly weakened form and is still pending transposition into national law. As part of the EU's "Green New Deal", it complements other regulatory initiatives designed to address environmental and social risks along supply chains, including the Batteries Regulation (European Parliament, 2023b), the Corporate Sustainability Reporting Directive (European Parliament, 2022), and the Regulation on Deforestation-free Products (European Parliament, 2023a). The CSDDD requires companies to identify actual and potential adverse impacts in their supply chains and to apply due diligence in order to prevent these impacts (European Commission, 2024). The directive is crucial for material sourcing, covering supply chains for minerals that have previously been excluded from existing or proposed EU due diligence instruments, such as the Conflict Minerals Regulation (European Parliament, 2017). From the outset, however, the CSDDD faced considerable political pressure and was amended again in 2025 in the context of the EU's "Omnibus" package, which reduced the number of companies covered and postponed implementation timelines. The CSDDD also aligns with various emerging global disclosure frameworks and standards with similar objectives, including those by the OECD (2023) and the Taskforce on Nature-related Financial Disclosures (TNFD, 2023).

Forest loss is a telling example of an impact embodied in global supply chains, significant not only for its contribution to climate change but also for its deep ecological and social ramifications, including biodiversity loss (Gibson et al., 2011; Barlow et al., 2016) and human rights violations such as land dispossession and land grabbing (Schilling-Vacaflor and Gustafsson, 2024). Whereas the deforestation footprints of agricultural and forestry commodities have been quantified, equivalent assessments for mining have so far been hindered by data limitations (West et al., 2025). This is an important gap, as mined materials are predominantly embodied in international trade (Wiedmann and Lenzen, 2018), with 71% of metal ore extraction linked to global supply chains in 2020 (Giljum et al., 2025). Compared to agriculture and forestry, mining's contribution to global deforestation is small in absolute numbers, with estimates ranging between 1.37 and 1.98 million hectares over the past 20 years (Kramer et al., 2023; Zhang et al., 2026; Ranjan and Gorai, 2024). However, ecologically sensible regions, such as tropical and subtropical ecosystems are consistently reported as the most affected. Thus, global totals obscure the growing local significance of mining-related tree cover loss and deforestation, both directly at mine sites and through associated land use changes in the mine surroundings (Pendrill et al., 2022; Sonter et al., 2017; Giljum et al., 2022; Ladewig et al., 2024). These characteristics render mining relevant in light of the recent EU initiatives promoting supply chain responsibility.

While the EU's biodiversity and forest strategies aim to curb deforestation and forest degradation (European Commission, 2020, 2021), they primarily address intra-European issues. The Regulation on Deforestation-free Products (European Parliament, 2023a) is currently the only binding EU policy that explicitly targets the origins of imported products in relation to deforestation. Its scope, however, is restricted to agricultural commodities (cattle, cocoa, coffee, palm oil, rubber, soy, and wood) and does not extend to metals or minerals. As the spatial distribution and magnitude of mining-related forest loss varies across regions and commodities (Zhang et al., 2026; Giljum et al., 2022), and given that the EU sources many raw materials from specific supplying countries, developing a better understanding of these linkages is essential.

This study assesses mining-related tree cover loss as a key environmental pressure by combining satellite-based evidence with an environmentally-extended multi-region input–output (EE-MRIO) framework (see Figure S1 in the Supplementary Information for an overview). In doing so, it traces how forest disturbances associated with mining are embodied in the EU's final demand and offers new perspectives on the geography of extraction-related pressures. In addition to providing new empirical evidence, the study further situates these findings within a broader discussion on the potential and limitations of recently introduced EU supply chain initiatives.

2. Methods

2.1. Measuring mining-related tree cover loss

We quantified annual tree cover loss associated with mining across extraction sites worldwide from 2001 to 2019 by overlaying spatial data on mining areas with annual tree cover maps. These records comprise all cleared areas within the boundaries of mining operations as of 2019. By integrating this information with further details on mining operations, we were able to identify specific commodities and production activities.

Data: Following the approach of Maus (2026), we combined the mine area datasets from Maus et al. (2022), Tang and Werner (2023) and OpenStreetMap contributors (2021), as well as riverine mining mapped by Dethier et al. (2023) to compile a global dataset of land area covered by mining. The dataset features 217,613 spatial polygons, adding up to 145,870 km^2 of land area used by large-scale and artisanal and small-scale mining infrastructure, such as open cuts, tailings dams, waste rock dumps, water ponds, and processing plants.

Tree cover loss was obtained from the Global Forest Change (GFC) dataset (Hansen et al., 2013), which provides yearly information on tree cover and tree loss at 1-arcsecond resolution (approximately 30 by 30 m at the equator) on a global scale. We classified any pixel with detected tree cover loss and an initial tree cover greater than 25% as cleared, consistent with established literature (Pendrill et al., 2022). We did not distinguish between partial and complete canopy removal, as mining activities typically result in extensive surface modification and the complete removal of existing vegetation. Moreover, the GFC dataset defines tree cover based on vegetation height and does not distinguish between natural forests and plantations. To account for this limitation in major tropical plantation regions, we excluded areas mapped as tree plantations (e.g. oil palm and rubber) using the plantation mask developed for the GFC dataset by Hoang and Kanemoto (2021).

Not all instances of tree cover removal constitute deforestation, which is defined by a persistent, long-term change in land use away from natural forest (Curtis et al., 2018). In this study, tree cover loss occurring within mapped mining areas is attributed to mining activities, except where it overlaps with areas classified as plantations. Other proximate drivers of forest clearing, such as logging, wildfire, or agricultural land use, may in some cases precede the establishment or expansion of extraction sites. However, distinguishing the exact sequence and motivation of land use change is generally not possible with globally consistent Earth Observation data. While satellite images can detect when and where tree cover was removed, they do not allow us to determine whether clearing occurred to prepare for mining or independently. Given that economically viable mineral deposits are spatially highly localised and mining projects typically involve long exploration and development phases, land clearing within present-day mining areas is likely related to the preparation or expansion of extraction activities, even if it occurs before production begins. We therefore interpret the observed changes as mining-related tree cover loss, while acknowledging that some uncertainty remains. The analysis captures gross tree cover loss within mining areas and does not account for subsequent vegetation regrowth or site remediation. Tree cover loss is recorded once at the time of detection and is not adjusted for later land cover changes, implying that the results represent cumulative tree cover loss rather than net forest change.

To identify the mined commodities and production associated with tree cover loss, we applied the clustering algorithm introduced by Maus (2026) to link mining area polygons with point-based data from S&P Global Market Intelligence (2024), Jasansky et al. (2023), and the Global Energy Monitor (2023). The method uses hierarchical clustering with optimised distance thresholds to integrate these heterogeneous datasets, thereby connecting spatially explicit mining areas (polygons) with information typically reported as point locations. It was comprehensively validated in Maus (2026), showing robust results against manually assigned materials from Werner et al. (2020). The resulting matches often associate multiple commodities with a single mining area, reflecting the fact that many sites extract several commodities (Nassar et al., 2015). Consequently, tree cover loss may be linked to several commodities.

Geospatial assessment and allocation procedure: We intersected the tree cover loss data at 1-arcsecond resolution with the mining polygons to compute the annual tree cover loss within each mining polygon between 2001 and 2019. The year 2019 was selected as the endpoint, as the earliest mining polygon dataset used in this study (Maus et al., 2022) is derived from cloudless satellite imagery for that year.

Subsequently, we followed the results from the clustering, utilising mine-specific information on commodity types and historical commodity production to identify the specific commodities associated with each mining area. This allowed us to allocate tree cover loss to specific commodities in cases where a single polygon was associated with multiple commodities — a frequent scenario in coupled production, where different metals occur together in the same ore. The clustering procedure also yielded a subset of unassigned polygons. According to Maus (2026), these are primarily associated with quarrying sites identified in the OpenStreetMap database and small-scale artisanal mining activities, and are typically small and spatially isolated. Consequently, approximately 20% of mining-related tree cover loss could not be attributed to the extraction sectors analysed here and was therefore not included in the subsequent trade modelling.

We tested four allocation approaches: equal shares, reported primary commodities, extraction mass, and commodity prices. An overview of the allocation methods is shown in Figure S13. For this study, we employed the price-weighted allocation method, with detailed results presented in Figure S17. However, a comparison of allocation methods indicates that the tree cover loss accounts and related findings are robust regardless of the allocation method chosen (see Figures S14–S16).

It is important to note that our investigation focuses on the immediate, or 'direct', repercussions of tree cover loss, specifically referring to clearance within the confines of mining areas resulting from the establishment or expansion of extraction sites, as well as associated on-site infrastructure and processing facilities. The estimates presented here should therefore be interpreted as a lower-bound estimate of total impacts, as mining activities have been empirically linked to considerable deforestation in the broader vicinity through 'indirect' pathways, such as the development of transportation and energy infrastructure, as well as population pull effects (Sonter et al., 2017; Giljum et al., 2022; Ladewig et al., 2024; Luckeneder et al., 2025).

A further source of potential underestimation relates to the spatial coverage of the mining area dataset. Despite its extensive global scope, some mining activities remain unmapped. As highlighted in recent studies (Tang and Werner, 2023; Maus and Werner, 2024), this particularly concerns small, short-lived, informal, or illegal operations that are difficult to detect in satellite imagery or lack documentation. Consequently, these mining sites are not represented in the dataset. To the extent that such sites contribute to forest clearance, they are not captured in our analysis and therefore lead to an additional underestimation of mining-related tree cover loss.

2.2. Environmentally-extended multi-region input output analysis

The tree cover loss accounts were then integrated in an EE-MRIO framework. EE-MRIO models are widely used to examine environmental pressures along global supply chains, including those related to carbon emissions, raw materials, land use, water resources and biodiversity (Wiedmann and Lenzen, 2018; Wang et al., 2021; Shi and Yin, 2021). Recent advances have also applied EE-MRIO approaches to mining-related pressures: Cabernard and Pfister (2022) link global biodiversity loss to mining-related land use, Wieland et al. (2025) map land footprints and associated pressures in the iron ore and steel sector, and Nakajima et al. (2017) trace land use embodied in nickel consumption.

EE-MRIO models support analyses of environmental pressures and impacts from both production and consumption perspectives. The production perspective attributes impacts to the regions and sectors where they occur, whereas the consumption (or footprint) perspective attributes impacts to the final demand for products and services at the end of global supply chains. Consequently, EE-MRIO models provide a direct link between the pressures and impacts of material extraction around mine sites and the final demand for goods and services occurring elsewhere.

Data: We used Release 059 of the GLORIA global MRIO database (Lenzen et al., 2022), constructed in the Global MRIO Lab (Lenzen et al., 2017). It features 160 countries and 4 rest of the world accounts, each divided into 120 industry sectors to describe the structure of the global economy. We harnessed the availability of 11 primary extraction sectors: bauxite (aluminium ore), copper ores, gold ores, iron ores, lead/zinc/silver ores, nickel ores, other non-ferrous ores, tin ores, uranium ores, hard coal, and lignite and peat.

Model: The EE-MRIO setting, based on a generalised version of the open IO model, leverages the fundamental input–output balance, which states that the total output of an economy is the sum of all intermediate and final consumption (Leontief, 1941; Lenzen, 2001; Schaffartzik et al., 2014). Let $\boldsymbol{Z}$ be an $n \times n$ matrix representing the *intermediate demand* between n industry sectors, and let $\boldsymbol{y}$ be an $n \times 1$ vector of the *final demand* for products (or services) from n sectors. Thus, the total output x_i of a sector i equals the sum of the respective row entries $\sum_{k=1}^{n} \boldsymbol{Z}_{ik}$ plus y_i.

Additionally, let $\boldsymbol{A}$ be the $n \times n$ *direct requirement matrix* (or *technology matrix*), where the element $\boldsymbol{A}_{ij}$ indicates the inputs required from industry i by industry j to produce one unit of total output of sector j. From the relationships:

$$\boldsymbol{x} = \boldsymbol{Z}\boldsymbol{\iota}_n + \boldsymbol{y} \tag{1}$$

where $\boldsymbol{\iota}_n$ is a vector of size n consisting of ones, serving as a summation vector to obtain the row sums of $\boldsymbol{Z}$, and

$$\boldsymbol{A} = \boldsymbol{Z}\hat{\boldsymbol{x}}^{-1} \Rightarrow \boldsymbol{Z}\boldsymbol{\iota}_n = \boldsymbol{A}\boldsymbol{x} \tag{2}$$

where $\hat{\boldsymbol{x}}$ indicates a matrix diagonalising $\boldsymbol{x}$, it follows that:

$$\boldsymbol{x} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{y} \Rightarrow \boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} = \boldsymbol{L}\boldsymbol{y} \tag{3}$$

where $\boldsymbol{L}$ is the *total requirements matrix*, or Leontief inverse, reflecting both direct and indirect intermediate requirements of each sector to produce one unit of final demand for a respective product or service.

Until now, the model and its components are purely described in monetary terms. However, in this study, we employ an environmentally extended version of the MRIO framework (Kitzes, 2013), requiring the addition of information on environmental inputs. Let $e^{\intercal}$ be a $1 \times n$ *direct intensity vector* of environmental inputs (e.g., tons of material, hectares of land, cubic metres of water) associated with one monetary unit of output from each sector. The environmental footprint $\boldsymbol{f}$ associated with the final demand for products and services (consumption perspective) is then defined as:

$$\boldsymbol{f} = \boldsymbol{e}^{\intercal} \boldsymbol{L} \odot \boldsymbol{y} \tag{4}$$

where $\odot$ denotes the element-wise product, and $\boldsymbol{f}_i$ represents all the environmental inputs required by sector i to provide goods and services to final consumers, encompassing both direct inputs and indirect upstream environmental pressures or impacts embodied along the supply chain.

In this study, we investigate tree cover loss associated with the production of metals and coal as our environmental focus. Drawing on the tree cover loss accounts described in the previous section, which we aggregated to the 11 domestic primary extraction sectors considered in the GLORIA database, we constructed a direct intensity vector $\boldsymbol{e}^{\intercal}$, which serves as an environmental extension to our model. This vector denotes the area of tree cover loss per unit of monetary output for each metal and coal extraction sector featured in GLORIA, thereby representing the "tree cover loss intensities" of mining sectors across countries. The environmental extension is measured as tree cover loss area per 1000 USD sectoral output. For example, it reflects the 1208 ha of tree cover loss associated with Australian bauxite mining in 2019, relative to the 1.14 billion USD total output of the Australian bauxite mining industry in that year (with output data taken from national statistics underlying GLORIA), resulting in an intensity of approximately 11 m^2 per 1000 USD of output. Accordingly, the environmental extension identifies the sectors in which tree cover loss occurs at the stage of resource extraction. Expressed relative to monetary output, these sector-specific intensities can be linked to inter-industry transactions in the input–output system, enabling the MRIO framework to trace tree cover loss embodied in supply chains from extraction sectors through intermediate production stages to final demand. The full extension is illustrated in Fig. 2C and Figure S8. Further information on the components used for constructing $\boldsymbol{e}^{\intercal}$ can be found in the Supplementary Information (Figures S5 and S7).

Both the input–output data and the tree cover loss intensities were compiled on an annual basis for the period 2001–2019, and the model described above was applied separately for each year. We also report results aggregated over the full study period, representing the sum of the corresponding annual footprints.

Limitations All models, including the EE-MRIO model applied in this study, are simplifications of the complex realities they aim to represent. These simplifications, while necessary for managing the complexity of global economic structures, inherently introduce certain limitations that must be acknowledged.

Primary limitations stem from the general assumptions of the MRIO framework (Kitzes, 2013), including the treatment of economic sectors as homogeneous entities with standardised products, maintaining constant input–output structures, and simplifying environmental pressures. We are aware that such assumptions do not fully capture the heterogeneity and non-linear dynamics present in real-world economic and environmental interactions. Nonetheless, these model types have proven valuable for capturing global trends and trade relationships.

Regarding the spatial resolution of tree cover loss accounts in relation to national data in GLORIA, aggregating high-resolution tree cover loss data unavoidably sacrifices spatial detail, which may impact result accuracy. The model operates under the assumption that subnational tree cover loss patterns and trade flows align with national averages. Thereby, the model is unable to consider subnational regions' trade flows with other global regions, but integrates them into national trade (Wiedmann and Lenzen, 2018). This approach can obscure important details, such as when resources from one region in country A are predominantly consumed in country B, while the same resources from another region in country A – potentially with different environmental impacts – are predominantly consumed in country C.

Like most MRIO databases, GLORIA is expressed in monetary units, with inter-industry flows, international trade and final demand reported in current USD. Commodity price changes thus have effects on the footprint calculations, for example through altering environmental intensities as well as values for intermediate inputs and final demand of sectors affected by price fluctuations (Jakobs et al., 2021). Results may also be influenced by price differences across countries, sectors, and time. In particular, commodities may be supplied to domestic and export markets at different prices, while input–output tables assume uniform sectoral prices within each country. Such price-related effects are a known limitation of monetary MRIO models and have motivated the development of hybrid (Steubing et al., 2022) or entirely physical (Bruckner et al., 2019) input–output approaches. However, globally consistent physical input–output databases for metals and mining are still at an early stage of development (Wieland et al., 2021) currently lacking the raw material coverage required for this analysis. The use of a monetary MRIO framework therefore remains the most suitable option for tracing global supply chain linkages in the present study.

These limitations need to be considered when interpreting the results of this study. They highlight the necessity for further research to refine EE-MRIO models, particularly by integrating high-resolution spatial data with subnational and international trade flows, and accounting for regional and temporal variability in environmental impacts.

3. Results

Accumulated global tree cover loss within mining areas totalled 1.482 million ha between 2001 and 2019, as depicted in Fig. 1 at 2 degrees resolution (approximately 220 km at the equator). The results reveal that mining-related tree cover loss is a geographically widespread phenomenon, occurring across nearly all world regions. While 91% of the mapped tiles show tree cover loss of less than 1000 ha, hotspots with values of up to 75,851 ha were identified in South America (e.g., Fig. 1A), Ghana (Fig. 1B), Russia, Myanmar, and Indonesia (Fig. 1C), as well as in Canada, the United States, and Australia (see Figure S2 in the Supplementary Information). Although modest when compared with the 6.4–8.8 million ha of forest loss driven annually by agricultural and forestry expansion in tropical regions (Pendrill et al., 2022), these findings suggest that mining constitutes a geographically widespread source of forest disturbance with locally significant ecological consequences.

3.1. Tree cover loss intensities vary across countries and materials

Global mining-related tree cover loss, as illustrated in Fig. 2B, mirrors the notable upsurge in metals and coal extraction depicted in Fig. 2A. Between 2001 and 2012, material extraction of the 11 analysed commodity groups substantially accelerated, from 9.8 bn tonnes to 16.2 bn tonnes. Correspondingly, mining-related tree cover loss exhibited a marked increase from 30,500 ha in 2001 to 132,700 ha in 2012. Post-2012, tree cover loss rates stabilised, maintaining a yearly average of approximately 92,700 ha, while extraction of the selected commodities experienced only marginal growth. Nonetheless, it is important to note that dynamics across commodities (Figure S3) and countries varied significantly, with notable outliers at the upper end (Figures S5 and S6).

The largest shares of accumulated tree cover loss associated with mining during the period from 2001 to 2019 can be attributed to the extraction of gold ores (40%) and various forms of coal (hard coal, lignite and peat; 24%), followed by bauxite (4%), the aggregated group of "other non-ferrous ores" (4%) and iron ore (3%) (Figure S4). This tree cover loss occurred predominantly in Indonesia, Brazil and other South American countries, Russia, the United States, Canada, Ghana and Australia. Approximately 20% of the observed tree cover loss could not be conclusively linked to any of the key commodities.

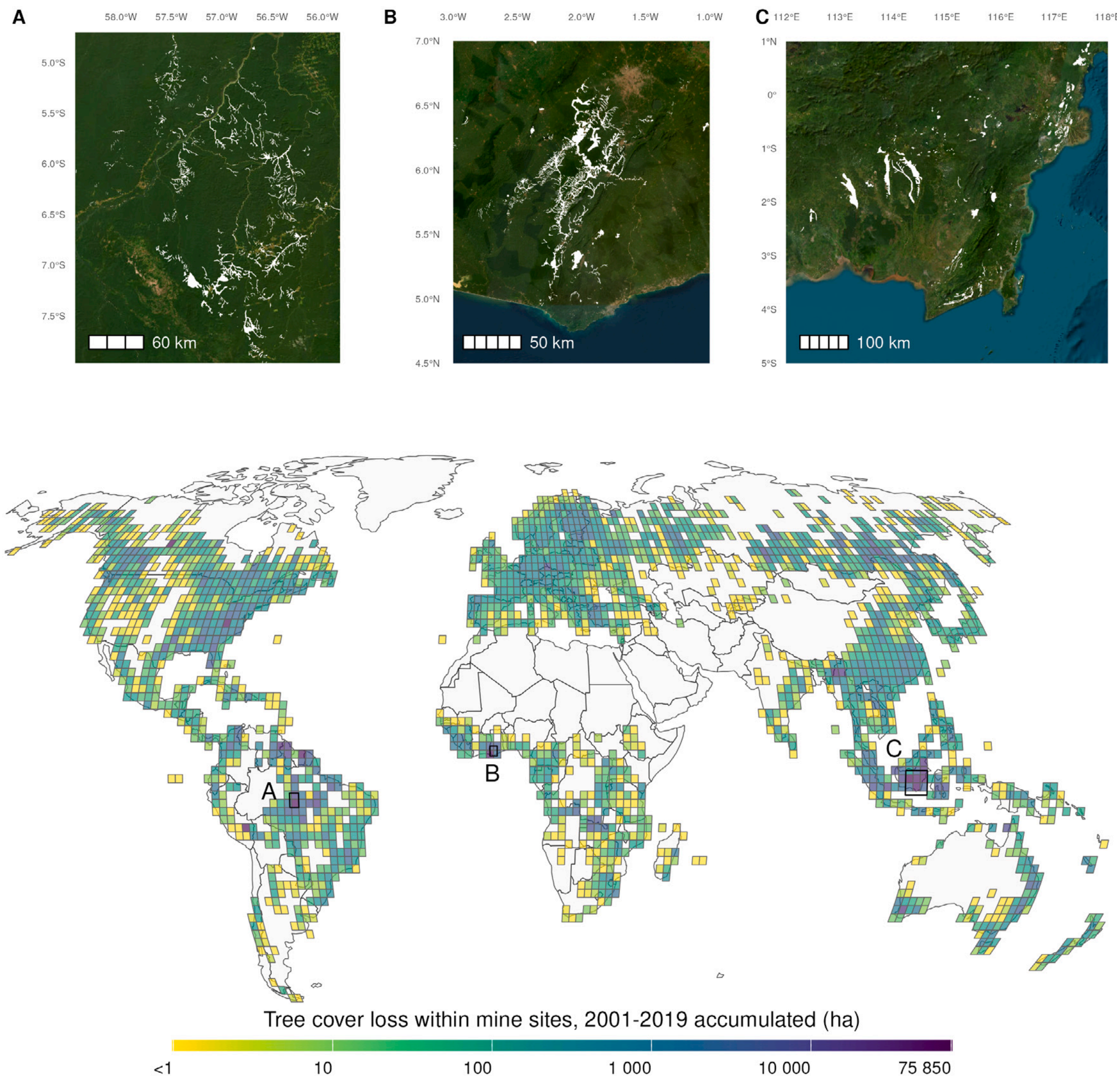

Fig. 1. Accumulated 2001–2019 tree cover loss within mining areas at 2 degrees resolution using a Robinson map projection. Areas were obtained by intersecting mining area polygons (Maus et al., 2022; Tang and Werner, 2023; OpenStreetMap contributors, 2021; Dethier et al., 2023) and forest cover maps from the Global Forest Change (GFC) dataset (Hansen et al., 2013). Tree plantations were excluded using the plantation mask developed by Hoang and Kanemoto (2021). Zoom-in maps highlight mining areas (white) in the Brazilian Amazon (A, 75,300 ha tree cover loss within shown mining areas, mostly artisanal gold mining), Southern Ghana (B, 53,400 ha, mostly gold mining), and Indonesian Borneo (C, 234,600 ha, mostly coal mining).

It is important to understand the magnitude of tree cover loss impacts relative to the scale of each country's respective extraction sectors. Direct tree cover loss intensities, denoting the spatial extent of tree cover loss in relation to gross production of specific primary extraction sectors, exhibit significant variation across commodities and global regions. The boxplots depicted in Fig. 2C illustrate that country-specific coefficients span a broad spectrum for all commodities. The highest median intensities were observed for gold ores (median = 7.4 m^2 per 1000 USD, mean = 1357, sd = 8359), followed by tin ores (2.5, 10.1, 18.5), nickel ores (1.7, 41.2, 134) and bauxite (1, 6.6, 10.5), while the smallest median intensities were associated with copper ores (0.02, 1.9, 13.4). While 90% of intensities fell below 39 m^2 per 1000 USD output within the respective sector, outliers were notable (see Figures S5–S8 in the Supplementary Information for more detailed depiction of yearly tree cover loss and gross production). In Venezuela, gold ores were, for instance, associated with 20 ha tree cover loss per 1000 USD in 2004.

Although some of these average intensities at the country level involve countries with small production volumes, Fig. 2C also reveals that major producing countries (represented by red dots, constituting 80% of global production per commodity) span various intensity levels. For instance, among the top three bauxite producers – Australia, China, and Guinea (USGS, 2024) – median direct tree cover loss intensities were 13.0, 0.04, and 0.6 m^2 per 1000 USD, respectively.

3.2. The EU's final demand induced 12% of global tree cover loss within mine sites

Raw materials, especially metallic minerals, integrate into international trade networks and global supply chains. By linking the data on mining-related tree cover loss outlined above to the GLORIA model, we obtained footprint-type indicators to portray local environmental impacts at extraction sites that are embodied in the final demand (mainly private and government consumption, and capital formation) of products and services elsewhere. In total, 148,200 ha of tree cover loss within mining areas between 2001 and 2019 were attributable to the final demand in the EU. While this footprint is small relative to the approximately 190,500 ha of deforestation linked each year to the EU's direct imports of agricultural commodities (Titley, 2024), it nonetheless highlights that mining-related pressures are widely dispersed and structurally embedded in European supply chains. As shown in Fig.

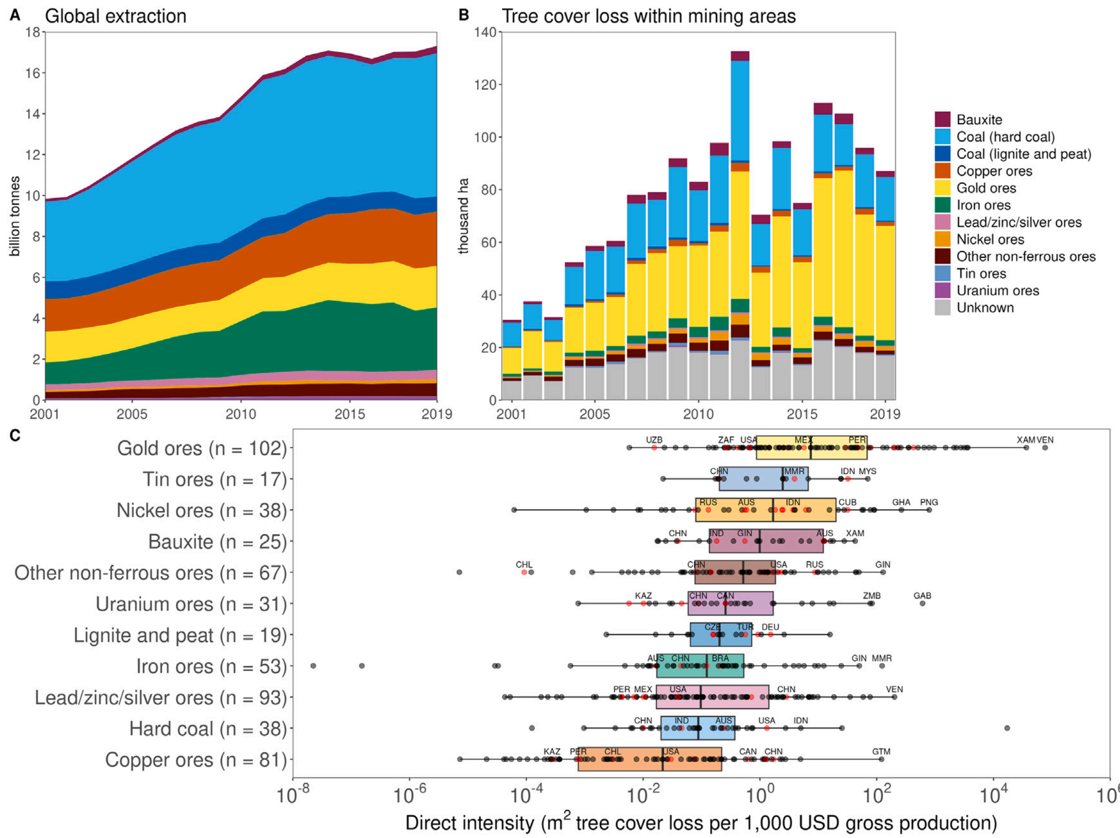

Fig. 2. Global 2001–2019 extraction of selected metals and coal in billion tonnes (Lenzen et al., 2022, 2017) (A). Yearly tree cover loss (in thousand ha) within mining polygons by commodity (B). Direct intensities in m^2 of tree cover loss per 1000 USD output by primary extraction sector (C; Points denote 2001–2019 country average, red points indicate major producers together responsible for more than 80% of global production per commodity, *n* is the number of countries observed where respective mining activities were recorded.).

3A and B, 85% of this pressure occurred outside the EU, primarily associated with material flows originating from the Americas (66,813 ha), Indonesia (22,585 ha), Russia (21,322 ha), Ghana (4564 ha), and Australia (3794 ha).

The EU ranked second in terms of consumption-driven tree cover loss, following the United States (194,702 ha) and ahead of China (134,553 ha). When accounting for the United Kingdom (30,320 ha), which was a member state during the study period, the combined total would nearly reach the United States' footprint. Based on the EU-27, EU demand accounted for 12% of global mining-related tree cover loss between 2001 and 2019. Table S1 in the Supplementary Information shows a full list of countries and per capita values.

Mining-related tree cover loss embodied in EU consumption stemmed from different materials across producing regions. As illustrated in Fig. 3B, the EU's footprint in Indonesia was predominantly linked to gold ores (11,714 ha) and coal (8259 ha), while Brazilian tree cover loss was mostly due to gold ores (15,903 ha) and smaller yet considerable portions of bauxite (3755 ha) and iron ores (1053 ha). Besides gold (10,039 ha) and coal (6172 ha), Russia shows a substantial amount of tree cover loss related to other non-ferrous ores (3243 ha). Gold extraction also dominated tree cover loss dynamics in Peru (4950 ha), Ghana (4950 ha), Ecuador (674 ha) and Venezuela (330 ha). Bauxite and coal emerged as significant factors in Australia (1675 ha and 1654 ha, respectively). Copper-related tree cover loss occurred primarily in the Democratic Republic of the Congo and Zambia (586 ha and 436 ha, respectively). Apart from Indonesia and Russia, coal embodied in EU consumption (mostly as a source of energy and as an ingredient in steel production) was a prominent factor of tree cover loss at extraction sites in the United States (7340 ha), but mostly within the EU itself. Half of the 22,585 ha tree cover loss related to extraction and consumption inside the EU was associated with the extraction of coal, particularly in Germany (7135 ha), Poland (1619 ha) and Romania (1138 ha). EU demand for nickel – essential for enhancing battery performance, longevity and energy density (IEA, 2021) – notably contributed to tree cover loss in the EU (647 ha) and Indonesia (618 ha), followed by Canada (225 ha), Cuba (140 ha), and Madagascar (125 ha).

One quarter of the EU's tree cover loss footprint was attributed to just three industrial sectors: civil engineering construction, i.e. a subset of the construction industry focused on large-scale infrastructure projects such as the construction of roads, dams and railways, automotive manufacturing, and machinery and equipment production. The GLORIA dataset provides a detailed sectoral breakdown encompassing 120 distinct industry sectors, facilitating a thorough analysis of impacts within national economies. Fig. 3C illustrates tree cover loss embodied in the EU's final demand, categorised by industry sector. Among these sectors, the EU's civil engineering construction and automotive industries showed the most significant footprints, accounting for 14,310 ha and 12,902 ha, respectively. Notably, only 7.5% and 6.9% of the mining-related tree cover loss linked to the two industry sectors occurred within the EU itself.

The locations of tree cover loss associated with the final demand across the EU's industrial sectors generally showed a proportional relationship to overall mining-related tree cover loss levels (see Figure S4), with some notable exceptions. For example, the electric power generation sector had a larger tree cover loss footprint within the EU and in the USA, likely due to the use of coal for energy production, and refined petroleum products left a substantial footprint in Russia.

Comparing the sectoral distribution of the EU's footprint with other major material-consuming economies reveals considerable regional

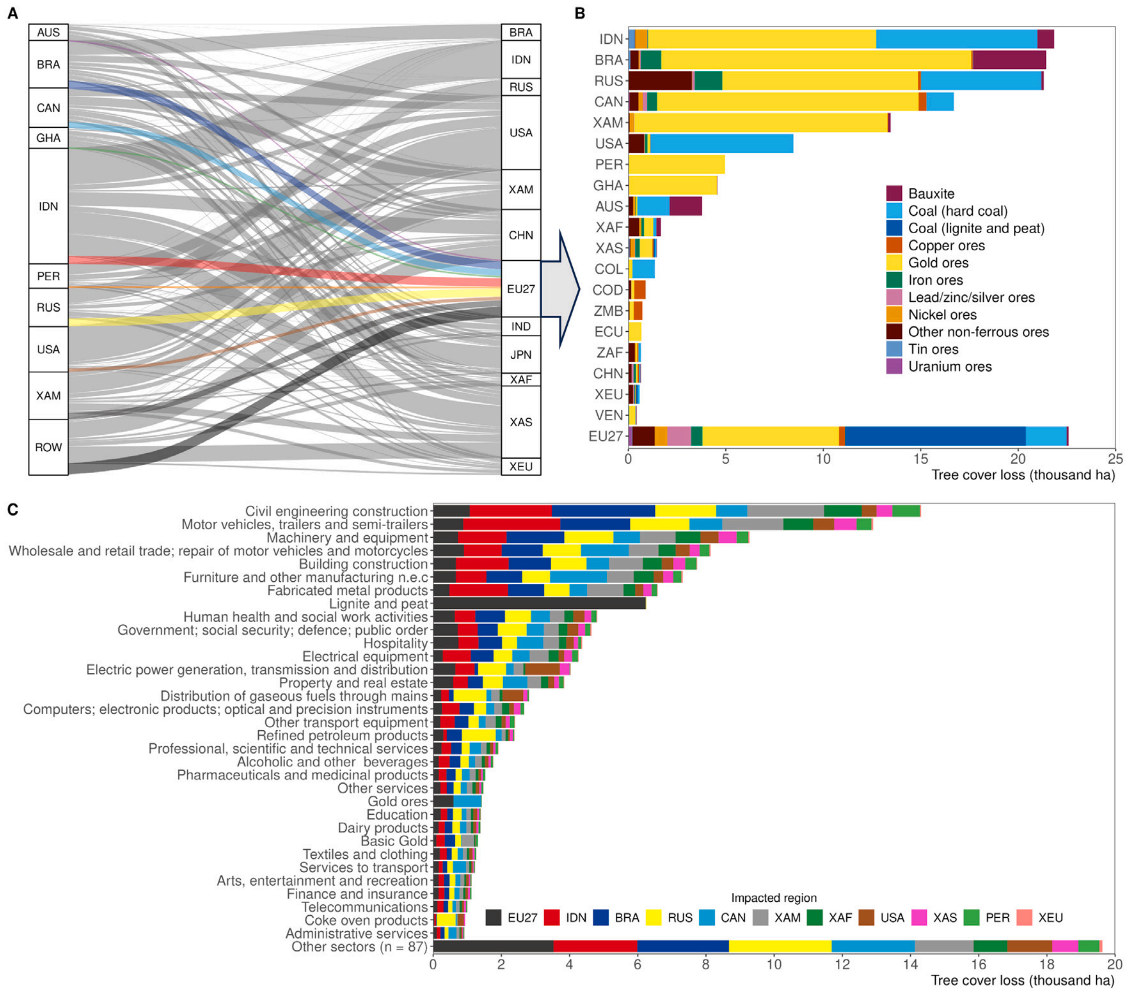

Fig. 3. Global flows from local occurrence of mining-related tree cover loss (production perspective) to where products and services associated with this tree cover loss are consumed (consumption/footprint perspective). Colours highlight EU-27 consumption (A). Mining-related tree cover loss associated with EU-27 consumption by impact region and mined commodity (B). Mining-related tree cover loss associated with EU-27 consumption by EU-27 industry sector and impacted region (C).

disparities. For instance, Chinese consumption predominates the tree cover loss footprint in the construction, machinery, and electrical equipment sectors (Figure S10) and the United States exhibits the largest footprint in electric power generation, notably fuelled by domestically mined coal, as well as in government, security, and defense sectors (Figure S11). Japan's footprint is disproportionately large in the professional, scientific, and technical services sector. Conversely, the EU's footprint is relatively modest in the construction sectors, electric power generation, and electrical equipment (Figure S12).

4. Discussion

This study advances emerging efforts to trace environmental pressures from resource extraction to final demand by linking satellite-based observations of mining-related tree cover loss as a representative case with global MRIO modelling of EU consumption. The following discussion situates the findings within broader debates on regional and commodity-specific dynamics, the effectiveness of current EU policies, and the prospects for integrating mining into binding supply chain regulations.

4.1. Drivers of regional and commodity-specific variation in mining-related tree cover loss

While mining is inherently land-intensive, the extent of forest disturbance depends on the type of resource extracted, the technologies applied as well as on the ecological and governance context, which explains the large variation in mining-related tree cover loss across regions and commodities.

Compared with approaches using static land use intensity coefficients (Nakajima et al., 2017), our analysis allows for a more nuanced representation of heterogeneity across countries and commodities. Strip mining of near-surface deposits, such as bauxite and coal, typically requires the removal of large surface areas, whereas metals extracted from deeper or more localised deposits, including iron and copper, lead to more spatially concentrated disturbances. These structural differences in mining practices partly explain variation in tree cover loss intensities between commodities and, consequently, between producing countries depending on their resource endowments.

In addition, the ecological context of extraction sites strongly influences regional outcomes. Mining in tropical forest regions tends to result in disproportionately high tree cover losses due to the coincidence with dense vegetation and high biodiversity. Our results are consistent with previous research showing that European consumption contributes significantly to mining pressures in tropical areas, particularly in Brazil (Wieland et al., 2025). Similar hotspots emerge in Peru, Ghana, and Indonesia, where mining-related tree cover loss overlaps with ecologically vulnerable landscapes. Beyond the tropics, significant tree cover losses – predominantly associated with gold mining – also occur in boreal regions, notably in Canada and Russia, demonstrating that high intensities arise wherever mining coincides with forest ecosystems.

Finally, institutional and governance conditions can influence the extent to which these biophysical factors translate into actual forest disturbance. Where environmental regulation and enforcement are weak, mining is more likely to expand into sensitive areas, whereas stronger governance frameworks can reduce impacts by restricting extraction or requiring less damaging practices. Gold extraction often occurs in artisanal or small-scale operations, which are frequently informal or illegal and typically lack effective environmental safeguards (Barenblitt et al., 2021). Similarly, recent nickel mining expansion in Indonesia illustrates how rapid development under poor governance conditions can lead to substantial landscape transformation (Hyldmo et al., 2025).

These heterogeneous patterns highlight the importance of accounting for spatial and commodity-specific differences when developing strategies for responsible sourcing. Within ongoing European supply chain initiatives, identifying countries that combine high production capacities with comparatively low environmental risk – and those where the opposite applies – can inform raw material sourcing strategies and investment decisions. To support such differentiation, Fig. 4 provides a complementary lens on the results. It positions producer countries according to their extraction volumes, tree cover loss intensities, and the share of this loss embodied in EU consumption. Countries located closer to the upper-left quadrant of each panel tend to pair higher production volumes with lower forest-degradation risk, whereas those further away indicate a combination of lower production or higher associated risk. Downstream companies in manufacturing sectors can benefit from these insights to reduce possible trade-offs between securing material supply and reducing forest loss risks through adapting their material sourcing procedures. However, it is clear that not all mining-related impacts can be avoided, underscoring the need for prioritisation. This includes, for example, the identification and protection of high-priority conservation areas – potentially overlapping with forest loss hotspots – as well as measures to reduce demand for high-impact materials (Sonter et al., 2023).

4.2. Limits of current EU supply chain policies in achieving effective forest protection

In 2008, the European Commission articulated an ambitious vision to halt global forest cover loss by 2030 and to reduce gross tropical deforestation by half by 2020 (European Commission, 2008). These objectives remain far from being achieved. Despite numerous public and private zero-deforestation commitments, global deforestation rates remain persistently high, and current supply chain initiatives have only marginally reduced forest losses (Lambin and Furumo, 2023). While most analyses focus on agriculture and forestry, our results highlight a similar need for more comprehensive governance in the mining sector. Achieving meaningful progress towards zero deforestation also requires policies that enhance the accountability of European companies for the environmental pressures associated with mining activities embedded in their global supply chains.

Existing EU frameworks provide only partial coverage of these issues. The EU Biodiversity Strategy (European Commission, 2020) and the EU Forest Strategy (European Commission, 2021) primarily address intra-European environmental objectives, while the Regulation on Deforestation-free Products (European Parliament, 2023a) is the only policy adopting a comprehensive supply chain perspective. Yet, all three target biotic commodities and omit tree cover loss from metal and mineral extraction. New legal instruments, such as the CSDDD, therefore represent a crucial opportunity to fill this policy gap by explicitly integrating mining-related environmental pressures.

However, the adoption of such policies does not automatically translate into effective forest protection. Their success depends on the availability of reliable data and robust traceability systems. Integrating spatially explicit environmental data with MRIO models, as demonstrated here, enhances transparency by pinpointing where tree cover loss occurs at the extraction stage of global supply chains. Deforestation footprint analyses can further support land use governance by identifying commodity-specific hotspots, clarifying the actors and supply chains involved, and informing the design of environmental policies (West et al., 2025). They can also foster dialogue among producers, financial institutions, consumers, and civil society organisations that are often geographically distant from affected regions. Continued methodological refinement – particularly through the incorporation of company-level data – would strengthen the capacity of such approaches to guide policy and corporate due diligence.

At the same time, the scope of our analysis points to inherent challenges. Focusing solely on tree cover loss captures only one dimension of mining-related pressures. Strategies to minimise forest loss may entail trade-offs with other environmental or social objectives. For instance, relocating bauxite sourcing from Australia to China might reduce forest impacts (Fig. 4A) but could increase pollution or health risks (Li et al., 2014). Similarly, copper mining in Chile and Peru entails low tree cover loss but high water and energy demands (Peña and Huijbregts, 2014).

Finally, even the most comprehensive national supply chain policies are limited in scope, highlighting the need for integrated policy mixes and global cooperation (Lambin and Furumo, 2023). Even with optimal implementation of binding supply chain due diligence instruments, European measures could mitigate only a limited share of global mining-related tree cover loss — approximately 12%. Addressing the wider challenge of deforestation therefore demands coordinated international action and a mix of complementary policy instruments, including market-based measures and diplomatic engagement (Vasconcelos et al., 2024).

4.3. Integrating mining into binding supply chain regulations: potential and challenges

International standards for responsible mining and transparent reporting are increasingly recognised as essential (Sonter et al., 2023; Parkhurst et al., 2025). Yet progress also requires demand-side engagement, where binding due diligence frameworks such as the CSDDD offer an opportunity to align economic activities with environmental and social responsibility across borders. This study adds empirical specificity to ongoing policy debates by quantifying how mining-related tree cover loss is embodied in the supply chains of individual EU industry sectors, thereby identifying concrete leverage points for intervention. The automotive sector emerges as one particularly prominent example due to its large and geographically dispersed footprint. The sector is expected to undergo substantial transformation in the coming years: While the transition towards electric mobility may reduce coal-related pressures, it is likely to intensify demand for metals such as nickel, lithium, and copper (Xu et al., 2020; IEA, 2021). Our results indicate that, without targeted safeguards, this shift risks relocating rather than reducing environmental pressures along supply chains.

Addressing these dynamics requires policy approaches that go beyond aggregate targets and instead account for sector-specific and geographically differentiated risks. This includes comprehensive due diligence, transparent monitoring across all stages of supply chains, credible recycling strategies, and demand-side measures such as, in the automotive case, rethinking transport and logistics systems towards public and shared mobility. By linking environmental pressures to specific sectors and sourcing regions, the analysis provides a basis for prioritising such interventions and for aligning supply chain governance with environmental objectives. Consistent and ambitious implementation could strengthen the EU's position as a frontrunner, encouraging other consumer regions to follow suit and contributing to a gradual transformation of global production networks.

However, translating such insights into effective supply chain policy remains challenging, and the transformative potential of instruments like the CSDDD is contested. Critics argue that – while arguably creating significant bureaucratic burden for companies – its current

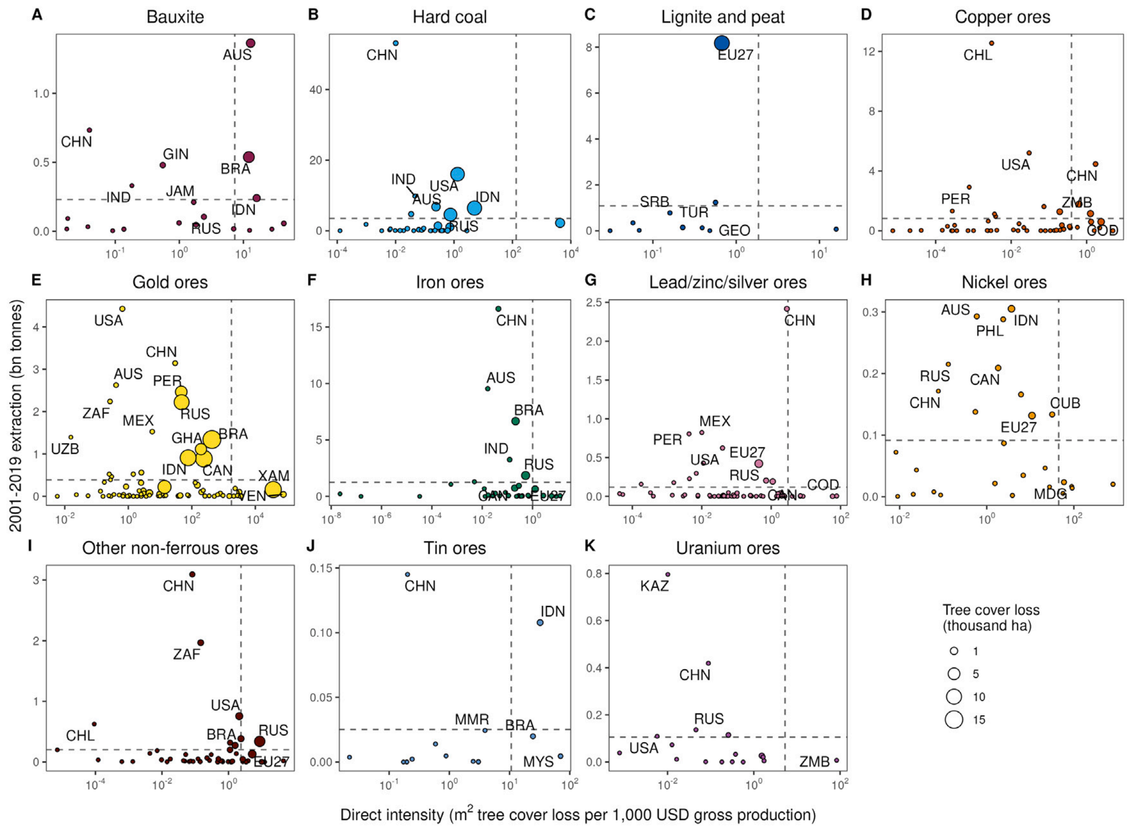

Fig. 4. Mining-related tree cover loss embodied in EU-27 consumption by commodity and impact region. Dot sizes illustrate the scale of tree cover loss, x-axis indicates 2001–2019 country average direct intensity (m^2 per 1000 USD) and y-axis indicates 2001–2019 accumulated extraction (bn tonnes) in each country. Dashed lines indicate means.

formulation offers limited coverage, weak environmental provisions, and significant loopholes, including the exclusion of the financial sector. Whether such frameworks will reinforce existing inequalities or contribute to their reduction likely depends on how effectively they empower local actors in producing regions – including workers, communities, and civil society – and whether they can withstand resistance from corporate interests in highly competitive markets (Durán et al., 2024).

The EU's regulatory influence can nonetheless extend beyond its borders through market mechanisms. By linking access to its large consumer market with compliance to social and environmental standards, the EU can incentivise producer countries to strengthen domestic governance; a dynamic known as the Brussels Effect (Bradford, 2015). For example, maintaining competitiveness under stricter sourcing standards may require Indonesia's nickel industry to lower its tree cover loss intensity, which this study identifies as high. Yet such shifts are not without complications. Trade restrictions may trigger substitution and leakage effects, as exports are redirected to markets with weaker environmental or social standards. Mitigating these systemic risks calls for internationally coordinated governance rather than fragmented regulatory efforts (Vasconcelos et al., 2024). Ultimately, the effectiveness of supply chain regulations will hinge on balancing economic competitiveness with international cooperation. Sustainable outcomes require supply chains that are transparent, traceable, and socially and environmentally equitable — a goal that remains conceptually clear but institutionally and practically difficult to achieve.

5. Conclusion

Between 2001 and 2019, close to 150 thousand hectares of global tree cover loss within mining areas were associated with EU consumption, with the majority of pressures occurring outside European borders. The results of this study reveal pronounced spatial and commodity-specific differences, underscoring the need to adapt governance responses to distinct resource and regional contexts. Moreover, they underscore the importance of supply chain due diligence, as significant environmental pressures remain embedded in global supply chains despite existing governance efforts. At the same time, the study captures only one dimension of the environmental pressures associated with material extraction. As global material demand continues to rise, future research and policy must move beyond single-issue assessments to address the interlinked environmental, social, and economic dimensions of extraction and trade. For environmental and social impact assessments, this will require integration of satellite data as used in this study with data from other domains, such as company data, regional statistics and local field-based evidence. Forward-looking, scenario-based analyses will be crucial to anticipate emerging risks and guide transitions towards just and sustainable global supply chains. The findings also place particular responsibility on the EU to advance these transitions through consistent policy action and international cooperation, fostering more sustainable supply chains and a more responsible use of the planet's resources.

CRediT authorship contribution statement

Sebastian Luckeneder: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Stefan Giljum:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Victor Maus:** Writing – review & editing, Supervision, Resources, Methodology, Data curation. **Laura J. Sonter:** Writing – review & editing, Supervision. **Manfred Lenzen:** Writing – review & editing, Validation, Supervision.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Laura J. Sonter provides consultancy services on deforestation embodied in traded goods. All other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resconrec.2026.109064.

Data availability

All codes and data used in the analysis are available at https://doi.org/10.5281/zenodo.17964742.

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Further reading

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