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The Many Pathways of Mining Impacts on Biodiversity

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ABSTRACT

Mining is a significant driver of biodiversity loss, with impacts expected to escalate due to rising metal demand for the energy transition. However, global assessments of mining impacts are still in their infancy, as global biodiversity models overlook many relevant impact pathways. Here, we present a comprehensive synthesis of the biodiversity impact pathways of mining to inform the conservation and modeling community, as well as the policies and corporate actions to address these impacts. Our review highlights pollution, primarily driven by the disposal of reactive waste materials, as the most diverse pathway, especially in freshwater ecosystems, where acid mine drainage, heavy metal contamination, and sedimentation result in significant ecological impairment. Mining-induced habitat loss, habitat fragmentation, and hydrological disruptions further exacerbate biodiversity loss. To improve the representation of mining impacts in biodiversity models, we recommend incorporating pollution effects and refining the representation of physical habitat change effects. Future modeling efforts should also consider cumulative and interactive effects to ensure comprehensive impact estimation. Our findings provide a roadmap for more accurate global biodiversity models, aiding informed conservation and policy initiatives in light of assessing the cumulative impacts of increasing mineral demand for the energy transition.

1 | Introduction

While mining sites account for less than 1% of the Earth's land surface (Maus et al. 2022), mining activities pose disproportionate threats to biodiversity (Sonter et al. 2020). Many mining sites are located in biodiversity-rich areas, exposing wildlife to habitat loss and degradation while threatening vulnerable ecosystems (Durán et al. 2013; Luckeneder et al. 2021). These threats can extend far beyond mining sites (Sonter et al. 2018; Junker et al. 2024) and are likely to expand in the future (Giljum et al. 2025). For instance, toxic compounds from mine tailings transported downstream impact an estimated 479,200 km of river reach and 164,000 km^2 of floodplain ecosystems worldwide (Macklin et al. 2023). Mining-induced threats to biodiversity are expected to be exacerbated by the growing demand for mineral resources, including those needed to fuel the energy transition (Sovacool et al. 2020; Hund et al. 2023; Sonter et al. 2023). If current rates of mine closure and restoration persist, biodiversity hotspots will face increasing threats from the exploration and opening of new mines, particularly as extraction targets lower-grade ores, resulting in more mine waste (Murguía et al. 2016; Sonter et al. 2020).

Balancing the benefits of mining with its negative effects on biodiversity requires understanding the location, extent, magnitude, and duration of mining impacts. Global models are essential due to the large number of mining sites worldwide (Maus et al. 2022; Tang and Werner 2023) and for assessing prospective mine impacts (Northey et al. 2023). However, existing models assessing global mining impacts on biodiversity tend to be overly simplistic. Typically, potential impacts are evaluated by overlaying a global map of mining sites with spatial data on biodiversity features, such as biodiversity hotspots, protected areas, or species distributions (Durán et al. 2013; Harfoot et al. 2018; Sonter et al. 2020). Recent studies have advanced this type of assessment using IUCN Red List data to map hotspots of vertebrates threatened by mining or to model the probability of threat from mining to freshwater biodiversity (Lamb et al. 2024; Brabant et al. 2025). While instrumental in raising awareness (Torres et al. 2024), these efforts do not provide information on, nor model, the distinct causal pathways through which mining impacts biodiversity, and they also often rely on data that does not fully capture the pressures of mining (Sonter et al. 2025).

Beyond visible habitat loss and fragmentation at mine sites, mining presents additional threats across the broader landscape (Sonter et al. 2018). Including cumulative effects of these multiple impact pathways in global models is crucial for understanding mining trade-offs. This, in turn, requires a comprehensive overview of mining's impact pathways on biodiversity. Although many reviews address the environmental impacts of mining, they typically adopt a relatively narrow focus on a specific environmental realm, specific pressures, or specific regions (e.g., Wiener and Suchanek 2008; Simate and Ndlovu 2014). To our knowledge, no existing review offers a comprehensive synthesis of the causal mechanisms through which mining affects biodiversity within a structured framework, which is crucial for developing multi-pressure global biodiversity models needed to evaluate the cumulative effects of the energy transition.

To address this gap, we synthesize the diversity of pathways through which mining impacts biodiversity using a common conceptual causal framework. This synthesis clarifies the links from mining activities to biodiversity outcomes, thereby providing a roadmap for modelers, impact assessment practitioners, and policymakers to develop more comprehensive impact assessments and biodiversity-inclusive policies for the energy transition. We screened 620 review articles and extracted information from 34 reviews that examine the effects of metal, coal and aggregates mining on biodiversity across terrestrial, freshwater, and marine realms, either qualitatively or quantitatively. We focus on metal, coal and aggregates mining due to their energy transition connection. Metals and aggregates provide needed materials, while coal remains a crucial energy source worldwide (IEA 2023; Jasansky et al. 2023). We excluded oil and gas due to differing extraction method (Nijnens et al. 2023). We also omitted studies focused only on mine rehabilitation, offsetting, and potential (rather than actual) impacts. We identified impact pathways by searching for descriptions of the mechanisms by which mining activities impact biodiversity (see Supporting Information for further details). We organize our review into two main identified pressure categories: pollution (Section 3) and physical habitat change (Section 4), followed by a brief overview of pathways associated with climate change, overexploitation, and invasive species (Section 5). Lastly, we provide a roadmap for the biodiversity modeling community to integrate mining impacts into biodiversity assessment models (Section 6). The information presented in this review is essential for informing future model development, impact assessment methods, and ultimately guiding policies on corporate responsibility for sustainability issues, toward biodiversity-inclusive corporate and governmental strategies for transitioning to a carbon-neutral society.

2 | Overview of the Impact Pathways

From 34 reviews, we synthesized mining impact pathways by activity, pressure, state, impact mechanism, and biodiversity variable (Figure 1). Activities are mining operations (extraction, processing, transport) creating environmental pressure. We excluded exploration as impacts are rarely reported and likely similar to extraction/transportation. Refining refers to on-site refining only, while concentrates are often refined elsewhere (National Minerals Information Center 2024). Pressure is the direct stress on the environment caused by a mining activity, leading to changes in the state of the environment. Next, we report the impact mechanism as the causal link that triggers effects of changes in state on biodiversity. Lastly, we identify the various organizational levels at which biodiversity is impacted, from individuals to ecosystems, as indicated by the review studies.

We find that pollution pathways are the most diverse, with waste storage, acid mine drainage, wastewater discharge, emissions to the air from fumes and dust, and noise generation constituting the primary pressures. These result in changes to the chemistry of water, soil, and air. This impacts various levels of biodiversity via the toxicity and radioactivity of the released compounds, acidification of water and soils, as well as salinization, eutrophication, turbidity, and hypoxia in aquatic environments. Overall, we observe more pollution impact pathways in aquatic environments, particularly freshwater, than in terrestrial environments (Figure 1; Section 3). We also identify pathways related to physical habitat changes. These occur through land transformation and occupation, including changes in topography due to excavation, deforestation, and the development of roads, railways, pipelines, and dams, along with water abstraction that affects (sub-)surface freshwater habitats. These pressures result in habitat loss and fragmentation, as well as alterations in key hydrologic conditions for biodiversity (Figure 1; Section 4).

3 | Pollution

3.1 | Heavy Metals and Metalloids

Metal and coal mining operations are significant sources of heavy metal and metalloid pollution in the environment (Figure 2; Dudka and Adriano 1997; Byrne et al. 2012; Ferreira et al. 2016; Affandi and Ishak 2019; Frelich 2019). The main hazardous metals and metalloid pollutants from mining include antimony, arsenic, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, molybdenum, nickel, silver, tin, and zinc (Dudka and Adriano 1997; Hogsden and Harding 2012; Ordóñez et al. 2013). The release of heavy metals from mining primarily occurs through ore extraction, ore processing, and waste disposal. The mining of metal ores entails removing the top layer of rocks (i.e., the overburden) to access the ore, as well as crushing and disposing of waste rocks, which for some commodities exposes

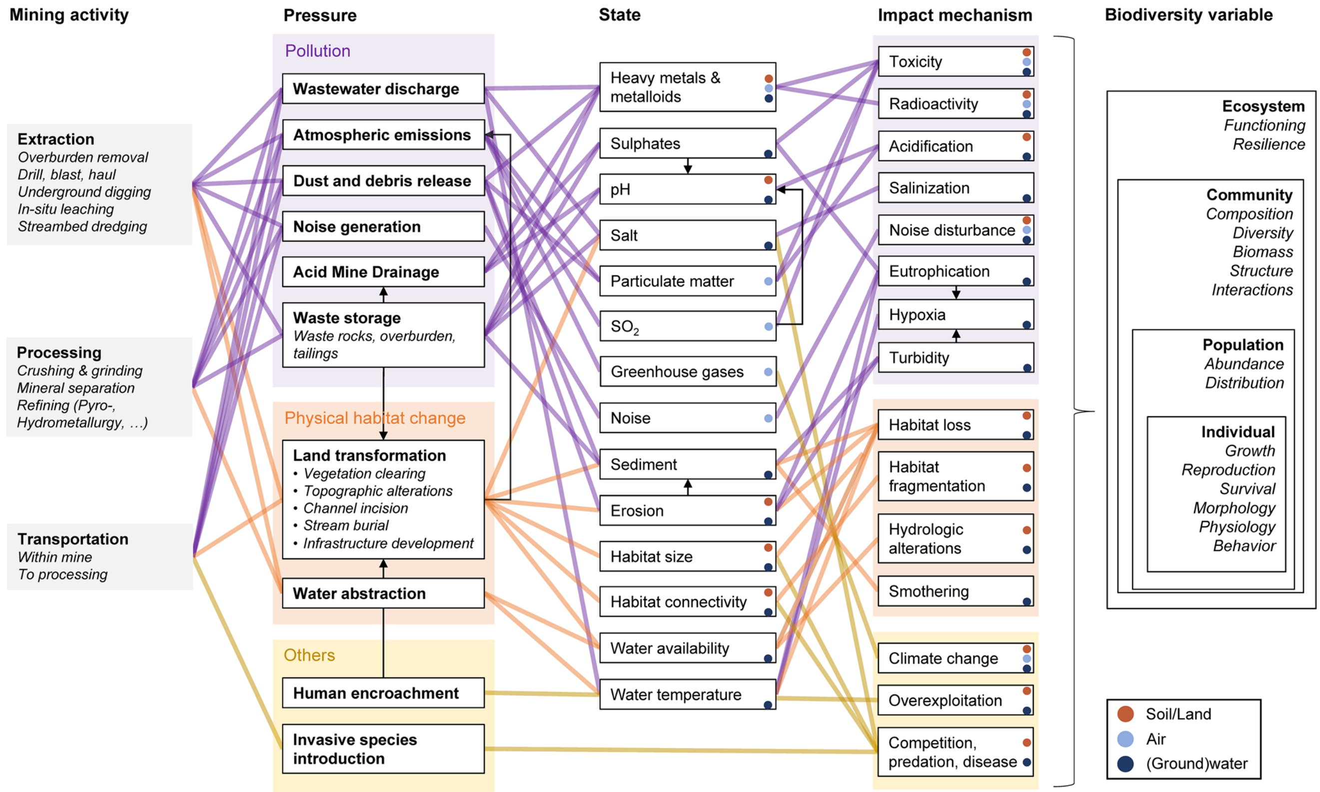

FIGURE 1 | Schematic representation of the main impact pathways of mining on biodiversity, as drawn from the 34 review articles. Mining activities (left) exert specific environmental pressures that alter the state of the environment. State variables have then impacts on biodiversity indicators at various levels of aggregation through various impact mechanisms. For visual clarity, the arrows from the impact mechanism to the biodiversity variables are illustrative and do not imply that every mechanism impacts every listed biodiversity variable; specific relationships are detailed in the main text. Each state variable and impact mechanism is flagged with a colored dot indicating the environmental compartment affected.

sulfide minerals such as pyrite, galena, and sphalerite to air and water (Byrne et al. 2012; Simate and Ndlovu 2014). Weathering of these sulfide minerals forms acid mine drainage (AMD), that is, acidic water with high dissolved toxic metal/metalloid concentrations (Byrne et al. 2012; Simate and Ndlovu 2014; Ferreira et al. 2016; Figure 2). When this leachate enters nearby surface water bodies, groundwater, and soil, it contaminates them with metals (Jain and Das 2017; Adeniyi et al. 2022). The metal concentrations in the drainage depend on various factors, including the drainage pH, type of mine, local geology, and the presence of carbonate minerals that can buffer the pH (Byrne et al. 2012; Ferreira et al. 2016; Adeniyi et al. 2022). AMD can increase after mining operations cease as formerly dewatered pits fill up with water (Dudka and Adriano 1997; Byrne et al. 2012). Heavy metals/metalloids are also released via process wastewater discharge (Hogsden and Harding 2012; Affandi and Ishak 2019; Perina and de Souza Abessa 2020). This is especially significant in the context of gold extraction, where artisanal mining (i.e., an informal small-scale type of surface mining) is a major source of mercury pollution (Wiener and Suchanek 2008). Furthermore, heavy metals and metalloids can enter the environment from the settling of dust generated during extraction or through the deposition of emissions from smelting and refining activities (Byrne et al. 2012; Affandi and Ishak 2019; Jones et al. 2020). Lastly, metals and metalloids can leach from tailings, that is, the finely ground waste products of mineral processing, or be accidentally spilled in the environment in the event of a tailing dam failure (Dudka and Adriano 1997; Byrne et al. 2012; Ordóñez et al. 2013; Jain and Das 2017; Karaca et al. 2018; Affandi and Ishak 2019).

Heavy metals and metalloids, notably mercury, arsenic and lead, can be toxic to organisms even at relatively low environmental concentrations (Nagajyoti et al. 2010). In freshwater systems, metals can cause a cascade of negative effects on various organisms and ecological processes (Ferreira et al. 2016). Toxic effects on microbes and detritivorous invertebrates in streams reduce litter decomposition, a crucial ecosystem function that supports energy flow and nutrient cycling (Ferreira et al. 2016; Jones et al. 2020). This often results in decreased insect density and diversity, with pollution-sensitive taxa such as Ephemeroptera, Plecoptera, and Trichoptera experiencing significant declines (Byrne et al. 2012; Hogsden and Harding 2012; Ferreira et al. 2016). Similarly, heavy metal pollution has been linked to increased mortality and reduced species richness and abundance in other invertebrates, such as nematodes, as well as physiological changes (e.g., reduced growth) in simpler organisms like algae and microorganims in biofilms (Ferreira et al. 2016; Rainbow 2020). Through accumulation in the food chain, metals and metalloids also pose risks to vertebrates, including fish and birds, impacting their health and survival (Affandi and Ishak 2019; Etteieb et al. 2020; Jones et al. 2020; Zipper and Skousen 2021). Exposure to metals and metalloids is also reported to disrupt physiological processes in freshwater vertebrates (e.g., deformed embryos of the

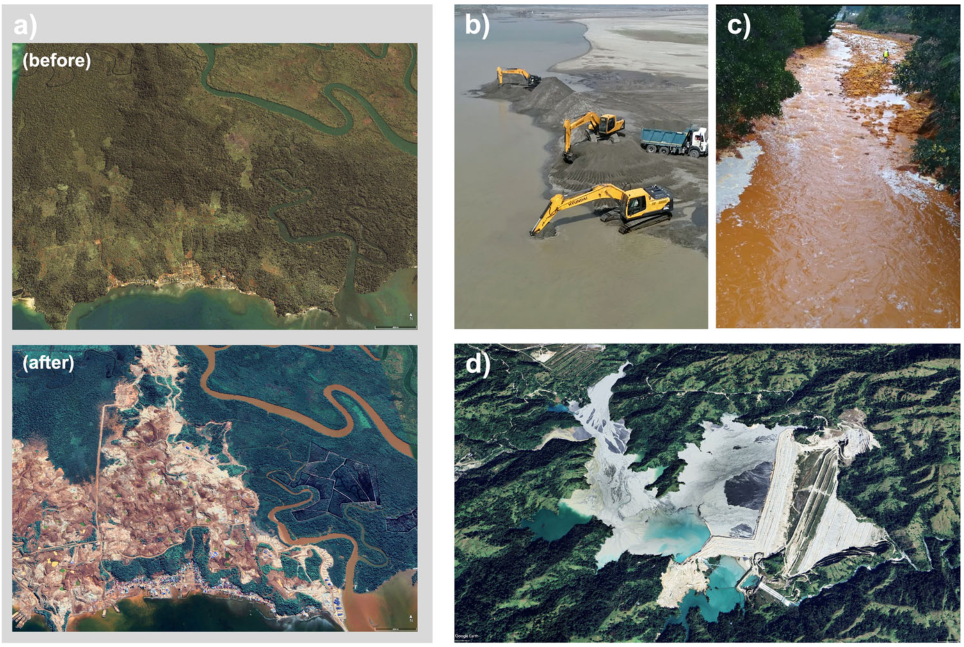

FIGURE 2 | Examples of various mining pressures. (**a**) Large-scale habitat loss from land transformation between 1985 (before) and 2022 (after) caused by the development of the Mandiodo Block for nickel mining in East Sulawesi, Indonesia (image from Google Earth). The additional effects of increased sediment in rivers and coasts are visible from the imagery. (**b)** Habitat alteration and removal from sand mining in the Yamuna river, India (photo courtesy of Manoj Thakur, Mongabay). (**c**) Severe heavy metal pollution caused by acid mine drainage downstream Mount Lyell Copper mine, Western Tasmania, Australia (Adapted from Figure 2 of Nascimento et al. 2023, licensed under CC-BY-4.0 http://creativecommons.org/licenses/by/4.0/). (**d**) A tailings dam used to store reactive waste material from the Copper-Gold Padcal mine, Philippines (image from 2024, Google Earth).

narrow-mouthed toad due to arsenic pollution), which in turn affects gene expression levels and may reduce genetic diversity, thereby increasing the risk of extinction for affected populations (Hogsden and Harding 2012; Affandi and Ishak 2019; Perina and de Souza Abessa 2020). Aquatic organisms in marine ecosystems can also be impacted by heavy metal pollution from land-based mining activities, particularly when tailings are dumped underwater in coastal areas (Rodríguez et al. 2021). These tailings release toxic metals into the marine environment, affecting, among others, (subtidal) benthic fauna and algae (Rodríguez et al. 2021).

Similarly, an increase in metal concentration in soil negatively impacts terrestrial plants and soil communities (Dudka and Adriano 1997). Metals and metalloids, including Rare Earth Elements, can be absorbed by plants, leading to their death or causing morphological and physiological changes such as reduced photosynthesis, inhibited growth, leaf and root browning, and decreased germination (Nagajyoti et al. 2010; Gwenzi et al. 2018; Das et al. 2021). Metals can adversely affect soil microbial communities, which are crucial for nutrient cycling and decomposition processes, ultimately impacting plant growth and diversity, resulting in increased mortality and morphological changes (Zamotaev et al. 2017; Das et al. 2021). Similarly, the uptake of metals and metalloids by soil-dwelling invertebrates is associated with impaired physiological functioning, reduced growth, and heightened mortality, leading to diminished species richness and diversity (Hogsden and Harding 2012; Ferreira et al. 2016). The bioaccumulation of metals and metalloids in invertebrates can induce toxic effects throughout the food chain, placing organisms at higher trophic levels at risk (Byrne et al. 2012). For instance, arsenic, related to gold mining, triggers severe physiological effects in birds, impairing muscle coordination and resulting in immobility and seizures (Eisler 2004). Grazing animals that consume plants with high levels of bioaccumulated selenium may suffer from alkali disease or blind staggers, a condition characterized by symptoms such as blindness, weakened legs, and abdominal pain (Etteieb et al. 2020).

3.2 | pH Changes

AMD from exposed ores and crushed waste rocks is the primary cause of acidic water entering surface water bodies, groundwater aquifers, and soil (see Section 3.1). The decrease in pH impacts the functioning of terrestrial plants and detrivores (Simate and Ndlovu 2014) and can render entire areas devoid of vegetation (Figure 2; Karaca et al. 2018). In soils, changes in pH can disrupt nutrient cycling and microbial communities and diminish the diversity and abundance of soil biota, such as chlorophytes, diatoms, and cyanobacteria (Dudka and Adriano 1997; Zipper and Skousen 2021). In freshwater ecosystems, a drop in pH reduces habitat suitability for algae, bacteria, microbes, invertebrates, and fish. It modifies community composition, with acid-resistant species replacing acid-sensitive ones, decreases ecosystem functioning, and alters the size, length, and complexity of the food chain (Hogsden and Harding 2012). In extreme cases ($pH < 4.5$), water bodies can become devoid of fish (Simate and Ndlovu 2014). Low pH levels also increase the solubility and bioavailability of metals, increasing their toxicity to aquatic life (Byrne et al. 2012; Ferreira et al. 2016). In streams, decreases in pH can lead to significant metal hydroxide precipitation, which can cover the streambed, interfering with plant and ecosystem functioning, sometimes nearly eradicating life (Hogsden and Harding 2012; Adeniyi et al. 2022). Conversely, an increase in pH may occur in coal mines when there is an adequate amount of buffering material in the ores that can react with the acid from AMD, thus creating an alkaline environment (Bernhardt and Palmer 2011). This has also been associated with changes in the community structure of macroinvertebrates (Bernhardt and Palmer 2011).

3.3 | Sediment Loads

Mining activities can significantly increase sediment loads in nearby water bodies (Figure 2). Ore excavation, processing, and transport involve earth-moving, generating debris and disturbing soil/vegetation, increasing erosion and runoff (Jain and Das 2017; Affandi and Ishak 2019; Frelich 2019). Mining operations also produce substantial waste materials, including tailings, overburden, and processed ores, which are often stored in open pits or piles (Byrne et al. 2012; Jones et al. 2020). These waste materials create loose debris when dumped and eroded by wind and rain, leading to higher sediment loads in nearby rivers and streams (Affandi and Ishak 2019; Jones et al. 2020; Rodríguez et al. 2021). In particular, in-stream sand mining fundamentally alters sediment dynamics by increasing water turbidity through the suspension of fine particles during dredging (Ahmed et al. 2020; Koehnken et al. 2020; Rentier and Cammeraat 2022; Figure 2). This increased influx of fine sediment particles into the water column reduces water clarity, thus raising turbidity.

The increased turbidity limits light penetration, thereby reducing photosynthesis (Rodríguez et al. 2021; Rentier and Cammeraat 2022). Photosynthesis may also be hindered by the deposition of suspended sediments on plants. A decrease in photosynthesis, in turn, lowers oxygen levels in the water, which can significantly diminish the quality of freshwater habitats (Wantzen and Mol 2013). Furthermore, large amounts of sediments can alter a stream's morphology, changing habitat structures (Castello and Macedo 2016), and their deposition can decrease the extent or quality of breeding habitats for certain species, such as the sculpin and the yellow-spotted sideneck turtle (Affandi and Ishak 2019). High turbidity also limits visibility, making it harder for animals to locate food and evade predators (Affandi and Ishak 2019). Additionally, increased dissolved solids may directly impair animals. For example, suspended particles can clog the gills of fish, reducing their ability to respire and obtain oxygen, which can ultimately lead to morphological changes or displacement (Wantzen and Mol 2013). When suspended particles resettle, they can also smother benthic organisms such as macroinvertebrates, algae, and fish eggs (Rentier and Cammeraat 2022; Koehnken et al. 2020). When tailings are dumped in marine environments, large quantities of dissolved solids precipitate, suffocating marine invertebrates (Rodríguez et al. 2021). Lastly, sediments may carry high concentrations of absorbed metals, which can be transported further downstream through rivers and streams, potentially extending the impacts of metals as discussed in Section 3.1 (Affandi and Ishak 2019; Jones et al. 2020; Perina and de Souza Abessa 2020).

3.4 | Particulates Emission

Particulates are released into the air through the extraction and transportation of ore and waste rock, wind erosion from exposed surfaces such as mine tailings and overburden dumps, and smelting and refining processes (Dudka and Adriano 1997; Frelich 2019; Mwaanga et al. 2019). Wind erosion is particularly pronounced in arid environments, where limited vegetation and soil moisture increase the susceptibility of exposed materials to dispersal (Dudka and Adriano 1997; Nagajyoti et al. 2010). Depending on particle size and weight and prevailing wind patterns, particulates can be transported over long distances, potentially affecting ecosystems far beyond the immediate mining area (Gwenzi et al. 2018; Frelich 2019; Mwaanga et al. 2019). High concentrations of particulate matter in the air can irritate the respiratory systems of animals, and exposure to metal particulates can cause various health problems, including oxidative stress and even death (Mwaanga et al. 2019). Particulates have the potential to accumulate in soils, leading to the contamination of food and water sources and bioaccumulating in animals at higher trophic levels. Plants directly uptake and accumulate these pollutants from the air, which may hinder plant growth and development (Mwaanga et al. 2019). Particulates can also cause acidification when dust contains metals, triggering AMD (see Sections 3.1 and 3.2 for details on the impacts on biodiversity) (Frelich 2019).

3.5 | Salinization

Mining activities can contribute to salinization through various pathways, including the discharge of saline mine water and the weathering of sulfide minerals in mine tailings (Cañedo-Argüelles et al. 2013). The primary anions released are sulfate ($SO4^{2-}$) from AMD processes (see Sections 3.1 and 3.2) (Bernhardt and Palmer 2011) and chloride (Cl^-) from its use in de-icing transportation roads to and from mining sites (Frelich 2019). The complementary cations include sodium (Na^+) and potassium (K^+), as well as calcium (Ca^{2+}) and magnesium (Mg^{2+}) are released from weathered carbonate minerals (Cañedo-Argüelles et al. 2013). Additionally, in coastal and deltaic regions, in-stream sand mining deepens river channels, which alters the hydrologic balance and can facilitate the inland intrusion of saline seawater (Ahmed et al. 2020).

An increase in salt concentration in freshwater bodies can have cascading effects on individual organisms, populations, communities, and entire ecosystems. Organisms that have evolved to regulate their internal salt concentration within specific salinity ranges (osmoregulatory species) are particularly vulnerable to the osmotic stress caused by changes in salinity (Cañedo-Argüelles et al. 2013). This stress can lead to developmental malformations in certain species, such as green frogs, and can reduce growth and food intake in invertebrates and fish (Cañedo-Argüelles et al. 2013). Fish abundance may decline as species avoid the salinized areas (Zipper and Skousen 2021). Increases in salinity can also alter the community composition and structure of ecosystems, as salt-tolerant species proliferate, displacing salt-sensitive species and weakening the ecosystem's resilience (Cañedo-Argüelles et al. 2013). Salinization also affects ecosystem function, potentially decreasing vegetation, which allows greater light penetration and shifts the ecosystem's composition from heterotrophic to autotrophic (Cañedo-Argüelles et al. 2013). Additionally, increased dissolved salt ions enhance water conductivity, further exacerbating stress on freshwater vertebrates and reducing their growth (Cañedo-Argüelles et al. 2013; Affandi and Ishak 2019). In terrestrial ecosystems, higher salt concentrations in soil can damage roots and hinder the uptake of water and nutrients by plants, increasing the likelihood of tree mortality (Frelich 2019).

3.6 | Other Pollutants

Although described in less detail in the review articles, we found evidence of biodiversity impacts from additional pollutants generated by mines. These pollutants include sulfur dioxide (SO_2), which is observed, for example, in mines where copper is extracted from ores containing sulfides (Mwaanga et al. 2019). Elevated concentrations of sulfur and sulfides have direct adverse effects on plants, manifesting as necrotic spots, and closer to the emission sources, exposure may lead to mortality (Mwaanga et al. 2019). Increased SO_2 concentrations can also lead to acid rain, significantly reducing soil pH (Section 3.2) (Mwaanga et al. 2019). Moreover, leached sulfates from overburden can form sulfides that react with the bonds between iron and phosphorus, releasing phosphorus into the environment and causing eutrophication (Bernhardt and Palmer 2011). Beyond metals and metalloids, cyanide is often found downstream of gold mines and can negatively impact biodiversity due to its high toxicity (Lemly 1994; Sonter et al. 2018). Lastly, the operation of heavy machinery during extraction and processing, along with the associated road and infrastructure development, results in noise pollution. Once a mine is established in an environment, traffic and its associated noises increase, which generally has a negative impact on terrestrial biodiversity, particularly on songbirds (Frelich 2019). In aquatic environments, noise from dredging has been reported to affect the echolocation of mammals (Rentier and Cammeraat 2022).

4 | Physical Habitat Change

4.1 | Habitat Loss

Mining causes significant land transformation by removing vegetation and topsoil, excavating vast amounts of rock to access mineral deposits, and creating waste rock dumps and tailings storage facilities (Figure 2; Dudka and Adriano 1997; Bernhardt and Palmer 2011; Jain and Das 2017). The excavated overburden and other non-ore waste materials often form massive waste rock piles that can cover hundreds of hectares, altering the topography (Dudka and Adriano 1997). Similarly, tailings are frequently stored in large impoundments that can cover extensive areas (Dudka and Adriano 1997; Jain and Das 2017). Thus, mining activities lead to profound land transformation hence loss of natural habitat, which is further exacerbated by the construction of roads, infrastructure, industrial facilities (e.g., processing plants), and human settlements driven by mining activities (Sonter et al. 2018; Frelich 2019).

The transformation of land and the resulting reduction in the extent of natural habitats often displaces numerous species, particularly vertebrates that rely on large patches of undisturbed forests (Frelich 2019). In open-pit mining, the overburden is often disposed of in nearby valleys, leading to the burial of streams and the subsequent loss of aquatic ecosystems (Bernhardt and Palmer 2011; Karaca et al. 2018). Similarly, the dredging of riverbeds for sand and gravel directly eradicates habitat, destroying critical spawning and hiding grounds for fish and eliminating benthic invertebrate communities (Ahmed et al. 2020; Koehnken et al. 2020; Figure 2). The removal of essential aquatic habitats results in a decline in the abundance and diversity of various species, such as salamanders, mussels, and other aquatic species (Bernhardt and Palmer 2011; Zipper and Skousen 2021). In addition to direct land transformation, mining activities also contribute to habitat loss through increased erosion. The removal of vegetation in and around the mine makes the soil more susceptible to erosion, resulting in degradation and a subsequent decline in habitat quality (Frelich 2019; Adeniyi et al. 2022).

4.2 | Hydrological Alterations

Mining activities can significantly disrupt natural hydrological processes, leading to long-term changes in groundwater tables, streamflow, and water temperature. The dumping of overburden can drastically alter downstream flow regimes (Bernhardt and Palmer 2011). Additionally, roads connecting mining areas can create barriers that obstruct streams and change downstream flow (Frelich 2019). Furthermore, underground mining, in particular, can lower the water table due to the dewatering necessary to access the ore (Frelich 2019). Further, in-stream dredging for aggregates mining causes severe hydrological alterations by deepening and widening river channels, which can increase flow velocity, destabilize banks leading to widespread erosion, primarily through channel incision, head cutting and the "hungry water" effect, and intensify saline intrusion in coastal delta regions (Ahmed et al. 2020; Koehnken et al. 2020; Rentier and Cammeraat 2022; see also Sections 3.3 and 3.5). Channel deepening can, in turn, lower the surrounding groundwater table and disrupt the recharge of local aquifers (Koehnken et al. 2020; Rentier and Cammeraat 2022). Finally, the construction of tailings ponds and waste rock dumps disrupts surface drainage, alters infiltration patterns, and increases the risk of erosion and sediment transport into waterways (see also Section 3.3).

The loss of headwater streams and changes in water temperature and flow directly impact aquatic species, leading to population declines, range contractions, and even local extinctions (Bernhardt and Palmer 2011; Zipper and Skousen 2021). These factors, in turn, affect riverine community structure (Bernhardt and Palmer 2011; Zipper and Skousen 2021). Vertebrate populations, particularly fish, are negatively impacted by changes in flow and water temperature (Hancock 2002; Bernhardt and Palmer 2011; Castello and Macedo 2016). A decrease in downstream water supply and lowered water tables can lead to parching vegetation, ultimately altering the composition of terrestrial ecosystems (Frelich 2019). Additionally, the reduced availability of drinking water for terrestrial wildlife may adversely affect their populations (Zipper and Skousen 2021).

4.3 | Habitat Fragmentation

Habitat fragmentation can occur through the establishment of mines, dumps, and tailing sites, as well as through the development of roads and other infrastructure associated with mining activities (Figure 2). These disturbances displace vertebrates and disrupt wildlife movements (Frelich 2019). Large-scale mining can also promote the construction of hydroelectric dams to meet the high energy demands of smelting processes, which reduces river connectivity and adversely affects riverine ecosystems (Castello and Macedo 2016). Furthermore, fragmentation can lead to an increase in forest edges, which is linked to changes in forest composition and a rise in the abundance of non-native invasive species, as well as edge-preferring species, negatively impacting native species (Frelich 2019).

5 | Other Impacts

With industrial development and human encroachment related to mining activities, all anthropogenic impacts increase, including over-exploitation through hunting and fishing (Sonter et al. 2018). Mining is also a carbon-intensive process, resulting in greenhouse gas emissions associated with the use of mining equipment and energy-intensive operations such as ore beneficiation and smelting. The resulting climate change can have severe consequences for biodiversity (Sonter et al. 2018). Moreover, during the exploration phase (i.e., before mining begins) and the development phase, invasive species can be introduced (Frelich 2019). The clearing of forests and other ecosystems can further worsen the spread of invasive species, as these often thrive in harsher conditions, exacerbating local ecosystem change (Frelich 2019). Finally, there may be additional sources of potential impacts not mentioned in our review, as these have not yet been observed or documented in review studies evaluated. For instance, we did not include deep-sea mining, an emerging technology that has raised concerns about the fragile ecosystems found at the bottom of the ocean (Orcutt et al. 2020), due to the absence of documented evidence-based pathways in the reviewed studies. However, this does not imply that these impacts are of lesser concern or priority for inclusion in global biodiversity models.

6 | A Way Forward to Model Mining Impacts on Biodiversity

Our review shows that mining impacts on biodiversity are manifold and complex. Recent advances in threat mapping have been invaluable for identifying global hotspots where biodiversity is at high risk from mining activities, by either overlaying maps of mining sites with protected areas or stacking IUCN range maps of species listed as threatened by mining (Durán et al. 2013; Kobayashi et al. 2014; Sonter et al. 2020; Luckeneder et al. 2021; Lamb et al. 2024; Brabant et al. 2025). While useful for identifying potential hotspots, these methods do not quantify biodiversity loss (e.g., community intactness, loss of diversity or richness) nor capture the heterogeneity of pressures across commodities, extraction techniques, and locations, which is essential to enable scenario exploration to understand how addressing individual pressures may lead to a reduction in predicted biodiversity loss. To effectively include biodiversity considerations into impact assessment for decision-making related to mining operations, it is essential to develop biodiversity models that can quantify relevant impact pathways. Existing multi-pressure biodiversity assessment models could provide a good starting point and allow comparing impacts on biodiversity across multiple pressures (Scholes and Biggs 2005; Visconti et al. 2016; Mcrae et al. 2017; Ohashi et al. 2019; Leclère et al. 2020; Schipper et al. 2020). Hereafter, we highlight key areas for improving the representation of mining impacts in biodiversity assessment models.

Pollution impacts biodiversity via multiple pathways, especially in freshwater (Figure 1). However, pollution effects are often underrepresented in biodiversity research and rarely included in global biodiversity models (Sigmund et al. 2023). There are ecotoxicological datasets about the effects of numerous chemical compounds on selected species, imputation methods to estimate the toxicity of data-deficient chemicals (Hou et al. 2020), as well as methods for assessing the compound effects of pollutant mixtures (Posthuma et al. 2019b, Posthuma et al. 2019a). These data and methods could be linked to fate and transport models to estimate impacts on biodiversity associated with the release and dispersion of contaminants in the environment (Jones et al. 2023; Macedo et al. 2024). However, comprehensive mine pollutant inventories and representation of mining-relevant processes (e.g., AMD) in transport models are lacking. This limits our capacity to comprehensively quantify and compare the ecotoxicological effects of mining and should be prioritized in future model developments.

Many global biodiversity models quantify the response of biodiversity to land-use changes (Leclère et al. 2020). However, these models do not classify mining as a specific land use, often because they use land cover as a proxy for land use pressures (Sonter et al. 2025). Conversely, various studies have examined the deforestation resulting from mining by analyzing remote sensing data (Sonter et al. 2017; Giljum et al. 2022), yet without translating the pressures of forest loss into assessments of biodiversity loss, for example, including impacts on species extinction risks and population abundance. To appropriately account for land-use impacts, future models should quantify biodiversity responses both at and beyond the mine site. For example, Giljum et al. (2022) employed a statistical method to attribute deforested areas near the mine to infrastructure or human settlement development related to mining. Such approaches are crucial to correctly allocate pressures, and therefore biodiversity impacts, to mining and prevent underestimating land use impacts.

As mining activities exert multiple pressures simultaneously, there is a key need for biodiversity models to represent the combined impacts of multiple mining-related pressures (Boënnec et al. 2024) However, while quantifying the effects of chemical mixtures on some species in aquatic environments is feasible (Posthuma et al. 2019a), understanding how combined changes in natural conditions and pollution pathways might have synergistic or antagonistic effects remains a significant modeling challenge (Holmstrup et al. 2010). For instance, warming water temperatures could amplify the physiological effects of metals on aquatic ectotherms, thereby amplifying pollution impacts (Sokolova and Lannig 2008). Methods such as life cycle impact assessment (LCIA) could encompass various impact pathways, including effects of warming waters (Li et al. 2022) and ecotoxicity (Owsianiak et al. 2023) on some aquatic taxonomic groups. However, these models cannot account for interactions among pressures (Damiani et al. 2023). Additionally, accurately quantifying spatially-explicit global biodiversity impacts through LCIA would require a detailed accounting of worldwide mines' operations and environmental flows, information that is currently unavailable (Maus and Werner 2024). Therefore, we suggest developing statistical response relationships from a large array of empirical studies while considering proxies that account for the local context as a first step toward estimating impacts globally. Similarly to what has been developed for the impact of, for example, linear infrastructure (de Jonge et al. 2022) or hunting (Benítez-López et al. 2017), such an approach would enable considering all pressures at once and allow for the quantification of a mine's total impact on community- or population-level biodiversity metrics. Nevertheless, this more straightforward approach would have the drawback of not being able to differentiate impacts across the various pressures of mining activities.

A relevant aspect that remained outside the scope of this review is mine rehabilitation, remediation, and recovery. The way a mine is managed after closure, including whether pollution is addressed and whether efforts are made to rehabilitate the area, significantly impacts its long-term effects on biodiversity (Sonter et al. 2023). When a mine closes, environmental pressures evolve and may worsen (e.g., if dewatering pumps cease operating, AMD is likely to escalate) or diminish through passive or active restoration. Achieving successful mine site restoration is, however, complex, as restoration does not always lead to a return to the previous state and requires sustained and sophisticated monitoring (Cristescu et al. 2012; Sonter et al. 2023; Harries et al. 2024). Restoration has been broadly studied (McKenna et al. 2020; Harries et al. 2024), and several of the reviews analyzed in our study provide restoration examples such as remediating acid mine drainage (Simate and Ndlovu 2014; Adeniyi et al. 2022), river pollution (Byrne et al. 2012), and restoring soil or flora through, for instance, forestry reclamation (Zipper and Skousen 2021; Frelich 2019). Although extensive national (McDonald et al. 2016) and international (Young et al. 2022) principles and standards for restoring a mine site now exist, only a few mines appear to undergo rehabilitation and achieve final relinquishment globally (Werner et al. 2020; Sonter et al. 2023). This gap between principles and practice is linked not only to the complex nature of national regulatory frameworks (Kragt and Manero 2021) but also to the great technical difficulty of restoring highly degraded landscapes, where failures remain common even when standards-based approaches are used (Campbell et al. 2024). In major mining jurisdictions like Australia and Canada, regulations may mandate progressive rehabilitation and financial assurances for closure; however, significant policy barriers related to final site relinquishment can still discourage the long-term investment required for high-quality restoration (Tiemann et al. 2022). In contrast, regulations in other regions may be less specific, leading companies to set their own biodiversity targets (e.g., in South Africa; Young et al. 2022) or face challenges with enforcement and the impacts of illegal mining (e.g., in Vietnam; Ahmed et al. 2020). Given these significant policy barriers and technical challenges that make successful, large-scale restoration uncertain, it is crucial to accurately model the initial impacts to avoid or minimize them in the first place. Therefore, we recommend that future model-based mining impact assessments incorporate explicit post-mining scenarios, potentially accounting for these country-specific restoration requirements, to distinguish between temporary and permanent biodiversity losses. Similarly, our review focused on land mining, thereby ignoring deep-sea mining, an emerging threat to marine biodiversity (Christiansen et al. 2020; Lins et al. 2021; Metaxas et al. 2024).

Our study provides a detailed overview of the various ways mining impacts biodiversity. We acknowledge that our review of published reviews approach might reflect potential publication biases driven by research interests and data availability, risking overemphasizing well-documented pathways such as pollution and underrepresenting emerging threats such as deep-sea mining. Nevertheless, we believe that our synthesis may serve as a useful foundation for future efforts to model the impacts of mining on biodiversity. By incorporating pollution pathways and addressing the effects of habitat changes caused by mining, biodiversity assessment models can improve our understanding of mining's global biodiversity footprint. This, in turn, would allow for better comparisons of different energy transition scenarios and support more informed conservation policies.

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Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study

References

Adeniyi, A. G., E. C. Emenike, K. O. Iwuozor, H. K. Okoro, and O. O. Ige. 2022. "Acid Mine Drainage: The Footprint of the Nigeria Mining Industry." *Chemistry Africa* 5, no. 6: 1907–1920.

Affandi, F. A., and M. Y. Ishak. 2019. "Impacts of Suspended Sediment and Metal Pollution From Mining Activities on Riverine Fish Population—A Review." *Environmental Science and Pollution Research* 26, no. 17: 16939–16951.

Ahmed, S. N., L. H. Anh, and P. Schneider. 2020. "A DPSIR Assessment on Ecosystem Services Challenges in the Mekong Delta, Vietnam: Coping With the Impacts of Sand Mining." *Sustainability (Switzerland)* 12, no. 22: 9323.

Benítez-López, A., R. Alkemade, A. M. Schipper, et al. 2017. "The Impact of Hunting on Tropical Mammal and Bird Populations." *Science (1979)* 356: 180–183.

Bernhardt, E. S., and M. A. Palmer. 2011. "The Environmental Costs of Mountaintop Mining Valley Fill Operations for Aquatic Ecosystems of the Central Appalachians." *Annals of the New York Academy of Sciences* 1223, no. 1: 39–57.

Brabant, C., N. Noorbhai, M. Bendixen, and L. L. Iversen. 2025. "Mapping the Global Impact of Mining Activities on Freshwater Biodiversity to Inform Conservation Priorities." *Aquatic Conservation: Marine and Freshwater Ecosystems* 35: e70094.

Byrne, P., P. J. Wood, and I. Reid. 2012. "The Impairment of River Systems by Metal Mine Contamination: A Review Including Remediation Options." *Critical Reviews in Environmental Science and Technology* 42: 2017–2077.

Boënnec, M., V. Dakos, and V. Devictor. 2024. "Sources of Confusion in Global Biodiversity Trends." *Oikos* 2024: e10732. https://doi.org/10.1111/oik.10732.

Campbell, T., K. W. Dixon, S. D. Bradshaw, et al. 2024. "Standards-Based Evaluation Inform Ecological Restoration Outcomes for a Major Mining Activity in a Global Biodiversity Hotspot." *Restoration Ecology* 32: e14236.

Cañedo-Argüelles, M., B. J. Kefford, C. Piscart, N. Prat, R. B. Schäfer, and C. J. Schulz. 2013. "Salinisation of Rivers: An Urgent Ecological Issue." *Environmental Pollution* 173: 157–167.

Castello, L., and M. N. Macedo. 2016. "Large-Scale Degradation of Amazonian Freshwater Ecosystems." *Global Change Biology* 22: 990–1007.

Christiansen, B., A. Denda, and S. Christiansen. 2020. "Potential Effects of Deep Seabed Mining on Pelagic and Benthopelagic Biota." *Marine Policy* 114: 103442.

Cristescu, R. H., C. Frère, and P. B. Banks. 2012. "A Review of Fauna in Mine Rehabilitation in Australia: Current state and Future Directions." *Biological Conservation* 149, no. 1: 60–72.

Damiani, M., T. Sinkko, C. Caldeira, D. Tosches, M. Robuchon, and S. Sala. 2023. "Critical Review of Methods and Models for Biodiversity Impact Assessment and Their Applicability in the LCA Context." *Environmental Impact Assessment Review* 101: 107134.

Das, P. K., B. P. Das, and P. Dash. 2021. "Chromite Mining Pollution, Environmental Impact, Toxicity and Phytoremediation: A Review." *Environmental Chemistry Letters* 19: 1369–1381.

de Jonge, M. M. J., J. Gallego-Zamorano, M. A. J. Huijbregts, A. M. Schipper, and A. Benítez-López. 2022. "The Impacts of Linear Infrastructure on Terrestrial Vertebrate Populations: A Trait-Based Approach." *Global Change Biology* 28: 7217–7233.

Dudka, S., and D. C. Adriano. 1997. "Environmental Impacts of Metal Ore Mining and Processing: A Review." *Journal of Environmental Quality* 26: 590–602.

Durán, A. P., J. Rauch, and K. J. Gaston. 2013. "Global Spatial Coincidence Between Protected Areas and Metal Mining Activities." *Biological Conservation* 160: 272–278.

Eisler, R. 2004. "Arsenic Hazards to Humans, Plants, and Animals From Gold Mining." *Reviews of Environment Contamination and Toxicology* 180: 133–165.

Etteieb, S., S. Magdouli, M. Zolfaghari, and S. K. Brar. 2020. "Monitoring and Analysis of Selenium as an Emerging Contaminant in Mining Industry: A Critical Review." *Science of the Total Environment* 698: 134339.

Ferreira, V., J. Koricheva, S. Duarte, D. K. Niyogi, and F. Guérold. 2016. "Effects of Anthropogenic Heavy Metal Contamination on Litter Decomposition in Streams—A Meta-Analysis." *Environmental Pollution* 210: 261–270.

Frelich, L. E. 2019. "Terrestrial Ecosystem Impacts of Sulfide Mining: Scope of Issues for the Boundary Waters Canoe Area Wilderness, Minnesota, USA." *Forests* 10: 747.

Giljum, S., V. Maus, N. Kuschnig, et al. 2022. "A Pantropical Assessment of Deforestation Caused by Industrial Mining." *Proceedings National Academy of Science USA* 119: e2118273119.

Giljum, S., V. Maus, L. Sonter, et al. 2025. "Metal Mining Is a Global Driver of Environmental Change." *Nature Reviews Earth & Environment* 6: 441–455.

Gwenzi, W., L. Mangori, C. Danha, N. Chaukura, N. Dunjana, and E. Sanganyado. 2018. "Sources, Behaviour, and Environmental and human Health Risks of High-Technology Rare Earth Elements as Emerging Contaminants." *Science of the Total Environment* 636: 299–313.

Hancock, P. J. 2002. "Human Impacts on the Stream-Groundwater Exchange Zone." *Environmental Management* 29: 763–781.

Harfoot, M. B. J., D. P. Tittensor, S. Knight, et al. 2018. "Present and Future Biodiversity Risks From Fossil Fuel Exploitation." *Conservation Letters* 11: e12448.

Harries, K. L., J. Woinarski, L. Rumpff, M. Gardener, and P. D. Erskine. 2024. "Characteristics and Gaps in the Assessment of Progress in Mine Restoration: Insights From Five Decades of Published Literature Relating to Native Ecosystem Restoration After Mining." *Restoration Ecology* 32: e14016.

Hogsden, K. L., and J. S. Harding. 2012. "Consequences of Acid Mine Drainage for the Structure and Function of Benthic Stream Communities: A Review." *Freshwater Science* 31: 108–120.

Holmstrup, M., A. M. Bindesbøl, G. J. Oostingh, et al. 2010. "Interactions Between Effects of Environmental Chemicals and Natural Stressors: A Review." *Science of The Total Environment* 408: 3746–3762.

Hou, P., O. Jolliet, J. Zhu, and M. Xu. 2020. "Estimate Ecotoxicity Characterization Factors for Chemicals in Life Cycle Assessment Using Machine Learning Models." *Environment International* 135: 105393.

Hund, K., D. La Porta, T. P. Fabregas, T. Laing, and J. Drexhage. 2023. Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. World Bank Group.

IEA. 2023. *World Energy Outlook 2023*. IEA.

Jain, M. K., and A. Das. 2017. "Impact of Mine Waste Leachates on Aquatic Environment: a Review." *Current Pollution Reports* 3: 31–37.

Jasansky, S., M. Lieber, S. Giljum, and V. Maus. 2023. "An Open Database on Global Coal and Metal Mine Production." *Scientific Data* 10: 1–12.

Jones, E. R., M. F. P. Bierkens, N. Wanders, E. H. Sutanudjaja, L. P. H. van Beek, and M. T. H. van Vliet. 2023. "DynQual v1.0: A High-Resolution Global Surface Water Quality Model." *Geoscientific Model Development* 16: 4481–4500.

Jones, J. I., J. F. Murphy, A. L. Collins, et al. 2020. "The Impact of Metal-Rich Sediments Derived From Mining on Freshwater Stream Life." *Reviews of Environmental Contamination and Toxicology* 248: 111–189.

Junker, J., L. Quoss, J. Valdez, et al. 2024. "Threat of Mining to African Great Apes." *Science Advances* 10: 10.

Karaca, O., C. Cameselle, and K. R. Reddy. 2018. "Mine Tailing Disposal Sites: Contamination Problems, Remedial Options and Phytocaps for Sustainable Remediation." *Reviews in Environmental Science and Biotechnology* 17: 205–228.

Kobayashi, H., H. Watando, and M. Kakimoto. 2014. "A Global Extent Site-Level Analysis of Land Cover and Protected Area Overlap With Mining Activities as an Indicator of Biodiversity Pressure." *Journal of Cleaner Production* 84: 459–468.

Koehnken, L., M. S. Rintoul, M. Goichot, D. Tickner, A. C. Loftus, and M. C. Acreman. 2020. "Impacts of Riverine Sand Mining on Freshwater Ecosystems: A Review of the Scientific Evidence and Guidance for Future Research." *River Research and Applications* 36: 362–370.

Kragt, M. E., and A. Manero. 2021. "Identifying Industry Practice, Barriers, and Opportunities for Mine Rehabilitation Completion Criteria in Western Australia." *Journal of Environmental Management* 287: 112258.

Lamb, I. P., M. R. Massam, S. C. Mills, R. G. Bryant, and D. P. Edwards. 2024. "Global Threats of Extractive Industries to Vertebrate Biodiversity." *Current Biology* 34: 3673–3684.e4.

Leclère, D., M. Obersteiner, M. Barrett, et al. 2020. "Bending the Curve of Terrestrial Biodiversity Needs an Integrated Strategy." *Nature* 585: 551–556.

Lemly, A. D. 1994. "Mining in Northern Canada: Expanding the Industry While Protecting Arctic Fishes—A Review." *Ecotoxicology and Environmental Safety* 29: 229–242.

Li, D., M. Dorber, V. Barbarossa, and F. Verones. 2022. "Global Characterization Factors for Quantifying the Impacts of Increasing

Water Temperature on Freshwater Fish." *Ecological Indicators* 142: 109 201.

Lins, L., D. Zeppilli, L. Menot, et al. 2021. "Toward a Reliable Assessment of Potential Ecological Impacts of Deep-Sea Polymetallic Nodule Mining on Abyssal Infauna." *Limnology and Oceanography: Methods* 19: 626–650.

Luckeneder, S., S. Giljum, A. Schaffartzik, V. Maus, and M. Tost. 2021. "Surge in Global Metal Mining Threatens Vulnerable Ecosystems." *Global Environmental Change* 69: 102303.

Macedo, H. E., B. Lehner, J. Nicell, and G. Grill. 2024. "HydroFATE (v1): A High-Resolution Contaminant Fate Model for the Global River System." *Geoscientific Model Development* 17: 2877–2899.

Macklin, M. G., C. J. Thomas, A. Mudbhatkal, et al. 2023. "Impacts of Metal Mining on River Systems: A Global Assessment." *Science (1979)* 381: 1345–1350.

Maus, V., S. Giljum, D. M. da Silva, et al. 2022. "An Update on Global Mining Land Use." *Scientific Data* 9, no. 1: 433.

Maus, V., and T. T. Werner. 2024. "Impacts for Half of the World's Mining Areas Are Undocumented." *Nature* 625: 26–29.

McDonald, T., J. Jonson, and K. W. Dixon. 2016. "National Standards for the Practice of Ecological Restoration in Australia." *Restoration Ecology* 24: S4–S32.

McKenna, P. B., A. M. Lechner, S. Phinn, and P. D. Erskine. 2020. "Remote Sensing of Mine Site Rehabilitation for Ecological Outcomes: A Global Systematic Review." *Remote Sensing* 12: 3535.

Mcrae, L., S. Deinet, and R. Freeman. 2017. "The Diversity-Weighted Living Planet Index: Controlling for Taxonomic Bias in a Global Biodiversity Indicator." *PLoS ONE* 12, no. 1: e0169156.

Metaxas, A., C. D. Anglin, A. Cross, et al. 2024. "Comparing Environmental Impacts of Deep-Seabed and Land-Based Mining: A Defensible Framework." *Global Change Biology* 30: e17334.

Murguía, D. I., S. Bringezu, and R. Schaldach. 2016. "Global Direct Pressures on Biodiversity by Large-scale Metal Mining: Spatial Distribution and Implications for Conservation." *Journal of Environmental Management* 180: 409–420.

Mwaanga, P., M. Silondwa, G. Kasali, and P. M. Banda. 2019. "Preliminary Review of Mine Air Pollution in Zambia." *Heliyon* 5, no. 9: e02485.

Nagajyoti, P. C., K. D. Lee, and T. V. M. Sreekanth. 2010. "Heavy Metals, Occurrence and Toxicity for Plants: A Review." *Environmental Chemistry Letters* 8: 199–216.

Nascimento, S. C., D. R. Cooke, A. T. Townsend, et al. 2023. "Long-Term Impact of Historical Mining on Water Quality at Mount Lyell, Western Tasmania, Australia." *Mine Water and the Environment* 42: 399–417.

Nijnens, J., P. Behrens, O. Kraan, B. Sprecher, and R. Kleijn. 2023. "Energy Transition Will Require Substantially Less Mining Than the Current Fossil System." *Joule* 7: 2408–2413.

Northey, S. A., S. Klose, S. Pauliuk, M. Yellishetty, and D. Giurco. 2023. "Primary Exploration, Mining and Metal Supply Scenario (PEMMSS) Model: Towards a Stochastic Understanding of the Mineral Discovery, Mine Development and Co-Product Recovery Requirements to Meet Demand in a Low-Carbon Future." *Resources, Conservation & Recycling Advances* 17: 200137.

Ohashi, H., T. Hasegawa, A. Hirata, et al. 2019. "Biodiversity Can Benefit From Climate Stabilization Despite Adverse Side Effects of Land-Based Mitigation." *Nature Communications* 10: 5240.

Orcutt, B. N., J. A. Bradley, W. J. Brazelton, et al. 2020. "Impacts of Deep-Sea Mining on Microbial Ecosystem Services." *Limnology and Oceanography* 65: 1489–1510.

Ordóñez, A., R. Álvarez, and J. Loredo. 2013. "Asturian Mercury Mining District (Spain) and the Environment: A Review." *Environmental Science and Pollution Research* 20: 7490–7508.

Owsianiak, M., M. Z. Hauschild, L. Posthuma, et al. 2023. "Ecotoxicity Characterization of Chemicals: Global Recommendations and Implementation in USEtox." *Chemosphere* 310: 136807.

Perina, F. C., and D. M. de Souza Abessa. 2020. "Contamination and Toxicity in a Subtropical Estuarine Protected Area Influenced by Former Mining Activities." *Ocean and Coastal Research* 68: 1–29.

Posthuma, L., R. Altenburger, T. Backhaus, et al. 2019a. "Improved Component-Based Methods for Mixture Risk Assessment Are Key to Characterize Complex Chemical Pollution in Surface Waters." *Environmental Sciences Europe* 31: 1–11.

Posthuma, L., J. van Gils, M. C. Zijp, D. van de Meent, and D. de Zwart. 2019b. "Species Sensitivity Distributions for Use in Environmental Protection, Assessment, and Management of Aquatic Ecosystems for 12 386 Chemicals." *Environmental Toxicology and Chemistry* 38: 905–917.

Rainbow, P. S. 2020. "Mining-contaminated Estuaries of Cornwall—Field Research Laboratories for Trace Metal Ecotoxicology." *Journal of the Marine Biological Association of the United Kingdom* 100: 195–210.

Rentier, E. S., and L. H. Cammeraat. 2022. "The Environmental Impacts of River Sand Mining." *Science of the Total Environment* 838: 155877.

Rodríguez, F., C. Moraga, J. Castillo, E. Gálvez, P. Robles, and N. Toro. 2021. "Submarine Tailings in Chile—A Review." *Metals (Basel)* 11: 780.

Schipper, A. M., J. P. Hilbers, J. R. Meijer, et al. 2020. "Projecting Terrestrial Biodiversity Intactness With GLOBIO 4." *Global Change Biology* 26: 760–771.

Scholes, R. J., and R. Biggs. 2005. "A Biodiversity Intactness Index." *Nature* 434: 45–49.

Sigmund, G., M. Ågerstrand, A. Antonelli, et al. 2023. "Addressing Chemical Pollution in Biodiversity Research." *Global Change Biology* 29: 3240–3255.

Simate, G. S., and S. Ndlovu. 2014. "Acid Mine Drainage: Challenges and Opportunities." *Journal of Environmental Chemical Engineering* 2: 1785–1803.

Sokolova, I., and G. Lannig. 2008. "Interactive Effects of Metal Pollution and Temperature on Metabolism in Aquatic Ectotherms: Implications of Global Climate Change." *Climate Research* 37: 181–201.

Sonter, L. J., S. H. Ali, and J. E. M. Watson. 2018. "Mining and Biodiversity: Key Issues and Research Needs in Conservation Science." *Proceedings of the Royal Society B* 285, no. 1892: 20181926.

Sonter, L. J., M. C. Dade, J. E. M. Watson, and R. K. Valenta. 2020. "Renewable Energy Production Will Exacerbate Mining Threats to Biodiversity." *Nature Communications* 11: 1–6.

Sonter, L. J., D. Herrera, D. J. Barrett, G. L. Galford, C. J. Moran, and B. S. Soares-Filho. 2017. "Mining Drives Extensive Deforestation in the Brazilian Amazon." *Nature Communications* 8: 1–7.

Sonter, L. J., M. Maron, J. W. Bull, et al. 2023. "How to Fuel an Energy Transition With Ecologically Responsible Mining." *Proceedings National Academy of Science USA* 120, no. 35: e2307006120.

Sonter, L. J., I. Nursamsi, L. Bennun, et al. 2025. "Global Land Cover Maps Do Not Reveal Mining Pressures to Biodiversity." *Scientific Reports* 15: 1–10.

Sovacool, B. K., S. H. Ali, M. Bazilian, et al. 2020. "Sustainable Minerals and Metals for a Low-Carbon Future." *Science (1979)* 367: 30–33.

Tang, L., and T. T. Werner. 2023. "Global Mining Footprint Mapped From High-Resolution Satellite Imagery." *Communications Earth & Environment* 4: 1–12.

Tiemann, C., V. MacDonald, R. Young, and K. Dixon. 2022. "Rehabilitation and Mine Closure Policies Creating a Pathway to Relinquishment: An Australian Perspective." *Restoration Ecology* 30: e13785. https://doi.org/10.1111/rec.13785.

Torres, A., S. O. S. E. zu Ermgassen, L. M. Navarro, et al. 2024. "Mining Threats in High-Level Biodiversity Conservation Policies." *Conservation Biology* 38: e14261.

National Minerals Information Center. 2024. *Minerals Yearbook, volume III, Area Reports—International*. U.S. Geological Survey.

Visconti, P., M. Bakkenes, D. Baisero, et al. 2016. “Projecting Global Biodiversity Indicators Under Future Development Scenarios.” *Conservation Letters* 9: 5–13.

Wantzen, K. M., and J. H. Mol. 2013. “Soil Erosion From Agriculture and Mining: A Threat to Tropical Stream Ecosystems.” *Agriculture (Switzerland)* 3: 660–683.

Werner, T. T., P. M. Bach, M. Yellishetty, et al. 2020. “A Geospatial Database for Effective Mine Rehabilitation in Australia.” *Minerals* 10: 745.

Wiener, J. G., and T. H. Suchanek. 2008. “The Basis for Ecotoxicological Concern in Aquatic Ecosystems Contaminated by Historical Mercury Mining.” *Ecological Applications* 18: A3–A11.

Young, R. E., G. D. Gann, B. Walder, et al. 2022. “International Principles and Standards for the Ecological Restoration and Recovery of Mine Sites.” *Restoration Ecology* 30: e13771.

Zamotaev, I. V., I. V. Ivanov, P. V. Mikheev, and V. P. Belobrov. 2017. “Transformation and Contamination of Soils in Iron Ore Mining Areas (a Review).” *Eurasian Soil Science* 50: 359–372.

Zipper, C. E., and J. Skousen. 2021. “Coal’s Legacy in Appalachia: Lands, Waters, and People.” *Extractive Industries and Society* 8: 100990.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplementary Materials: conl70000-sup-0001-SuppMat.pdf