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Current Biology

Article

Global threats of extractive industries to vertebrate biodiversity

Highlights

- 8% of vertebrates have mineral extraction threats (METs)
- Tropics are global hotspots of METs for vertebrates
- Ecological traits that correlate with METs differ among taxa

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In brief

Lamb et al. reveal mineral extraction as a prominent threat to global vertebrate biodiversity, identifying hotspots of risk located pan-tropically and in the Arctic, as well as species' ecological traits, including habitat use, range size, and slow life history, that correlate with the likelihood of mineral extraction threats.

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Global threats of extractive industries to vertebrate biodiversity

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SUMMARY

Mining is a key driver of land-use change and environmental degradation globally, with the variety of mineral extraction methods used impacting biodiversity across scales. We use IUCN Red List threat assessments of all vertebrates to quantify the current biodiversity threat from mineral extraction, map the global hotspots of threatened biodiversity, and investigate the links between species' habitat use and life-history traits and threat from mineral extraction. Nearly 8% (4,642) of vertebrates are assessed as threatened by mineral extraction, especially mining and quarrying, with fish at particularly high risk. The hotspots of mineral extraction-induced threat are pantropical, as well as a large proportion of regional diversity threatened in northern South America, West Africa, and the Arctic. Species using freshwater habitats are particularly at risk, while the effects of other ecological traits vary between taxa. As the industry expands, it is vital that mineral resources in vulnerable biodiversity regions are managed in accordance with sustainable development goals.

INTRODUCTION

Mining is rapidly expanding globally to meet growing demand for metal minerals and construction materials.[1] Mineral and fuel extraction is one of the most lucrative global industries, with a total revenue of US$943 billion in 2022 by the largest 40 companies.[2] The rush to provide society with mined commodities and associated profits means the extractive industry is often the pioneer of threat to remote and biodiverse environments.[3] Between 2000 and 2018, mine exploration or extraction caused 78% (2,398) of global protected area (PA) downgrading, downsizing, or degazettement (PADDD) events,[4] while in sub-Saharan Africa, the number of mines located <10 km from a PA increased by 250% between 2000 and 2018.[5]

Mineral extraction causes a range of direct and indirect threats to biodiversity. Direct impacts include habitat loss and degradation at the extraction sites,[6] whereas indirect threats can impact environments far from extraction sites. Major infrastructural developments can increase the access of human populations to a landscape, catalyzing further habitat degradation and loss, rural development, and increased hunting and trapping of wildlife.[3,7] The land area impacted by indirect threats from mineral extraction could dwarf the area impacted by the direct global footprint of terrestrial mines. Mines have a relatively small direct global footprint (101,583 km^2),[8] yet mining can increase deforestation up to 70 km from mining sites in the Amazon,[9] and pollution from metal mineral mines affects 479,200 km of rivers and 164,000 km^2 of flood plains globally.[10] Thirty-seven percent of the non-Antarctic terrestrial land mass currently lies within 50 km of a mine (50,000,000 km^2),[11] 500 times the area of land directly used for mining. Off-site impacts exist across a variety of industry practices: small-scale artisanal gold mining is the largest source of mercury pollution globally,[12] while sand mining changes riverbed structure and water levels across whole river deltas.[13] In marine environments, oil spills can impact huge areas: 15,000 km^2 of the Gulf of Mexico in the Deep Horizon disaster.[14] The proximity of biodiversity impacts to extraction sites can vary considerably. Meaning, we cannot rely solely on mine locations as a proxy for threat, and investigation into threat from the perspective of species is also required.

Given the sheer spatial scale of potentially impacted land, the variety of impacts, and range in severity of direct and indirect impacts, mineral extraction potentially threatens a significant proportion of global biodiversity, and vulnerability may be linked to species' ecological traits. For instance, large-bodied vertebrates experience severe reductions in abundance in the Amazon and Congo basins where oil roads facilitate hunting within PAs and provide access to markets for bushmeat,[15,16] while oil spillages have caused large-scale mortality of wildlife, particularly seabirds.[14,17] At its most extreme, mining threatens species across their entire range (e.g., Chiku Bent-Toed Gecko *Cyrtodactylus hidupselamanya* by a large limestone quarry).[18] It is currently unknown whether certain taxa or species with particular ecological traits (e.g., large body size)[19,20] are more vulnerable to threats from mineral extraction than others.

To avoid biodiversity loss amid the predicted drastic expansion of the industry, it is vital to understand the extent that biodiversity is currently at risk. We use three main objectives to provide the most-complete global assessment of threat to biodiversity from the extraction of metal minerals, fossil fuels, and construction materials (hereafter referred to as mineral extraction): (1) summarize the number of vertebrates listed as

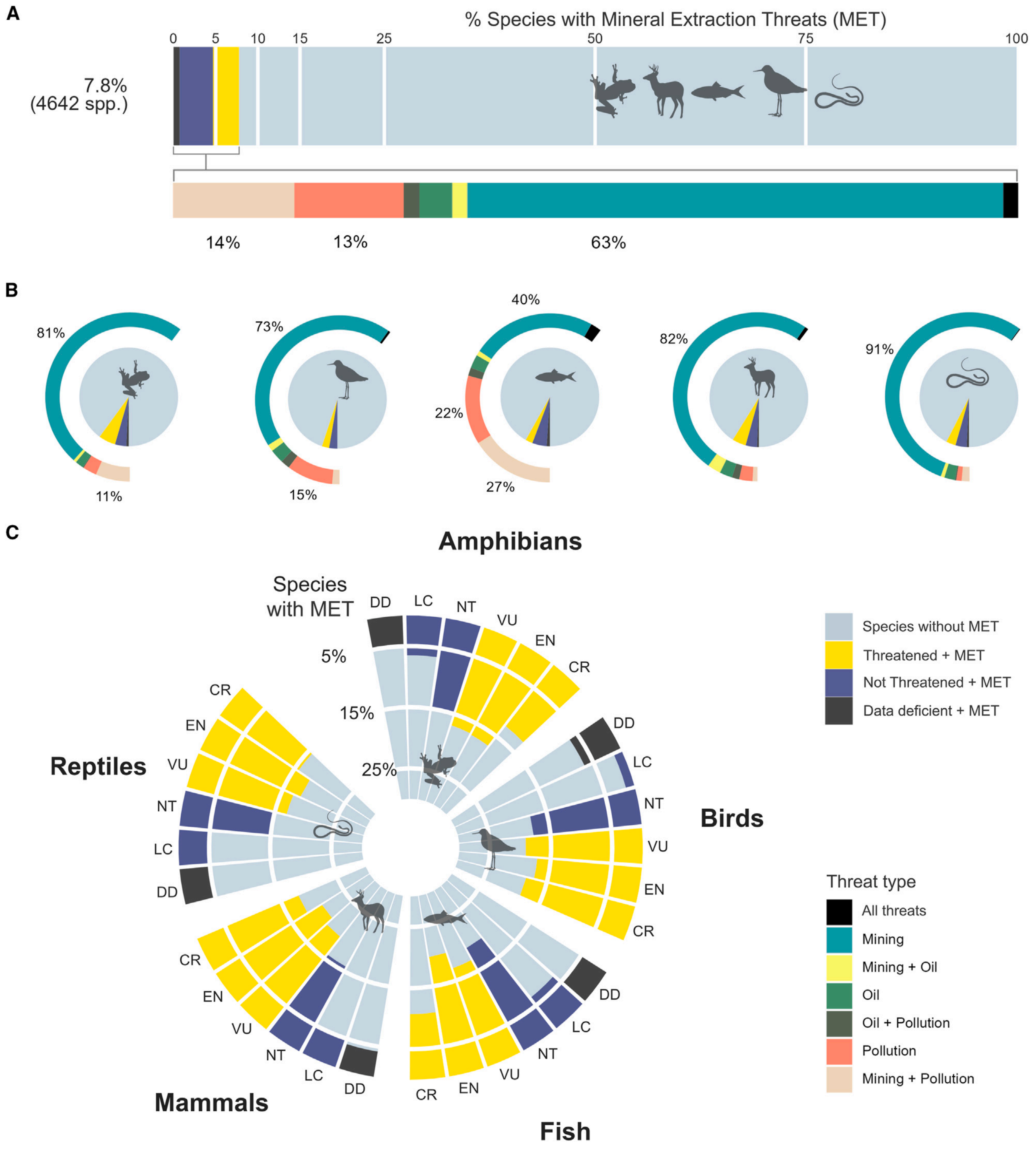

Figure 1. Percentage of vertebrates with METs stratified by taxonomic groups, IUCN Red List threat status, and type of threat

(A) Upper bar shows the percentage of all vertebrate species with MET in combination with whether they are globally threatened (IUCN Red List categories VU, EN, and CR), and the lower bar shows the percentage of species affected by each type of MET.

(B) Inner pies show the percentage of species with METs for each vertebrate group; outer rings the percentage of species affected by each type of MET type for each taxon.

(C) Percentage of species with METs within each IUCN Red List category for each vertebrate group. Threat status: DD, data deficient; LC, least concern; NT, near threatened; VU, vulnerable; EN, endangered; CR, critically endangered. Upper legend (all panels): yellow indicates the percentage of species with METs that are

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threatened by mineral extraction by the IUCN across taxonomic group, IUCN Red List threat category, and different types of mineral extraction threat (MET); (2) analyze the relationship between species' ecological traits and the likelihood of threat from mineral extraction, controlling for the expected effect of species' spatial distributions; and (3) identify where global hotspots of biodiversity threatened by mineral extraction are currently located. We address these critical knowledge gaps by focusing on terrestrial, freshwater, and marine vertebrates (amphibians, birds, fish, mammals, and reptiles) and using the IUCN Red List's species assessments and range maps. Hereafter, "species with METs" describes species with METs in their IUCN assessments, and "threatened" or "Red List threatened" describes species categorized as vulnerable, endangered, or critically endangered by the IUCN.

RESULTS AND DISCUSSION

What type of mineral extraction are vertebrates currently threatened by?

Mineral extraction is recorded as a threat for 4,642 (7.8%) of the 59,803 extant vertebrate species assessed by the IUCN (Figure 1A). Of these species, 3,775 (81%) have mining and quarrying as a threat (category 3.2; mining); 1,000 (22%) have seepage from mining (cat. 9.2.2) and 584 (12%) have oil spills (cat. 9.2.1) (combined into the category "pollution"; Figure 1); and 431 (9%) have oil and gas drilling (cat. 3.1; Figures 1A and 1B). Mining and quarrying are the most common threats for all taxa, with fish commonly having pollution threats. Fish had the highest number of species with METs with 2,053 (8.1% of 25,247), followed by reptiles 764 (7.6% of 10,164), amphibians 747 (10% of 7,448), birds 558 (5.1% of 11,024), and mammals 520 (8.8% of 5,886; Figure 1B). Mineral extraction is thus a potential risk to biodiversity across all vertebrate groups and from all IUCN MET types.

Mineral extraction is a driver of extinction risk across IUCN Red List categories in a broadly consistent pattern between taxa (Figure 1C). Red List threatened categories (vulnerable, endangered, and critically endangered) have the higher percentages of species with METs than least concern or data deficient (Figure 1C). This is especially the case with birds, where only 1.4% of least-concerned species but 18.4% of critically endangered species have METs. Species with high extinction risk also have METs, emphasizing its potential importance as a global threat to biodiversity. The low percentage of data-deficient species with METs likely indicates a lack of current knowledge of their threats; assessment of these species is critical as many of them are likely to be globally threatened.[21,22]

Although, at the class level, vertebrate groups have similar numbers of species with METs, this differs at the order level (Figure S3). Suliriformes (catfish), a large group of mainly freshwater species,[23] exhibit the highest number of fish species with METs (490, 18% of 2,689). Worryingly, catfish also have a high proportion of data-deficient species 25%, suggesting the actual number of species with METs could be larger.[22] Characiformes—a group of tropical freshwater fish[23]—have 324 (22% of 1,427), whereas only 296 (4% of 6,711) Perciformes and 16 (2% of 876) Anguilliformes (eels) have METs. Sphenisciformes (penguins) are particularly susceptible with 12 (66% of 18) species with METs, mainly from oil spills. For mammals, primates have disproportionately high numbers of species with METs (117/552 species; 22%), as do Carnivora (57/297; 19%) and Chiroptera (bats; 166/1,332 species; 12%). Rodenta, the largest mammalian group, have a comparatively low proportion of species with METs 65/2,375 (2%). Forty-five vertebrate orders had no species with METs, the largest being Aulopiforms (lizard fish—marine ray-finned fish)[24] with 282 species, although 20% data deficiency suggests a lack of study and full assessment of the threats they face. This variation in vulnerability to mineral extraction suggests that threat may be correlated to species ecological characteristics, their spatial distribution, or potentially bias within assessments.

Which ecological traits relate to threat?

We find that the likelihood a species has METs varies depending on a species' ecological traits. Habitat use, range size, and slow life history all correlate with the likelihood of having METs for vertebrates, with varying importance for different taxa. Use of marine, desert, and rocky habitats increases the likelihood of threat for birds. Mineral extraction is more likely to be a threat for fish (ray-finned species only; STAR Methods), and amphibians using freshwater and wetland habitats, whereas amphibians using savanna habitats are less likely to have METs (Figure 2A; Table S2). This indicates the extent to which mineral extraction threatens freshwater ecosystems globally, supporting Olden et al.[25] that freshwater fish have comparatively high levels of extinction risk. Mineral extraction can impact watercourses in numerous ways and a variety of scales, including mercury pollution from artisanal gold mining,[12] bioaccumulation of selenium from coal mining,[26] and changing patterns of flow and hydrological structures of watercourses and wetlands.[13] Impact mitigation efforts should consider these as focal habitats, evaluating restoration possibilities after operations have ceased.[10] They should also assess the cumulative risks of mineral extraction in a holistic way; for example, high volumes of oil transport within ranges of vulnerable marine birds cause increased risk of chronic oil spill.[27]

Range size is an important variable for birds and fish (Figures 2B and 2E; Table S2) and, to a lesser extent, reptiles and mammals (Figures 2D and 2C; Table S2), all revealing a negative relationship between range size and the probability of having METs. Range size is a driver of extinction risk in vertebrates,[28–31] and the IUCN Red List category can be determined by global range size.[32] Species with small range sizes may be more sensitive to disturbance from mineral extraction because impacts are likely to occur over a larger proportion of their ranges. This leaves global

also globally threatened and dark blue indicates the percentagebop21ipl of species with METs that are not globally threatened (IUCN threat categories LC and NT); lower legend (A and B): species with METs (across all IUCN categories) are grouped into three threat types: mining (threat 3.2); oil (threat 3.1); and pollution (threat 9.2.1 and 9.2.2).
See also Figure S3.

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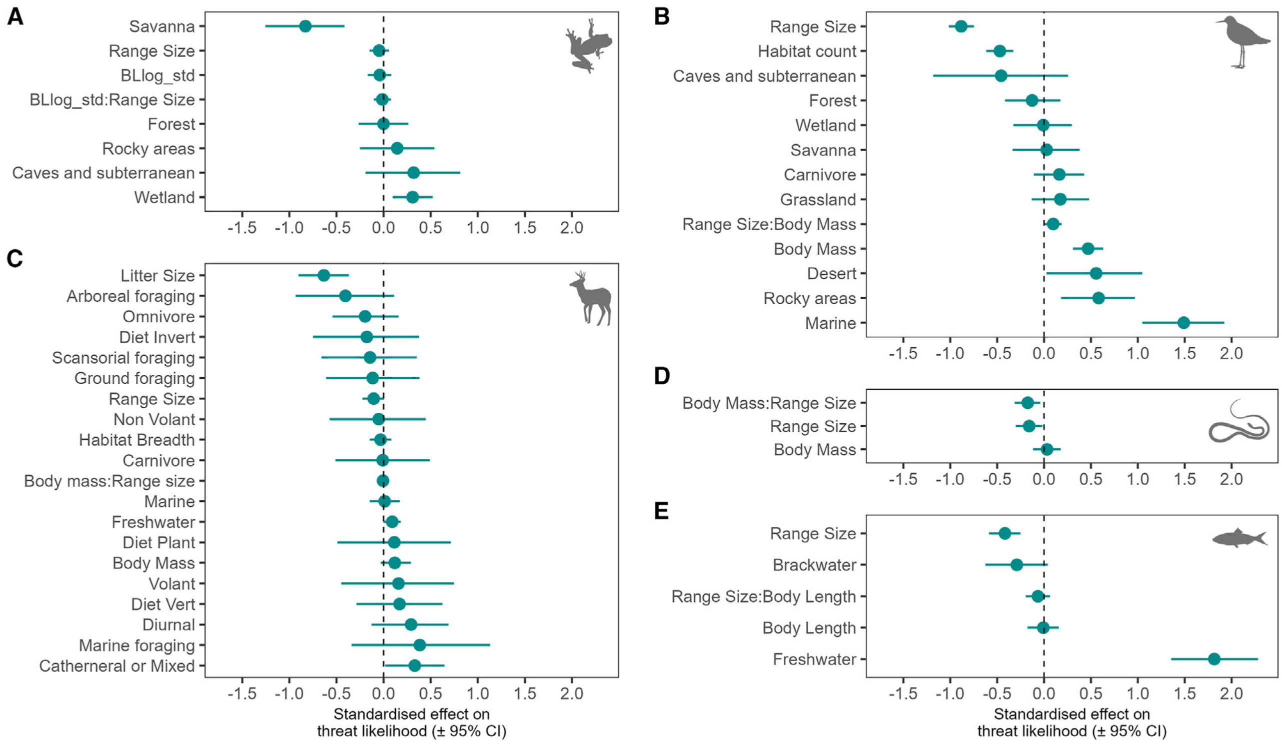

Figure 2. Effect size of ecological traits on the likelihood of a species having METs

(A) Amphibians, (B) birds, (C) mammals, (D) reptiles, and (E) fish. Effects are given as point estimates and 95% credible intervals. We interpret effects with a 95% credible interval overlapping 0 as having no clear directional effect. All trait values are standardized or binomial. Note: the effects of the interactions between mammal diet variables were omitted from (C) for clarity but can be found in Table S2.

See also Figure S2 and Tables S1, S2, S3, and S4.

regions of high endemism vulnerable to increased biodiversity losses.[3]

Few life-history traits are associated with threat from mineral extraction, and the traits with clear correlations with the likelihood of METs vary across taxa (Figure 2). For birds, threat from mineral extraction is negatively associated with habitat breadth, meaning specialists are more likely have METs than generalists, and body mass—which was also positively correlated with generation length (Pearson correlation coefficient = 0.63)—is positively associated with threat from mineral extraction (Figure 2B). Mammals with smaller litter sizes are more likely to have METs (Figure 2C; Table S2; only mammals and birds had sufficient litter/clutch size data for inclusion in analysis). Litter size and generation length both limit population growth rate and, thus, the ability of populations to adapt to and recover from impacts.[33] The interaction of body size and range size also has a positive effect for birds: larger-bodied species with small range sizes are more likely to have MET (Figure 2; Table S2). This again points to the risks that mineral extraction poses to species with small ranges and large body size.[19,20,32] Species with ecological traits that we have highlighted may need special conservation attention to manage the threats and potential impacts of mineral extraction.

Extinction risk from mineral extraction appears to be strongly affected by geographical location as well as ecological traits. The inclusion of a spatial proximity matrix (distance of a species to all other species) improved all models' predictive accuracy (Table S1), indicating that MET tends to be spatially clustered and a species is more likely to have METs if nearby species have METs. Therefore, the associations we see between traits and threat from mineral extraction occur while accounting for the likelihood that species in similar locations will have similar traits[34] and similar exposure to mineral extraction impacts.

The IUCN currently uses phylogenetic proximity to infer threat by currently unconfirmed drivers of risk. For example, species can by listed as having chytridiomycosis as a threat because other species within the same genus have said threat (*Plectrohyla acanthodes*)[35] or likely collection for food due to exploitation of closely related species (*Conraua alleni*).[36] The inclusion of spatial terms in future modeling of extinction risk from mineral extraction also needs to be considered. Additionally, better trait data (coverage across species and other traits, e.g., trophic level, breeding traits, and foraging activity) and mining characteristics would allow more nuanced analysis of the impacts of specific components of mineral extraction on biodiversity. Differences in species' ecological traits can increase extinction risk from many forms of human encroachment. For example, small-ranged birds are especially vulnerable to historic land-use change,[30] and highly specialized reptiles are more at risk to climate change.[28] MET is a broad term that encompasses a great variety of potential impacts to species that range multiple scales of operation and severities of disturbance. There are undoubtably more intricate relationships between species traits and specific mineral extraction

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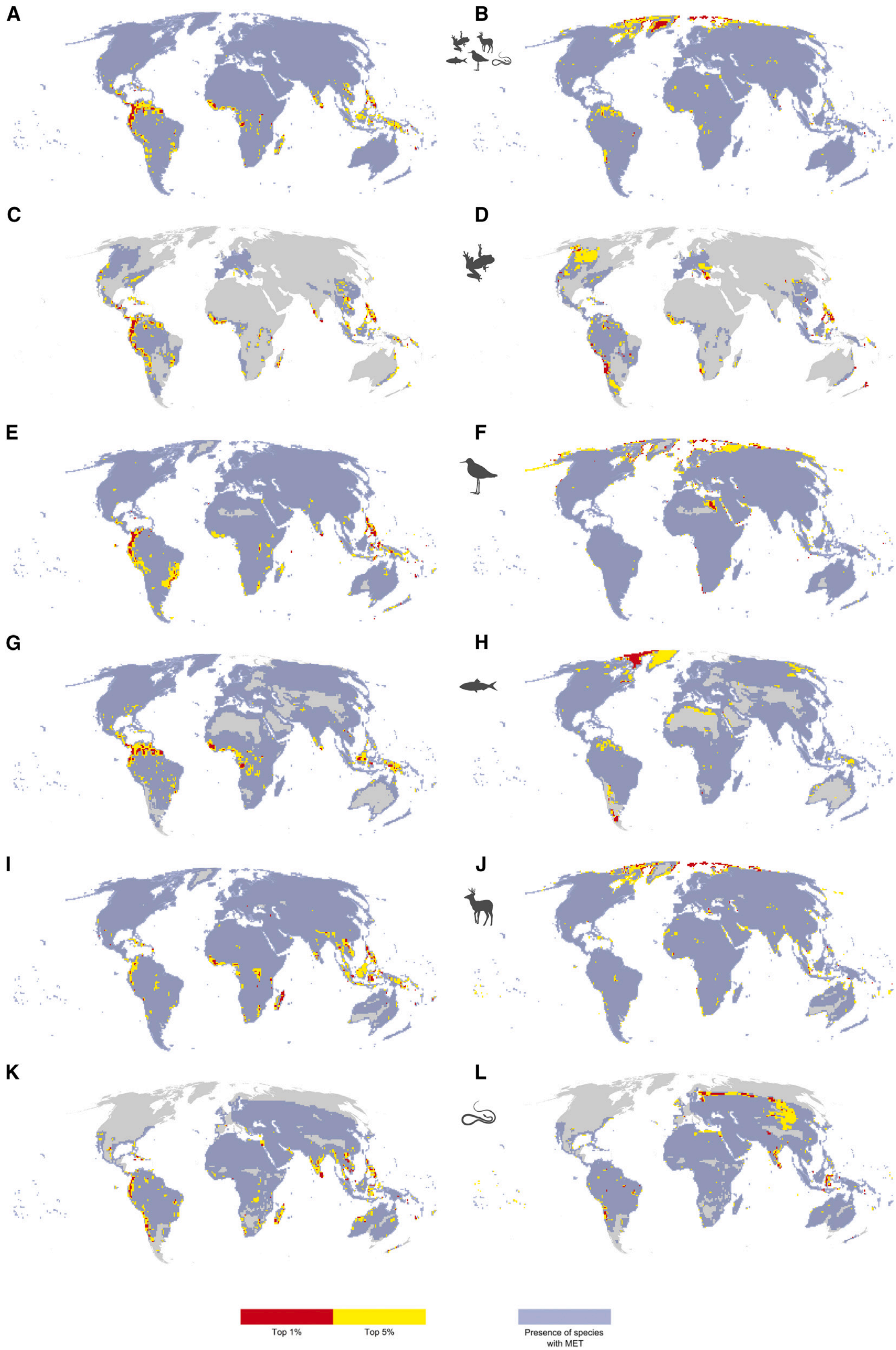

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activities that are not captured within our analysis but worthy of further investigation.

Current global hotspots of biodiversity with METs

Across all vertebrate groups, we uncovered a pantropical concentration of threat to species from mineral extraction (Figure 3A), particularly in the montane tropics, tropical Africa, and tropical islands. Hotspots of species with METs are the Andes, coastal West and Central Africa, and Southeast Asia (Figure 3A). Islands including Sri Lanka, Madagascar, New Caledonia, Davao and Palawan (Philippines), Papua, Jamaica, and Cuba are also regions of high levels of threat to biodiversity. Pixels with the highest threat values from all terrestrial environments occur in Sri Lanka, New Caledonia, Central Sulawesi (Indonesia), and the Colombian states of Valle del Cauca and Choco (Figure S4). Reanalysis to compare hotspots of species with METs to spatial location of mines[8]—which maps the direct impacts of the mine footprint but not wider-scale indirect impacts—reveals co-occurrence of high mine density in these areas (Figure S1). Areas of high levels of threat from mineral extraction overlap with many of the world's most valuable biodiversity hotspots, containing a hyperdiversity of species, high endemism, and unique habitats.[37,38] This contributes toward and potentially catalyzes the intense human impacts occurring in these regions of highest conservation priority.[9]

Hotspots of species with METs vary between taxa. The Atlantic Forest in Brazil is a hotspot for birds (Figure 3E) and amphibians (Figure 3C). The Congo basin, Central America, northern South America, Borneo, and Papua are hotspots for fish. Madagascar and areas of Indochina are hotspots for reptiles and mammals (Figures 3K and 3I), with reptiles also highly threatened across the Atacama Desert and Chilean Andes (Figure 3K). Due to current data coverage, we focus on species with MET without indication of the severity of impact. Reanalysis of birds, the only taxa with sufficient impact coverage, highlight similar regions of high impact to those with high threat (Figures S4N and S4O).

Variation between taxa is likely driven by three main interlinked effects: (1) spatial variation in mineral extraction methods and mine characteristics (e.g., open cut mining, underground mining, alluvial mining, tailing pond, commodities, mine footprint, etc.)[39] and thus threats,[7] combined with (2) variation in species' responses to extraction methods and characteristics[40] and/or (3) variation in hotspots of underlying species diversity and endemism.[19] For example, coal mining causes extensive deforestation in East Kalimantan, Indonesia,[41] a global hotspot of threatened and endemic mammals,[42,43] artisanal small-scale alluvial gold mining (ASGM) in Ghana threatens important bird areas through environmental mercury pollution compounded by high deforestation pressure for farming,[44–46] while amphibians are sensitive to the loss of complex habitat structures due to historic copper mining and smelting areas in Canada.[40] Addressing conservation issues at a regional level relies on effective impact assessments that reveal how each species group responds to different extraction methods and mine characteristics.

All threat values for vertebrates and individual taxonomic groups were positively correlated with the underlying diversity of species weighted by range size—their maximum potential threat values (STAR Methods) (amphibians, rho = 0.569, n = 15,721; birds, rho = 0.445, n = 15,721; fish, rho = 0.788, n = 18,112; mammals, rho = 0.688, n = 18,684; reptiles, rho = 0.540, n = 16,202; all vertebrates, rho = 0.853, n = 18,684; p values for all tests were <0.05). Therefore, threat values broadly follow the biogeographical diversity of small-ranged species (Figure S4M). To account for this underlying variation in diversity of small-ranged species, we scaled maps by the maximum potential threat value of each grid cell to generate a community sensitivity score, where the scaled value would be 1 if all species within a cell are threatened by mineral extraction, highlighting areas where a large proportion of community diversity are threatened by mineral extraction (Figure 4). Across all vertebrate groups, northern South America, Chilean Andes, and West Africa remain hotspots (Figure 3B). Within individual taxa, other hotspots were also similar. For example, West Africa for amphibians and mammals (Figures 3D and 3J), Sri Lanka for birds (Figure 3F), the Llanos and Northern Amazons for fish (Figure 3H), and South-Eastern India for reptiles (Figure 3L). Focusing conservation efforts within these regions, where mineral extraction impacts a large proportion of species in their highly diverse communities, may have a disproportionate influence on mitigating the effects of mineral extraction on global biodiversity decline.

There were also substantial differences in hotspots of community sensitivity versus hotpots of richness. Across all vertebrate groups, additional hotspots of community sensitivity highlight much of the Arctic, plus smaller areas of Western China and the Sahara Desert (Figure 3B). Here, individual species have stronger influence on community sensitivity due to low regional species diversity and endemism[47] (Figure S4M). For example, in the Arctic, threatened species including gyrfalcon *Falco rusticolus*, long-tailed duck *Clangula hyemalis*, polar bear *Ursus maritimus*, and reindeer *Rangifer tarandus* have more influence on community sensitivity scores than individual species in regions with greater diversity of smaller-ranged species, potentially leading to areas highlighted as hotspots but where threat may not be occurring across the whole area. Hotspots of community sensitivity, but low species threat, also vary by taxa. For amphibians, mid-west Canada is a large hotspot of community sensitivity (Figure 3D); for reptiles, the Gobi and Atacama deserts and the southern limits of the Eurasian boreal forest (Figure 3L); and for birds, Alaska. Reanalysis comparing hotspots of community sensitivity to global mining footprints[8] indicates little direct impact of mining across these regions (Figure S1B). Further research is needed to understand if species in these regions are especially sensitive to threats and/or indirect extraction

Figure 3. Global hotspots of METs

(A and B) All taxa, (C and D) amphibians, (E and F) birds, (G and H) fish, (I and J) mammals, and (K and L) reptiles. Left column (A, C, E, G, I, and K) are hotspots of threat value, denoting the number of threatened species weighted by range size. Right column (B, D, F, H, J, and L) are hotspots of community sensitivity, denoting threat value as a proportion of the total potential threat value (if all species that occur within that cell have METs, the cell value will be 1). Red cells indicate the top 1% of terrestrial cells, yellow cells indicate the top 5% of cells, and blue cells indicate the presence of a species with METs (threat value >0).
See also Figures S1 and S4.

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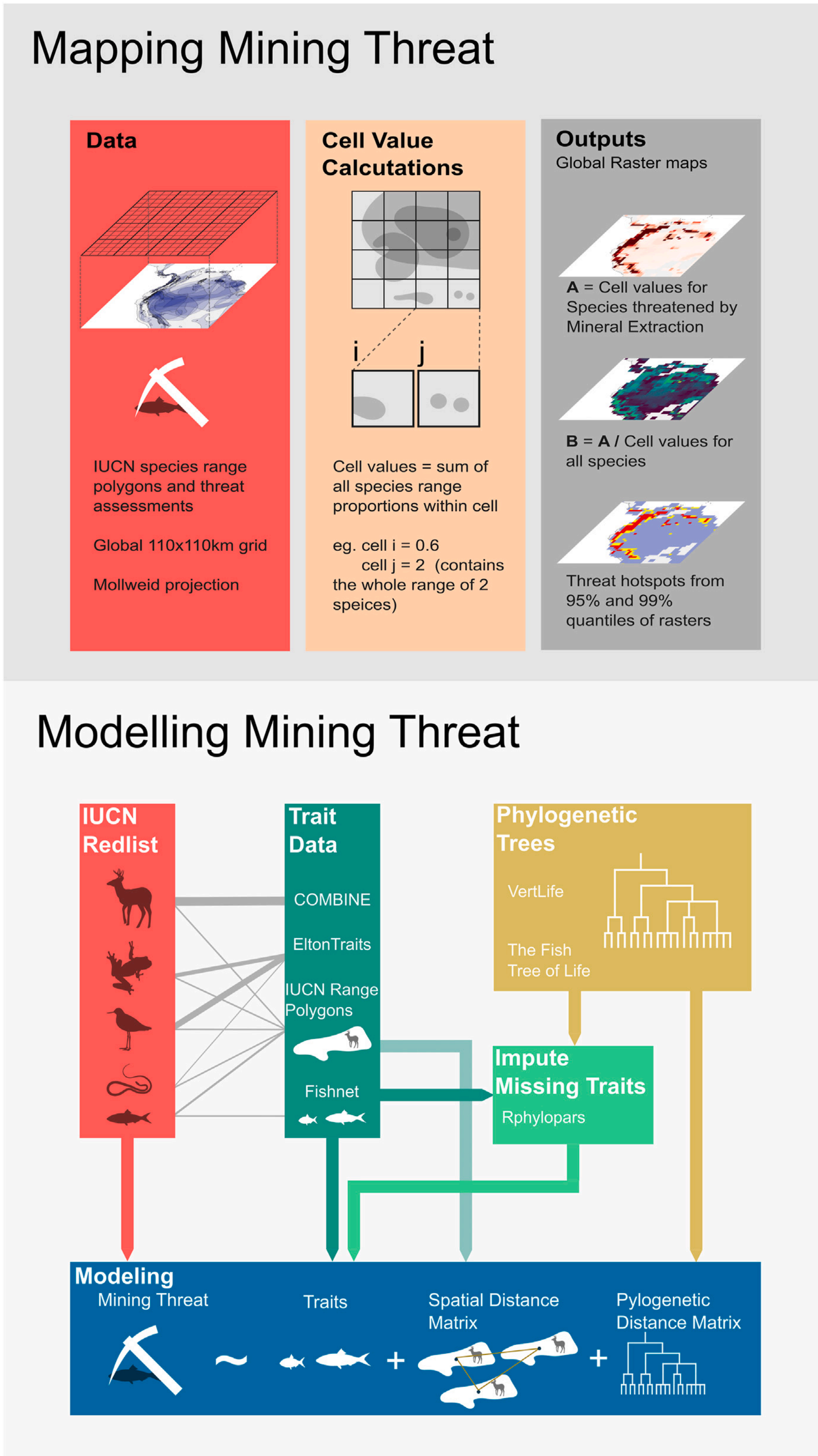

Figure 4. Methods flow schematic of data sources and processing stages

(A) Mapping mineral extraction threats and (B) modeling mineral extraction threats via trait analysis. The thickness of the gray lines between IUCN Red List taxonomic images and trait data sources represent the number of traits used from each data source.

activities in these regions are particularly extensive in their negative effects on biodiversity—affecting large proportions of the community (e.g., oil spills for sea birds).[14,17]

Conclusions and management implications

This study identifies that mineral extraction is a threat to a significant proportion of the world's vertebrate biodiversity, threat is linked to ecological traits of species, and the tropics as a global epicenter for mineral extraction-driven extinction risk across multiple taxonomic groups, pointing to the need for targeted conservation action. Conservation concerns arise in particular from mining activity in areas containing high diversity of small-ranged species,[48] especially montane regions and islands, which are also hotspots of extinction risk via other anthropogenic stressors.[49] Biodiversity risks of mining activity are also high in close proximity to PAs,[11,50] especially given the risks of off-site tropical deforestation.[9,41]

The spatial and ecological variation in mining-induced threat across vertebrate biodiversity suggests a nuanced relationship between threat and the presence of different extraction methods and characteristics. The impact of mines on biodiversity is diverse and span a breadth in intensities, varying according to methods of waste management,[51] active recovery and reclamation efforts (e.g., tree planting and pond creation),[52] infrastructure,[9] and commodities[53] specific to extraction sites, or simply the size of operation in relation to species' available habitat. For example, birds are highly threatened across the iron quadrangle region of Brazil, where endemic mountain top species have a median 27% of their range within 5 km of mines.[54] Because we do not identify precise locations of extraction-induced threat, in some areas we will overestimate potential risks (Figure S1B). Although we do overcome some of this uncertainty by weighting our threat values by species range size, which generates more confidence of where small-ranged species (versus a large-ranged species) are threatened. The categoric threat-assessment data we use from IUCN is limited in describing the detail of threats caused by extraction. For example, species with mining and quarrying (threat 3.2) encompasses those threatened by ASGM through to large open pit copper mines, with no more details threat categories available in the IUCN threat structures.[55] Further analysis investigating how different extraction methods, mine sizes, extracted commodities, and longevity impact on biodiversity is vital for informing future mine developments and conservation planning.

Changing trends in the industry could also influence biodiversity impacts. For example, reduced-impact extraction methods[56] or increased deep-sea nodule mining could reduce the pressure caused by terrestrial mining and its secondary impacts, but there will be as-yet unknown threats to marine biodiversity.[57] It is vital that currently unexploited areas of high vulnerability[3] are not opened to impacts from secondary threats that follow the infrastructure developments of mineral projects, including deforestation[9] and hunting pressure.[58] If unregulated expansion occurs in high-risk regions, especially the hyperdiverse tropics, then the extensive threats of mineral extraction will likely increase extinction pressures to biodiversity. We based our assessments of risk on the IUCN Red List, which may underestimate threat from mineral extraction. This is because the indirect threats from mineral extraction, such as off-site forest loss and life-cycle impacts (e.g., failings of tailing storage facilities), are often not captured within the assessment process since these indirect threats of mineral extraction require extensive analysis[9,10,41] combined with ambiguous categorization of threats within the assessment process—whereby threats from mining infrastructure such as forest loss may not result in mining being included in the species assessment as a threat at all.[55,59] Additionally, species imminently threatened by planned mineral extraction or exploration are not assessed as threatened,[59] and some data-deficient species that lack formal assessment are likely to be threatened due to their smaller range and population sizes.[22]

The resources and power held by the mineral extraction industry have potential to drive expansion in ecologically important areas and impact regions we highlight as vulnerable. Extraction corporations have access to vast initial capital, meaning they can build necessary infrastructures and attract migrant workforces into remote areas, especially for highly profitable metallic minerals.[60] The power asymmetry between corporations versus governments and other stakeholders in lower-income countries means they can negotiate unfair deals (sometimes via corruption)[61,62] without proper compensation for damage to ecosystems and biodiversity,[63,64] including development within PAs (i.e., PADDD)[4] and areas of high biodiversity value.[3] The development of new mines within western nations, which may have lower biodiversity risks, stricter enforcement, etc., could subvert many of these issues, but this is often opposed,[65] thus externalizing development to biodiverse tropical regions. Although tropical mines can still face strong local resistance, oppression of communities is often greater.[65] For instance, European demand for lithium could be partially met by expansion of mining within Europe, reducing pressure to expand operations in Chile and China,[66] areas that we highlight as conservation concerns.

The mineral extraction industry faces many challenges, and if left unchecked, mineral expansion may continue to cause major direct and indirect threats to biodiversity. Expansion of mineral extraction is necessary for the drastic transition to renewable energy sources,[67] but mineral resources are decreasing in grade, producing more waste for the same quantity of resource.[68] The industry is also required to reduced fossil fuel use, meet rising global demands through population growth and development, and reduce its impact on the environment and biodiversity. Policy must focus on creating more circular economies, increasing material recycling and reuse.[69] Where new mineral extraction is unavoidable, rebalancing power dynamics through supporting governments in spatial planning, legislation, and enforcement are important steps.[60,63] Sustainable development licenses to operate (SDLO) could improve industry transparency and hold companies accountable to international sustainable development goals (SDGs)—including those linked to biodiversity and habitat protection within hotspots of risk. The collaboration of corporations, governments, and the conservation community is imperative if we are going to confront these challenges.

Mining companies are motivated to achieve biodiversity goals,[70] using environmental impact assessments, mitigation hierarchy, and biodiversity offsetting.[71] Some of these efforts have been successful at achieving "no-net loss,"[71] but social implications of offsetting are complex. Restricting communities use of resource can lead to vulnerable people within the communities suffering the losses of the change, putting SDG 1 (no poverty) and SDG 17 (partnerships for the goals) at risk.[71] Offsets can have beneficial impacts on biodiversity but need to be strictly monitored using stringent and appropriate frameworks as their premise is trading known losses for uncertain gains, and no-net loss can also be hard to demonstrate without use of proxies.[71,72] This presents an important opportunity for the research community and industry to combine efforts in providing detailed impact assessments of the whole life cycle of extraction operations, as well as indirect impacts that result from development. The results we present are a guideline for avoiding development and further impact within known vulnerable areas, as well as a base from which further research can fill the potential gaps in knowledge in terms of what species are threatened that are missing from IUCN assessments and how might species be falling through the gaps.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2024.06.077.

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AUTHOR CONTRIBUTIONS

Conceptualization, I.P.L., M.R.M., R.G.B., S.C.M., and D.P.E.; data curation and formal analysis, I.P.L.; writing – initial draft, I.P.L.; writing – review and editing, I.P.L., M.R.M., R.G.B., and D.P.E.; visualization, I.P.L.; supervision, M.R.M., R.G.B., and D.P.E.

DECLARATION OF INTERESTS

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
R (version. 4.2.2)	The R Foundation	https://www.r-project.org/
R Studio version 2023.06.1+524	RStudio	https://www.rstudio.com/products/rstudio/download/
Additional code	Author's own	https://github.com/ieuanlamb/Mineral_threat_to_biodiv
Other		
IUCN Red List species assessments	IUCN[73]	https://www.iucnredlist.org/search
IUCN species range shape files	IUCN[74]	https://www.iucnredlist.org/resources/spatial-data-download
Birdspecies range shape files	BirdLife International	https://datazone.birdlife.org/species/requestdis
Global terrestrial shapefiles	rnaturalearth[75]	https://CRAN.R-project.org/package=rnaturalearth
COMBINE traits	Soria et al.[76]	https://doi.org/10.1002/ecy.3344
Elton Traits	Etard et al.[77]	https://doi.org/10.1111/geb.13184
Fishbase	Boettiger et al.[78]	https://doi.org/10.1111/j.1095-8649.2012.03464.x
Actinopterygii Phylogeny	Rabosky et al.[79]	https://doi.org/10.1038/s41586-018-0273-1
Amphibian Phylogeny	Jetz and Pyron[80]	https://doi.org/10.1038/s41559-018-0515-5
Bird Phylogeny	Jetz et al.[81]	https://doi.org/10.1038/nature11631
Mammal Phylogeny	Upham et al.[82]	https://doi.org/10.1371/journal.pbio.3000494
Squamate Reptile Phylogeny	Tonini et al.[83]	https://doi.org/10.1016/j.biocon.2016.03.039
Mine footprint spatial polygons	Maus et al.[8]	https://doi.org/10.1594/PANGAEA.942325

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Ieuan Lamb (ilamb1@sheffield.ac.uk).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- All datasets used can be downloaded from the original sources or requested from the respective authors as listed in the key resources table.
- All original code has been deposited in the GitHub repository listed in the key resources table and is publicly available as of the date of publication.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Study site information

We focused on global terrestrial land (excluding antarctica). Spatial data processing was done in R, using Mollweide equal-area projection (ESRI 54009). We used a global grid 110km resolution – including marine areas – then rasterized and clipped all layers to land areas.[75]

METHOD DETAILS

Assessment of mineral extraction threat

We used IUCN species assessments to determine which species have mineral extraction threats (MET)[73]; species that are categorized in one or more of the IUCN threat categories of oil and gas drilling (category 3.1), mining and quarrying (category 3.2), oil spills (category. 9.2.1), or seepage from mining (category 9.2.2). The definitions of threat for these categories are:

- Oil and gas drilling and exploration: Exploring for, developing, and producing petroleum and other liquid hydrocarbons.
- Mining and Quarrying: Exploring for, developing, and producing minerals and rocks.
- Industrial & Military Effluents: Water-borne pollutants from industrial and military sources including mining, energy production, and other resource extraction industries that include nutrients, toxic chemicals and/or sediments. Our analysis included subcategories: Oil spills and Seepage from Mining only.

Species' global threat status

Species' global threat status is also determined by IUCN assessments. Five criteria contribute to a species being categorized as globally threatened – i.e. vulnerable, endangered, or critically endangered, based upon severity of population size reduction, geographic range size, small population size and decline, very small population size, and quantitative analysis indicating extinction probability.[84] IUCN updates the Red List database biannually with assessments for newly described species and reassessment, assessments become out of date after 10 years, and threatened and near threatened species take priority for reassessment, although reassessment frequency also varies among taxonomic group.[85]

Caveats of IUCN and dataset

Our analysis is a current overview of the species assessments conducted by the IUCN, used to guide conservation action and investment globally.[86] The IUCN likely underestimates future threats and the secondary threats that the mineral extraction industry poses to biodiversity and could have underlying biases. Sonter et al.[59] found 36 species of mammal with >30% of their habitat within 10 km of mining sites, many of which were threatened by exploration and potential future mining, yet these were not recognized by IUCN as being threatened by mining and quarrying. Additionally, off-site deforestation indirectly caused by mining occurs in two-thirds of countries across the tropics[41] and, within the Brazilian Amazon, there is significantly higher deforestation up to 70 km from extraction sites.[9] It is unlikely that these effects are captured by IUCN assessments, because in depth data and analyses like this are scarce. Life-cycle impacts of mines are also highly uncertain, due to stochastic events such as oils spills and tailing storage facility failures[10] and can be difficult to assess as threats to species.[7] Furthermore, we are not able to map data deficient species for which no formal assessment has been made and species without range data, yet these are more likely to be threatened due to their smaller range and population sizes.[22] For IUCN to be used in directing global conservation metrics such as STAR (as proposed)[86] it is vital that these potential underestimations are addressed, and threats are correctly recorded.

A major issue with the way that the IUCN categorizes known threats from mineral extraction is the inherently ambiguity for at the assessment process, for example, when the presence of mining facilitates logging (potentially through transport infrastructure), mining may not be listed as a threat despite being the underlying reason logging has become possible.[11] The IUCN's "*Guidance Threat Classification Scheme December 2022*" document[55] states the exposition for threat 3.1 Oil and Gas Drilling as: *"Oil and gas pipelines go into **4.2 Utility & Service Lines**. Oil spills that occur at the drill site should be placed here; those that come from oil tankers or pipelines should go in **4. Transportation & Service Corridors** or in **9.2 Industrial & Military Effluents**, depending on your perspective."* And threat 3.2 Mining and Quarrying as: *"It is a judgement call whether deforestation caused by strip mining should be in this category or in 5.3 Logging & Wood Harvesting – it depends on whether the primary motivation for the deforestation is access to the trees or to the minerals. Sediment or toxic chemical runoff from mining should be placed in 9.2 Industrial & Military Effluents if it is the major threat from a mining operation."* Highlighting the potential for disparity and potential expedition of mineral extraction as a threat to a species in assessments.

Trait data preparation

The species included in our analysis were limited to those with available geographic range data and phylogenetic trees (35598 species). Phylogenies were obtained for Actinopterygii,[79] amphibians,[80] aves,[81] mammals[82] and squamate reptiles.[83]

We compiled a master synonym dataset from IUCN synonyms as well as synonyms from trait datasets,[77] amphiaweb,[87] and *rfishbase* package (4.1.2.),[78] to match names across the trait databases (see KRT), the phylogenetic tree and IUCN assessment data. We cross-referenced the IUCN assessed species with trait data and phylogenetic data. We excluded 6553 species across all vertebrate groups in our trait analysis due to a lack of either species range data, phylogenetic position, or the joining or splitting of species names used in the phylogenetic tree and IUCN names (species list available in Table S4).[22]

Trait data imputation

We imputed 11467 data points for 19 traits across all vertebrate groups using the Rphylopars package,[88] in R. Following guidelines from Johnson et al.[89] and González-del-Pliego et al.[22] we imputed traits with >60% coverage and Pagel's lambda >0.6. The imputations were checked for estimation accuracy using leave-one-out (loo) cross validation by comparing imputed traits to their known values. Imputed traits with a prediction coefficient, P-squared >0.7[90] were accepted. Tables of coverage, lambda, P-squared values are Table S3. For mammals, traits were obtained from the COMBINE dataset[76] where imputation for traits had already been conducted (following the same guidelines for pre-imputation coverage >60%).

For birds, three habitat-use traits (desert, shrubland, savanna), nocturnal diel activity, and habitat breadth had >97% coverage but were not suitable for imputation due to low lambda values. We therefore used two models; one where we removed 121/9143 (1.3%) species in order to include the five additional traits within the models, and the second we removed the five traits and used all 9143 species (Figure S2; Table S2).

We obtained the most comprehensive trait data for birds (17 and 12 traits for main model and the supplementary model respectively), then mammals (9 traits), Amphibians (7 traits), fish (5 traits), Reptiles (2 traits; see Table S2.).

QUANTIFICATION AND STATISTICAL ANALYSIS

Trait analysis

To assess the effect of ecological traits on whether a species is threatened by mineral extraction we used Bayesian logistic linear mixed effects models using the brms package[91] in R (version. 4.2.2).[92] We use group level effects of both phylogenetic and spatial distances (see supplementary methods for the parameter structures of models), as we would expect that species in close spatial and phylogenetic proximity to also have similar likelihood of threat from mineral extraction, as mineral extraction is mainly a spatially specific process and related species are more likely to be vulnerable to the same threats.[34] We model each taxonomic group individually, using the binary response variable: threatened by mineral extraction or not.

Models were fit using weakly informative, non-flat priors: intercept = normal(0,1), Beta = normal(0,0.5), sd = normal(0,1). With four chains run for 1000 warmup and 1000 post-warm up samples per chain. All models were checked for chain convergence and posterior predictive ability. Model parameters are available in the project code.

Mapping threat hotspots

All mapping and calculations were conducted in R.[92] We mapped global hotspots of threat using the species range shapefile data from IUCN.[74] We used a global grid with a Mollweide equal-area projection at a 110 km x 110 km resolution (consistent with similar analytical methods).[93] For each cell, we calculated two threat values. 1) species threat value: the sum of threat certainty values for each species – where threat certainty is the proportion of a species' total range that lies within each individual grid cell (Equation 1). This weighting by species range size accounts for the uncertainty of where a species is actually being threatened by mineral extraction, as the likelihood that a species' mining threat status owes to any particular cell is smaller for a large-ranged species than it is for a small-ranged species. 2) community sensitivity value: species threat values for each cell divided by the total potential threat value for the cell (Equations 2 and 3). For both threat values, the top first and fifth percentile of cells were used to highlight two levels of global hotspots of threat.

$$VT = \sum_{i=1}^{n_t} \frac{W}{T} \quad \text{(Equation 1)}$$

Cell species threat value. Where $n_t$is the total number of species threatened by mineral extraction found within the cell, W is the area of the species' range within the cell, T is the total area of the species' range.

$$VP = \sum_{i=1}^{n} \frac{W}{T} \quad \text{(Equation 2)}$$

Total possible species threat values. Where n is the total number species found within the cell, W is the area of the species' range within the cell, T is the total area of the species' range.

$$CS_i = \frac{VT_i}{VP_i} \quad \text{(Equation 3)}$$

Community sensitivity value. Where i is the individual global grid cell, VT is the cell's species threat value (Equation 1) and VP is the potential threat value for the cell (Equation 2).

When calculating the area overlap of species ranges with the global grid square, bird range polygons were simplified to a 10 km resolution using *sf::st_simplify()* to reduce file sizes and thus computational intensity. Additionally, three species were removed from the analysis due to errors within the geometries Orcinus orca, Megaptera novaeangliae, Eretmochelys imbricata. The impact of these removals is expected to be negligible as they have extremely large global ranges and are marine mammals and turtles. The proportion of terrestrial areas in their ranges is therefore zero or close to zero.

The limitation of this method is that species ranges potentially include areas of unsuitable habitat for the respective species. This means species could contribute to a regions threat score when the species does not actually occur in that area. We believe our weighting by range size will somewhat counter for this but accept it cannot fully account for this issue. The trade-off for this reduced accuracy is the ability to conduct this analysis on across all vertebrates, as Areas of Habitat (AoH) are not currently available for fish and reptiles and using AoH is comparatively extremely computationally intensive.

To spatially compare our hotspots of threat to locations of mining activity (Figure S1) we use the most up to date available data of global mining footprints[8] and recalculated the cell threat values and community sensitivity but only including species with mining related threats: mining and quarrying (3.2) and seepage from mining (9.2.2). Mining polygons were rasterized to a 110 x 110 km grid using Mollweide equal area projections.