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Mining and biodiversity: key issues and research needs in conservation science

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Mining poses serious and highly specific threats to biodiversity. However, mining can also be a means for financing alternative livelihood paths that, over the long-term, may prevent biodiversity loss. Complex and controversial issues associated with mining and biodiversity conservation are often simplified within a narrow frame oriented towards the negative impacts of mining at the site of extraction, rather than posed as a series of challenges for the conservation science community to embrace. Here, we synthesize core issues that, if better understood, may ensure coexistence between mining and conservation agendas. We illustrate how mining impacts biodiversity through diverse pathways and across spatial scales. We argue that traditional, site-based conservation approaches will have limited effect in preventing biodiversity loss against an increasing mining footprint, but opportunities to improve outcomes (e.g. through long-term strategic assessment and planning) do exist. While future mineral supply is uncertain, projections suggest demand will grow for many metals and shift mining operations towards more dispersed and biodiverse areas. Initiating dialogue between mining companies, policy-makers and conservation organizations is urgent, given the suite of international agendas simultaneously requiring more minerals but less biodiversity loss.

1. Introduction

The United Nation's Sustainable Development Goals (SDGs), alongside the Convention for Biological Diversity's 2020 Strategic Plan, lay out an ambitious conservation agenda [1,2]. Achieving these goals (i.e. SDG 14, 15; Aichi targets) will require coordination among multiple stakeholders, including conservation scientists, industry and cross-sectoral decision-makers, to understand and manage an increasingly diverse, distant and interacting suite of threats to species and ecosystems [3]. Mining is one such threat. Mineral resources exist in all significant biodiversity areas, and conservation priorities [4–6] and tensions between mining and conservation are expected to intensify as human populations grow and technologies advance [7,8]. With this recognition, mainstreaming biodiversity into the energy and mining sectors is now featured as a central agenda item in intra-governmental discussions for a post-2020 Strategic Plan for Biodiversity [9,10].

In many regions, the conservation community cannot achieve biodiversity goals without engaging the mining industry, yet few examples of effective collaboration exist. Mining companies have financial incentive to mitigate biodiversity losses caused by their operations [11–13] and increasingly frame corporate sustainability strategies around achieving SDGs and biodiversity conservation (e.g. [14]), but lack tools, guidance and buy-in from key actors to achieve outcomes effectively [15]. By contrast, conservation organizations have core knowledge about the location of important biodiversity areas [16] and increasingly use planning tools to prioritize action [17], but lack a comprehensive understanding of the scale of mining threats and the full range of potential

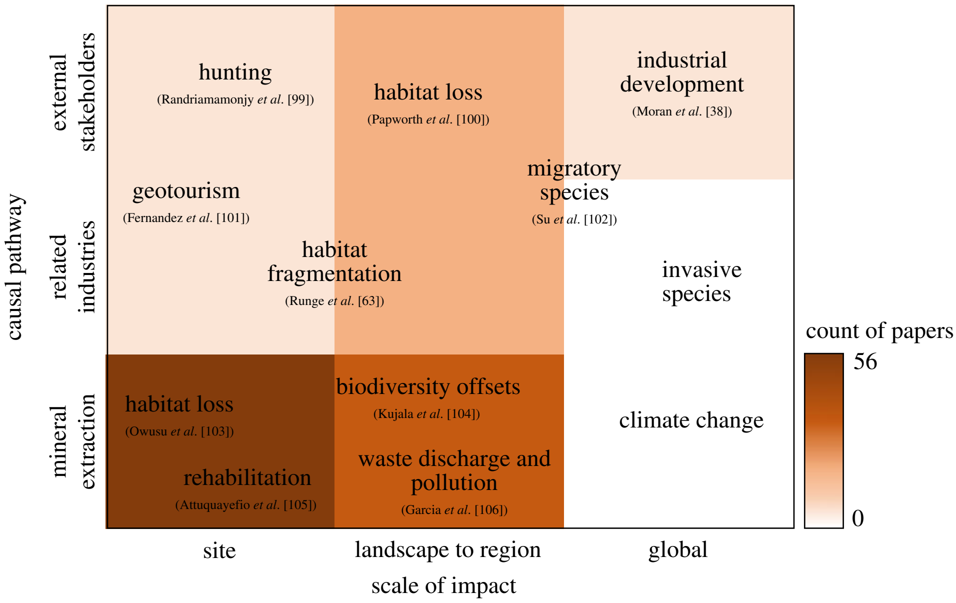

Figure 1. Body of evidence, with examples, of different impacts of mining on biodiversity across spatial scales (site, landscape to region, global) and their causal pathway (defined as either a proximate cause of biodiversity impact related to mining industry, other related industries (e.g. mineral processing or transportation infrastructure) or external stakeholders (i.e. surrounding farmers)). See the electronic supplementary material, S2 for search terms, reviewed papers and analysis methods. See the electronic supplementary material, S3 for references cited as examples.

management options. The scientific literature on mining and biodiversity is also scarce, with less than 1% of papers in leading conservation journals referring to mining-related threats (electronic supplementary material, S1).

This lack of long-term collaboration, coupled with scientific uncertainties, has resulted in a simplification of complex and often controversial issues. Several major fallacies about mining have also emerged in conservation science. For example, mining is often considered to have insignificant consequences for biodiversity relative to other threatening processes (but see [18]); mining companies have little incentive or capability to contribute towards conservation goals (but see [19]); and technological innovation and resource recycling will negate need for mining in the future (but see [7]). At the same time, leaders of mining companies continue to make unsupported statements about their positive environmental impacts (e.g. [20]) and, even when progressing towards sustainable operations, conservation commitments are subject to changes in the financial atmosphere (e.g. [21]). Sudden shifts in environmental priorities cause distrust among conservation organizations because effective biodiversity agendas require long-term commitments.

Our aim here was to synthesize current knowledge of how mining threatens biodiversity and to reveal where future research and engagement could most effectively improve conservation outcomes. Section 2 reviews the mining and conservation literature (electronic supplementary material, S2) to describe the scales to which mining impacts biodiversity. Section 3 illustrates mining-related threats to biodiversity and their uneven distribution among mined materials, ecosystems and regions. Section 4 describes opportunities to overcome conservation challenges across mining regions and §5 discusses future biodiversity threats and conservation opportunities. Section 6 summarizes key issues and remaining research needs. We argue that an improved understanding of the links between mining and biodiversity will contribute towards achieving global conservation goals and lay an essential platform for effective engagement and collaboration.

2. The many ways mining activities impact biodiversity

Mining affects biodiversity at multiple spatial scales (site, landscape, regional and global) through direct (i.e. mineral extraction) and indirect processes (via industries supporting mining operations, and external stakeholders who gain access to biodiversity-rich areas as the result of mining). To date, most research has examined impacts at the site-level, emerging directly owing to habitat loss and degradation (figure 1). This focus is unsurprising, given that site preparation for mine expansion and waste management is a destructive process, changing abiotic and biotic conditions [22–24], and in some cases singlehandedly causing region-wide declines in rare and threatened species and ecosystems [25,26].

Impacts on biodiversity also occur across landscapes and regions (figure 1). Research at this scale has focused on the direct impacts of chemical and physical (i.e. dusts and aerosols) mining waste discharge; chemical emissions include mercury or cyanide used to extract gold [27] and acids are released from oxidized minerals when some ores are exposure to the air [28]. Negative impacts to biodiversity occur over great distances (e.g. sediment export from Madre de Dios in Peru degrades ecosystems along connecting rivers in Brazil [22]) and leave only tolerant species behind [29]. Landscape and region-wide impacts on biodiversity also emerge through indirect/secondary and cumulative pathways [30]. Indirect impacts occur when mining facilitates additional biodiversity loss. For example, mining associated infrastructure development can attract human populations causing new threats [18] or exacerbate pre-existing threats, such as over-exploitation (e.g. hunting, fishing), invasive species and habitat loss for other land uses [31–34]. Cumulative impacts occur when multiple mines cause more biodiversity loss than the sum of individual mines. These processes and consequences for biodiversity have received little attention in the literature (figure 1).

Impacts of mining are more difficult to assess at the global scale. Mining directly emits carbon, as does associated mineral

processing activities, negatively affecting biodiversity via anthropogenic climate change [34,35]. Mineral supply chains can have extensive, yet often hidden impacts on biodiversity [36]. Although not at the global scale, steel making in Brazil causes extensive habitat loss in the sourcing of non-mineral resources [37]. Other research suggests that supply chains and global trade can have extensive ecological footprints [38]; however, consequences for biodiversity remain largely unknown.

3. Rethinking how we view and map mining threats to biodiversity

Implementing effective conservation strategies to mitigate the impacts of mining on biodiversity requires understanding the distribution of threats. Mined materials (e.g. metals, construction materials, fossil fuels) are unevenly spread across Earth's terrestrial biomes and extraction poses unique threats to their biodiversity (figure 2). For example, copper deposits tend to occur in deserts and xeric shrublands, nickel deposits are frequently mined in tropical and subtropical grasslands and savannahs, and lead deposits occur in boreal forests (figure 2). However, co-occurrence of mined materials and biodiversity does not always translate into a threat; many other factors are likely at play.

Different mining methods pose different threats to biodiversity. Extracting subsurface alluvial gold deposits affects riparian ecosystems [22] and downstream ecosystems dependent on regional hydrology; whereas high-value thermal coal is often associated with prime agricultural land (high-quality soils, flat accessible terrains; [41]) and thus already highly threatened ecosystems. Different materials are also extracted using different techniques with varying consequences for biodiversity. While stone, sand and gravel mining moves most earth, the geochemistry of metal ores (and reagents used to extract and process them) often cause greater chemical emissions than construction materials [42]. Differences also exist between industrial operations and small-scale artisanal mining [22]; large operations can have greater potential for impact but also greater capacity to minimize damage.

Threats by mining differ among species and ecosystems. While positive relationships exist between mineral deposits and plant species richness [6], protected areas [43] and intact areas of high conservation value [44,45], the full consequences of mineral extraction are not well understood. In some cases, mining permanently removes entire ecosystems, particularly where biota have co-evolved with mineral substrates [46]. Such is the case in Brazil, where iron mining removes exceptionally diverse plant communities entirely [47]. In other cases, spatial coincidence between minerals and biodiversity may lead to less significant impacts, because either extraction is infeasible, biodiversity is unaffected by mining, or mining causes less damage than alternative land uses [48]. Little is known about threats in extreme environments, such as mountaintops [24], karsts [49,50], marine systems [51–55] and polar regions [56,57].

Threats to biodiversity are also affected by socio-economic and political context. Some countries have long mining histories and almost complete spatial coincidence between minerals and biodiversity hotspots (e.g. New Caledonia; [58–60]). Others are undergoing mining booms (e.g. African countries, in the Cameroon-Gabon Lowlands, eastern Democratic Republic of Congo Lowlands and the Albertine Rift Mountains; [61]), or experiencing shifts in mined minerals (e.g. lithium in Bolivia; [62]). Existing capital, such as infrastructure to extract, process and transport minerals, and manage potential impacts, can reduce impacts of new mines on biodiversity [63] but if not planned for in a biodiversity-friendly manner, may also cause an additional impact. Mineral governance is another key factor. Emerging economies (particularly those with high proportions of world's rare earths) often have weak governance [7] in terms of environmental regulations and environment capabilities, and are prone to corruption and conflict, which can further exacerbate threatening processes [64–66].

4. Opportunities for overcoming biodiversity conservation challenges in mining regions

Sensible conservation strategies must first identify biodiversity priorities. A number of frameworks currently exist (e.g. [67]), and the International Union for Conservation of Nature (IUCN) Key Biodiversity Areas standard [16] is a globally consistent method for identifying conservation areas essential for stemming the loss of biodiversity. With these priorities identified and mapped, and a comprehensive assessment of likely impacts of mining on biodiversity undertaken, long-term strategic management plans can be put in place. These plans should follow the mitigation hierarchy: first by avoiding serious impacts (particularly to conservation priorities), then minimizing harm, before offsetting residual impacts [68].

One major issue with current conservation planning that needs urgent attention is that mining impact assessments do not capture the full extent of mining-related impacts on biodiversity. Regulatory approval of new projects (or expansion of existing projects) frequently only considers the most direct impacts of mining on biodiversity (figure 1), ignoring larger-scale and longer-term consequences, which often interact with other stressors and cumulate over space and time [69]. While spatial prioritization methods are improving the efficiency of decision-making by explicitly considering cumulative impacts of multiple proposed developments on multiple species over large spatial scales [70,71], greater efforts are needed to encompass the full array of impacts mines cause and also to deal with mitigation actions that only partially, or take time to, mitigate impacts.

In some cases, even the most rigorous attempts will not eliminate impacts of mining on biodiversity. Offsets have been proposed as means to address residual impacts and fully compensate biodiversity losses [72]. Biodiversity offsets are measurable conservation outcomes resulting from actions designed to compensate for residual adverse impacts generally (although, not always explicitly) under a 'no net loss' (NNL) paradigm [68]. However, their implementation remains a challenge [73]]. Few studies provide empirical evidence of success (e.g. [74]), and some suggest widespread trade-offs between biodiversity and ecosystem services occur [75]. Many other technical challenges exist to effectively measure losses and gains owing to mining and offsets [76,77], but despite this, offsetting unavoidable losses increasingly occurs as a tool and potential source of revenue for biodiversity conservation [78]. While rapid uptake of compensation policies is encouraging, it remains unclear whether compensatory actions such as offsets adequately contribute to broader biodiversity conservation goals. In part, this is owing to a lack of clarity and consistency about what NNL

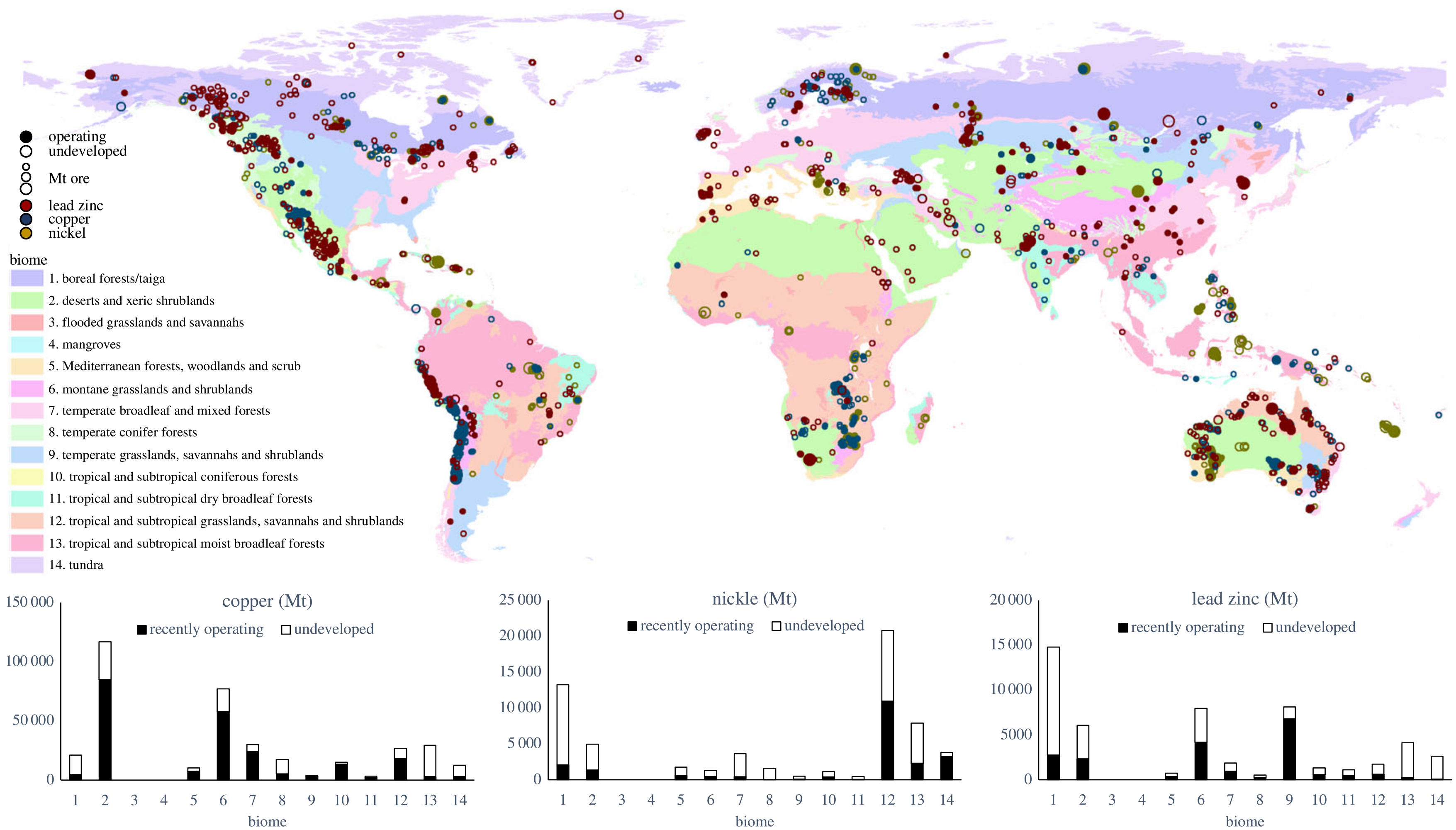

Figure 2. Distribution of operating metal mines and prospecting projects [39] among Earth's terrestrial biomes [40]. Mine symbol colour distinguishes between metals (lead/zinc, copper, nickel) and symbol size depicts reserve size (Mt). The three bar graphs represent each metal tonnage per biome and the biome numbers are found in the key.

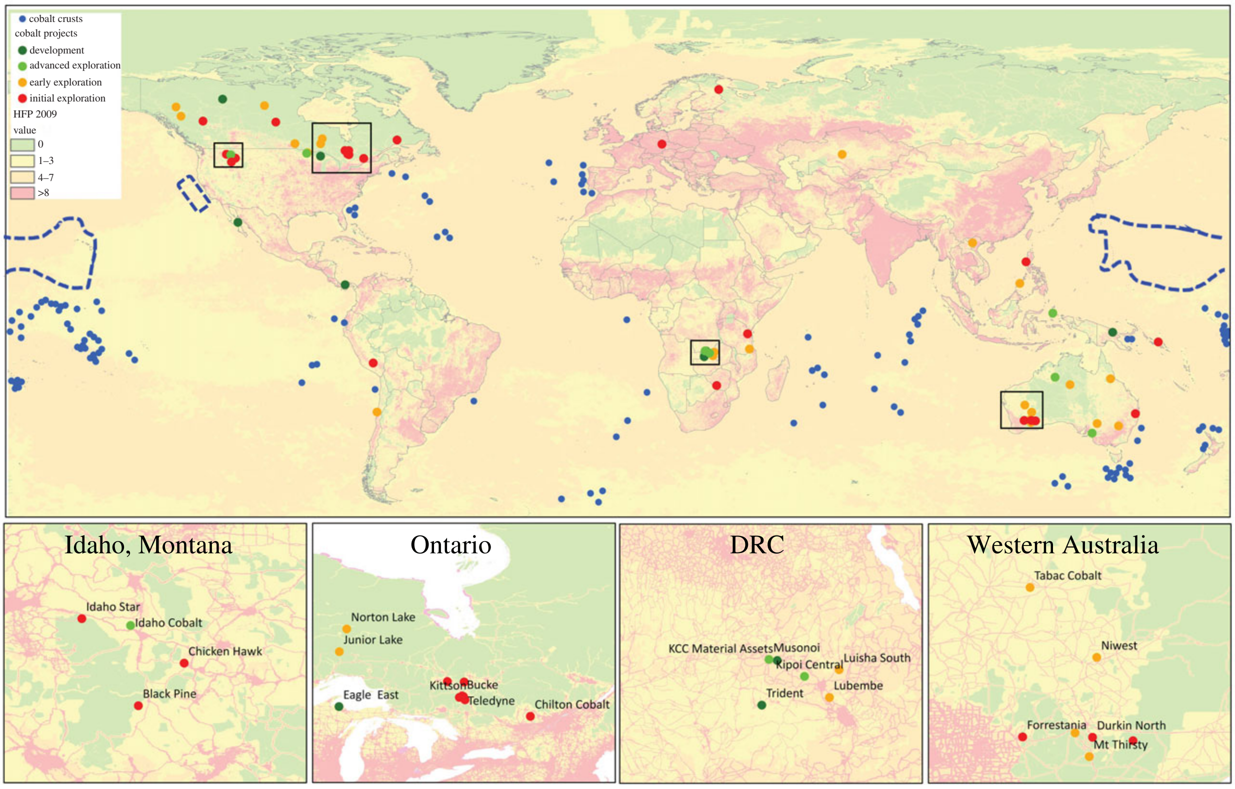

Figure 3. Distribution of a subset of current and future cobalt mines [82] and digitized estimates of marine cobalt crusts [83,84] overlaid with the degree of human footprint (HFP) indicators for terrestrial and marine systems [45,85]. An HFP score of '0' is defined as 'wilderness' with no evidence of significant human influence, low scores (e.g. less than 4) are areas of low human pressure on the environment where higher scores (greater than 7) indicate significant human pressure.

means, how it is calculated, and how it is incorporated into policy. It is critical that these issues are resolved, as poorly designed offsets contribute to biodiversity loss [79].

New mechanisms are emerging to both encourage and enforce effective conservation action, for example, via specific investment and performance standards for lenders and investors (e.g. World Bank, International Finance Corporation (IFC), and regional development banks). While some positive signs via increasingly rigorous standards are being generated by many in the lending sector (e.g. IFC performance standards), it is too early to demonstrate lasting impacts. Further, opportunities exist to use ecosystem services in framing conservation actions in mining regions. For example, the World Bank has worked with conservation organizations to develop the 'Wealth Accounting and Valuation of Ecosystem Services' (WAVES) platform to evaluate comparative return on investment of using natural capital for development options, including mining. When applied to Madagascar's development trajectory in comparing mining and tourism, the platform found that per unit water usage for mining versus tourism was more economically and ecologically efficient [80]. Lessons could be learned from initiatives outside mining, such as supply chains (e.g. Brazil's Soy Moratorium) and certification schemes, which in mining have to date focused on end-products (e.g. ResponsibleSteel™, those listed by Responsible Jewellery Council), rather than extracted minerals.

Given the current magnitude of the biodiversity crisis [81], and the diverse impact humans have on the planet (figure 3), mining must be placed thoughtfully within a wider environmental context. The impacts of mining on biodiversity will obviously differ if it takes place in a very degraded landscape versus wilderness area and the conservation responses across the mitigation hierarchy must vary accordingly. It is increasingly accepted that to ensure the long-term persistence of biodiversity, there is a fundamental need to minimize encroachment of activities that promote habitat loss, degradation and fragmentation [86]. Proactive activities including limiting road expansion [87], reducing negative impacts of hunting through legal controls coupled with sustainable resource use strategies [88], and preventing large-scale developments such forestry, and agriculture following a mining action, are essential in retaining the integrity of ecosystems [89]. Fundamentally, evaluating the full impact on biodiversity at all scales is a critical prerequisite to taking advantage of conservation opportunities. Anticipating and acting on foreseeable development-conservation decisions that will harm biodiversity will ensure effective conservation solutions because the cost of conserving species and communities increases rapidly as they become less widespread and options for their conservation narrow [90].

5. Future of mining and implications for biodiversity conservation

Future changes in mineral supply and demand will probably shift threats towards biodiverse regions and thus magnify conservation requirements. This is partly owing to depletion of higher-grade ores in accessible areas as well as competing economic land uses in non-conservation areas. However, the direction and magnitude of these shifts are highly uncertain. An increase in mineral demand is being driven by population and economic growth trajectories of rapidly industrializing countries where infrastructure investment and manufacturing are key drivers of growth. Nakajima *et al.* [91] mapped global flows of mineral demand for three metals (iron, copper and

nickel) and almost half of the consumption of these metals over the past two decades has occurred in China, the United States and Japan. China has embarked on a very deliberate strategy driven by state-owned enterprises for minerals security through strategic investments and development bargains in Africa and South America. The United States has relied largely on private-sector investment to source the mineral needs of its industries and military and Japan has followed a model of minority holding investments in major mineral deposits worldwide, also facilitated by organizations such as the Japan Oil Gas and Metals Corporation. Thus, biodiversity impact evaluation and management through the demand-driven route of mineral governance is likely to be very fragmented.

The supply side of mineral governance—i.e. the regulation of mineral prospecting, extraction and processing—is largely reliant on national laws for biodiversity protection and for specific countries this can be highly variable in terms of stringency of regulation and enforcement. A convergence of demand-driven leverage from mineral buyers of resources is likely to improve the regulatory stringency and enforcement in supply countries. This is particularly true for countries like the Democratic Republic of Congo, which supply a majority of the world's cobalt and have high biodiversity sensitivity (figure 3). Individual companies have tried to bridge the divide between demand and supply centres by making commitments to not mine in particularly sensitive areas, such as World Heritage Sites. The International Council on Mining and Metals made a commitment in 2003 through its membership of companies to stop mining in World Heritage Sites. In 2016, they reissued a call for all companies to make a commitment in this regard, largely owing to impacts on biodiversity [92]; the effectiveness of such commitments has yet to be quantified, though partnerships with groups such as the IUCN are being developed. Such a recognition of the limits of coexistence of mining and protected areas in some contexts, while the willingness to engage on mitigation measures of impact to allow for coexistence where possible, is a realistic and pragmatic way forward.

Finally, there is also the spectre of technological change affecting relationships between mining and biodiversity. Technology could reduce impacts of extraction through lower land-use impacts such as via *in situ* leaching, while also pose additional threats from chemical pollution. Technology could also provide new opportunities for using biological diversity for mineral extraction through harnessing plant properties for metal accumulation (phytomining). Thus, technological change in the mining sector, and more broadly in mineral supply chains, must be carefully monitored for its potential costs and benefits for biodiversity conservation.

6. Summary of key issues and research needs in conservation science

Relationships between mining and biodiversity are complex and interact with other threatening processes over multiple scales. To effectively manage biodiversity in mining regions, the full extent and distribution of threats must be better understood and incorporated into conservation plans and decision-making. Current research focuses on direct site-level impacts of mining (figure 1); however, knowledge is needed across the full range of scales (figure 1) and from different contexts to understand how these factors affect threats to biodiversity. Here we also highlight three other areas where new understanding and perspectives could create enormous impact.

First, knowledge of which conservation approaches (e.g. national policies, certification schemes, industry performance standards) achieve desired outcomes in mining contexts. To date, only a small number of site-level case studies have investigated benefits (and limitations) of conservation approaches to mitigate negative impacts of mining [19] and opportunities to use an ecosystem services approach to identify ways to align social economic and biodiversity conservation goals [80]. Evidence is needed at other spatial and temporal scales. Opportunities exist to learn from other extractive industries (e.g. forestry, fishing) to determine what works and how this can be applied to mining. For example, problems with supply chain initiatives related to agricultural products [36] may differ in a mining context, given that industry bodies exist and influencing practice in one company may be an effective lever to initiate industry-wide change.

Second, we must understand the role of changing technologies. This includes the effect of how future advances will influence mining threats to biodiversity, and how these advances can be factored into conservation plans and priorities. We expect technology to both create additional threats to biodiversity and provide new conservation opportunities [93]. Engineering advances are improving mineral extraction efficiencies—permitting exploration of previously uneconomical resources and, as a consequence, significantly extending the spatial footprint of mined areas (pits are larger and deeper) [94]. Technologies related to environmentally sound extraction, processing and rehabilitation must also keep pace with increasing ecological vulnerabilities. For example, phytomining and phytoremediation could negate the need for chemically intensive extraction of some metals [95,96]; however, challenges are currently associated with upscaling these technologies.

Third, accounting for the full impact of mining requires sophisticated scenario modelling to capture all possible casual pathways and predict all potential impacts across spatial (figure 1) and temporal scales. This would require mine proposals to account for all related infrastructure, natural resource use and associated changes in human behaviour, and for each of these impacts to be assessed and managed through the mitigation hierarchy. Spatially explicit life cycle analyses may be a useful tool to capture indirect impacts of mining, mineral processing supply chains and trade [97], although data and methodological limitations remain [93]. Land use change models and scenario analyses can predict future threats to biodiversity [98] and investigate potential consequences of policies designed to mitigate these threats [76]. However, such modelling is also highly uncertain (e.g. 5% chance of a tailings dam collapse, 10% chance of major change in the demography of a local community); research into how integrating uncertainty into the mitigation hierarchy will also be valuable. Additionally, because mines are rarely isolated events, regional scale planning will be essential to avoid death by a thousand cuts and exploit efficiency gains [70–72]. This takes scenario planning to a higher integrated, regional level, but will also require explicit dealing of huge uncertainty. Such integrative planning is appropriate in considering SDGs; particularly interplay between Goals 12 (sustainable consumption and production) and 14, 15 (life under water, and life on land, respectively).

Existing international institutions can help deliver funding and impetus to fill these research gaps and, at the same time, could provide clarity on where coexistence between mining and conservation is allowable or achievable versus where conservation is needed exclusively (e.g. [92]). The Convention on Biological Diversity and the Intergovernmental Platform on Biodiversity and Ecosystem Services has thus far given scant attention to this topic, yet these institutions are well positioned to give more attention to mining issues. The International Forum Mining Metals and Sustainable Development (IGF) is likely to become an increasingly important convening platform for countries and industries to consider relationships between mining and biodiversity and help to develop an integrated policy action plan. The high-level political forum on sustainable development (United Nations' group to implement SDGs) future work plans should also consider mining within its goals related to biodiversity conservation. However, to positively impact biodiversity, these high-level efforts must carry through to influence how mining is planned and undertaken on the ground, and ensure dialogue between the mining industry, policy-makers and conservation organizations is productive and aligned.

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