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Conservation implications and opportunities of mining activities for terrestrial mammal habitat

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Abstract

Mining companies increasingly commit to a net positive impact on biodiversity. However, assessing the industry's progress toward achieving this goal is limited by knowledge of current mining threats to biodiversity and the relevant opportunities available for them to improve conservation outcomes. Here, we investigate the global exposure of terrestrial mammal habitat to mining activities, revealing the 136 species with >30% of their habitat within 10 km of a mining property or exploration site. One third ($n = 42$) of these species are already threatened with extinction according to the International Union for Conservation of Nature (IUCN), suggesting projected increased demand for minerals may push some species beyond critical thresholds. Moreover, 28% ($n = 33$) of species are Data Deficient, illustrating tangible ways for industry to fill current knowledge gaps. However, large discrepancies between our results and the species currently listed as threatened by mining in the IUCN Red List, suggest other species may be at risk and that conservation tools and analyses based on these data may underestimate the benefits of averting such threats. We recommend ways to better capture mining threats to species within IUCN Red List assessments and discuss how these changes could improve conservation outcomes in mineral-rich areas.

1 | INTRODUCTION

Land use change drives habitat loss and degradation, which has led to global declines in biodiversity (Díaz et al., 2019; Newbold et al., 2015). Mining activities occupy more than 57 thousand square kilometers of Earth's land surface (Maus et al., 2020; Werner et al., 2020) and affect land use and ecosystems far beyond this immediate footprint (Bebbington et al., 2018; Sonter et al., 2017). Habitat loss caused by a single mine can negatively affect multiple species—sometimes threatening extinction to habitat specialists and those with narrow ranges (Sigwart et al., 2019). Cumulative impacts of multiple mines and their required infrastructure can affect habitat for other species and pose significant threats even to those that were once wide ranging (Johnson et al., 2020). Species with habitat at risk of mining may be ecologically linked to their underlying geology (Erskine et al., 2012; Jaffé et al., 2016), or simply occur in mineral-rich landscapes by chance, but suffer consequences of land clearing to extract, process, and transport materials (Edwards et al., 2014).

Managing land use impacts on biodiversity is central to achieving the United Nations Sustainable Development Goals (United Nations, 2015) and the Convention on Biological Diversity's post-2020 mission to prevent species extinctions and reverse population declines (UNEP, 2021). Mitigating negative impacts of mining is also now a policy requirement in many countries (Bull & Strange, 2018) and achieving a net positive impact on biodiversity is an increasingly common commitment made by mining companies seeking project finance (IFC, 2012) and membership to leading industry bodies (ICMM, 2020). Designing effective conservation, restoration, and impact mitigation plans requires a comprehensive understanding of mining threats to biodiversity (Sonter et al., 2018). Past work has examined fossil fuel extraction risks to biodiverse sites (Harfoot et al., 2018) and spatial coincidence between mines and biodiversity conservation priorities (Edwards et al., 2014; Sonter et al., 2020). Yet, none has examined potential consequences of global mining activities on specific species habitat—a major gap to understanding mining risks and opportunities for industry investment in conservation.

The International Union for Conservation of Nature's (IUCN) Red List of Threatened Species is the globally accepted standard in characterizing the status of, trends in, and threats to, species (IUCN, 2020, 2021). The Red List directly informs conservation actions (Bennun et al., 2018; Mair et al., 2021; Rodrigues et al., 2006) and has influenced mining industry decisions in many nations (Bennun et al., 2018). The Red List has categorized extinction risk for more than 142,500 species as of February 2022 (IUCN, 2021). Of these, 10,511 species are listed as directly threatened by mining and quarrying activities (IUCN, 2012), including 457 species of terrestrial mammals (7% out of 5968 listed extant mammal species; IUCN, 2021). Mammals are one of the best studied taxonomic groups and our focus here, given the direct threats of mining to them via habitat loss and fragmentation and indirect consequences via increased bushmeat hunting and wildlife trade (Edwards et al., 2014).

Given that mining often occurs in remote, data-poor environments and current assessments may not explicitly capture indirect or future mining threats, many more species than those included in Red List assessments may be at risk. Thus, the objective of this study was to use recent advances in spatial assessments of the global mining sector to examine coincidence with habitat for terrestrial mammals. Specifically, we asked: (1) which countries have mining areas overlapping habitats supporting high mammal species richness, (2) which species have large proportions of habitat within mining areas, and (3) how are these species at risk categorized in IUCN Red List assessments? We explore the implications of our findings for conservation practice—both within and beyond the mining sector—and recommend ways to improve industry engagement in achieving an increasingly ambitious post-2020 biodiversity conservation agenda.

2 | METHODS

Our analysis draws on two spatially explicit global datasets. First, we used maps of terrestrial areas potentially influenced by mining activities (Sonter et al., 2020), which were created by mapping 10 km buffers at 1 km^2 resolution around 62,381 known mining properties and mineral exploration sites (SNL, 2018). A 10 km distance was used as a conservative estimate of the direct and indirect effects of mining land use. While the direct (on site) effects vary among mines, a 10 km radius could occupy a substantial proportion of some large mine sites. For example, Werner et al. (2020) mapped 295 metal mines globally and found average mine area to be 12.7 km^2 (~2.0 km radius, assuming a circular mine footprint) but large variation among commodities and countries—ranging from 0.047 km^2 (~0.12 km radius) for a gold mine in the United States to 213 km^2 (~8.2 km radius) for a copper mine in Indonesia. Indirect effects of mining on habitat are caused by offsite infrastructure development or induced land use changes that follow establishment of a mine. These indirect land use changes occur in many mining regions globally (Giljum et al. 2022) and have been shown to occur up to 70 km from large scale metal mines in the Brazilian Amazon (Sonter et al., 2017).

Our analysis used several subsets of the mining maps produced by Sonter et al. (2020). We examined mining areas when only including operational mines and separately for areas that also captured mineral exploration sites and closed and abandoned mines. All three mining activities (exploration, operational and closed/abandoned) potentially threaten species habitat—even exploration activities can have direct and indirect land use effects on biodiversity (Edwards et al., 2014)—but the extent of these impacts will likely differ among them. We also examined the subset of mining areas that contained properties that targeted (as their listed primary commodity) one of the 31 minerals deemed critical for, among other uses, establishing renewable energy infrastructure and energy storage batteries that are necessary to fuel a green energy transition (World Bank, 2020). Comparing the threats to mammal habitat between mines that target energy transition minerals versus mines that produce other resources, such as fossil fuels, illustrates the potential new threats of a green energy transition and thus opportunities to address trade-offs between climate change mitigation and biodiversity conservation.

We compared mining maps to a second spatially explicit dataset of habitat suitability for 5297 terrestrial mammal species (Rondinini et al., 2011). A species' Area of Habitat (AOH) is bounded by its IUCN-identified potential range and modeled using three environmental variables (land cover, hydrological features, and elevation) along with information on species' habitat preferences (Brooks et al., 2019). These maps have been used already to assess broader human pressure influences on mammals (Crooks et al., 2017; Di Marco et al., 2018), and here we use them to examine the specific threats from mining. While mining activities could affect all three environmental variables used to develop AOH models, none of the variables explicitly considered mining; thus, we expected to find overlap between mining and AOH in our analysis (Rondinini et al., 2011). Specifically, we utilized the portion of AOH considered highly suitable (i.e., primary habitat required for a species' persistence), as opposed to habitat of medium or low suitability (Rondinini et al., 2011). To determine the countries with large proportions of mining areas containing habitat supporting high mammal diversity (Question 1), we intersected mining areas for each country with a species richness map, created by stacking AOH maps for all 5297 species at 1 km resolution (Rondinini et al., 2011). To identify mammal species with large proportions of habitat within mining areas (Question 2), we intersected mining maps with highly suitable habitat for each species. We also then identified species with >30% of their habitat extent within mining areas and, for species listed on the IUCN Red List, we investigated their threat status and key threatening process(es) (Question 3).

3 | RESULTS

Almost all mining areas (6.67 million km^2, 99.5% of the total extent), across 161 countries intersected with habitat for at least one mammal species (Figure 1; Table S1). We found the country of Guyana contained mining areas overlapping with habitat suitable for 196 mammal species per 1 km^2—the highest richness value in our data (Figure 1). Some countries had both large mining areas and high mean richness within mining areas, such as Brazil, which ranked 7th for mining area and 11th for mean richness. Other countries had relatively small mining areas but that ranked high in maximum richness values (e.g., Suriname ranked 2nd, French Guiana ranked 5th; Table S1).

We found 4432 species (83% of all species assessed) had some proportion of their habitat within mining areas (Table S2). On average, 6.9% of species' habitat ($n = 5297$) occurred within mining areas, with percent overlap values reaching up to 100% for two Data Deficient species in Papua New Guinea (Figure 2; Table 1). We also found 3766 species (71% of all species assessed) had habitat within operating mining areas, an average

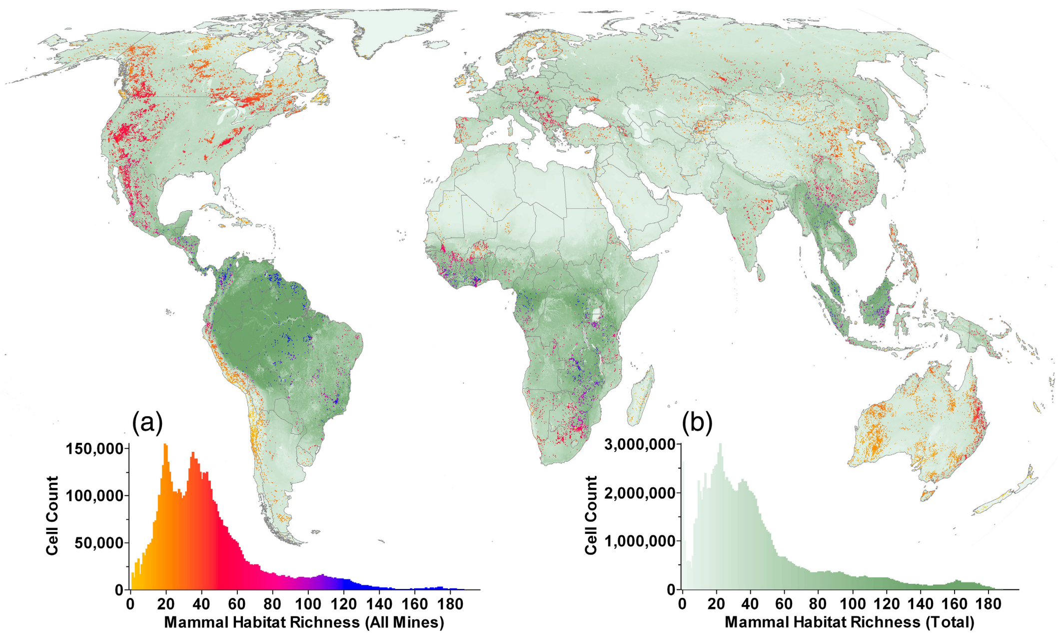

FIGURE 1 Mammal habitat richness (number of species with suitable habitat per 1 km^2) within mining areas (i.e., sites within 10 km of a pre-operational, operational, or closed mining property). Richness values are shown on histograms, which illustrate the distribution of values (a) within mining areas and (b) for all terrestrial land area (within and outside mining areas).

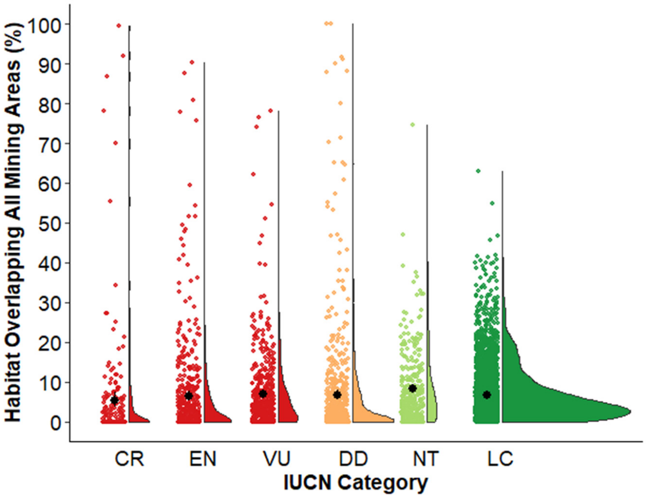

FIGURE 2 Mammal habitat within mining areas across IUCN Red List threat categories (CR = Critically Endangered, EN = Endangered, VU = Vulnerable, DD = Data Deficient, NT = Near Threatened, LC = Least Concerned). Black dots are mean values (±SE) and violin plots illustrate distributions.

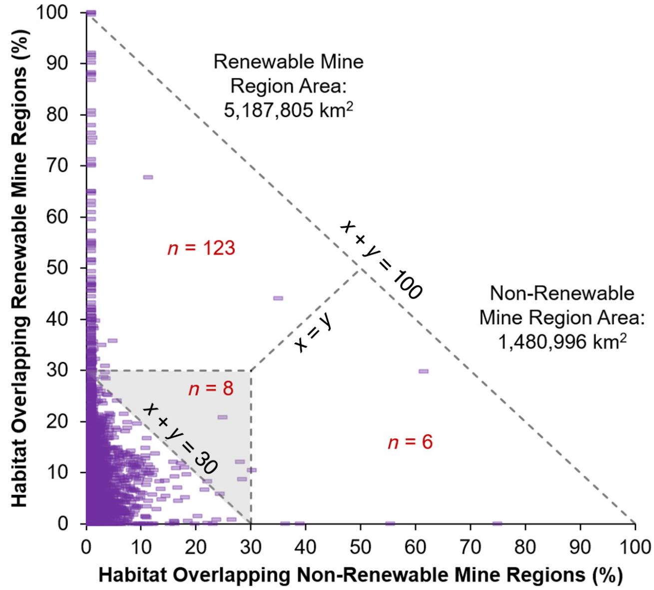

FIGURE 3 Percent of habitat within mining areas for each of the 5297 mammal species analyzed here, separated into those within mining areas targeting the materials needed to deliver renewable energy (y axis) and mining areas targeting other materials (x axis), such as fossil fuels. N on figure adds to 137 because 1 species had >30% habitat within both types of mining regions.

of 2.1% across all species and a maximum of 87% for a critically endangered rodent in Mexico (Figure S1; Table 1).

We found 136 species (2.5% of all species assessed) had >30% of their habitat within mining areas (Figure 3), including 17 species with >30% habitat within operating mining areas (Figure S2; Table S2). These species had an average of 11,588 km^2 of habitat within mining areas (median = 422 km^2, min = 0.36 km^2, max = 185,413 km^2; for operating areas mean = 159 km^2, median = 50 km^2, min = 0.63 km^2, max = 645 km^2). Further, most of the species with >30% within mining areas occurred in areas targeting minerals needed for renewable energy production (Figure 2).

Of the 136 species with >30% of habitat within mining areas, 131 species were listed on the IUCN Red List (Table S2; that is, 5 species were unidentifiable as they underwent a change in taxonomy). Of these species, 32% (n = 42) were listed as Threatened with extinction (i.e., Critically Endangered, Endangered, or Vulnerable), 25% (n = 33) were listed as Data Deficient, and 13% (n = 17) as directly threatened by mining or quarrying (Figure 4). When only considering operational mine, the 17 species with >30% of habitat within mining areas included 35% (n = 6) listed as threatened, 53% (n = 9 species) as Data Deficient, and 35% (n = 6) as directly threatened by mining or quarrying.

4 | DISCUSSION

Our analysis revealed considerable overlap between mining areas and mammal habitat. Almost all land within 10 km of a mining property or mineral exploration site intersected with habitat for at least one mammal species, and 136 species had >30% of their habitat within these mapped mining areas. These results reinforce the need to better understand mining threats to species and act on opportunities to strengthen conservation actions in regions under pressure from mineral demand. The IUCN Red List of Threatened Species is a valuable resource that is used to inform multi-sectoral decisions affecting biodiversity (Bennun et al., 2018; Mair et al., 2021; Rodrigues et al., 2006). However, we found discrepancies emerged between our results and the IUCN Red List assessments in the identification and characterization of mining threats to mammals. Here, we discuss potential reasons for these discrepancies, the implications they pose for biodiversity conservation actions and goal setting (both within and beyond the mining sector), and opportunities to fill current data gaps and move toward a more systematic treatment of mining threats to mammals.

4.1 | Discrepancies between data sets and approaches used to identify mining threats to mammals

Species listed by IUCN Red List as threatened by mining (n = 361) differed from those revealed by our analysis to have >30% of habitat within mining areas (n = 136;

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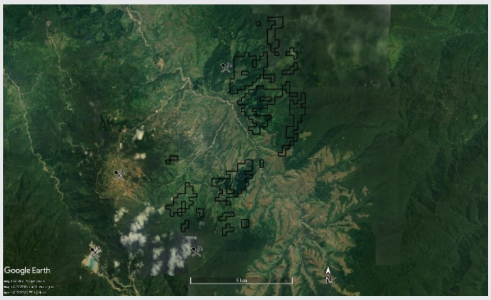
TABLE 1 Selected mammal species with habitat (black polygons depict each species highly suitable habitat area) occurring within mining areas (mining symbols indicate mines or mineral exploration sites)

a. ***Myoictis wavicus*** (Tate's Three-striped Dasyure), Papua New Guinea. Data Deficient; not threatened by mining (Woolley, 2016).

Species has 100% of highly suitable habitat (28.4 km²) within mining area. Includes exploration for gold, silver and copper and operational gold mine (Edie Creek).



b. ***Rattus omichlodes*** (Arianus's Rat), Indonesia. Data Deficient, not threatened by mining (Gerrie & Kennerley, 2017).

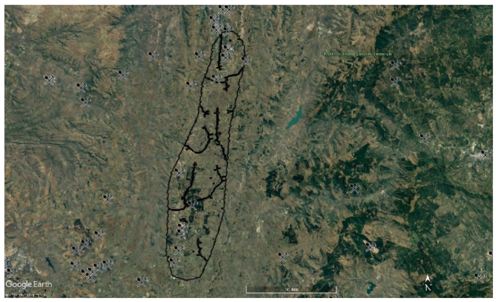
Species has 70% of highly suitable habitat (2.4 km²) within operating mining area. Habitat is adjacent to large operational copper mine.

c. ***Batomys russatus*** (Russet Batomys), Philippines. Endangered; threatened by mining (Kennerley, 2017).

Species has 62% of highly suitable habitat (478 km²) within mining area. Habitat covers almost entire island and thus nearby 14 nickel mines.

d. ***Amblysomus robustus*** (Robust Golden Mole), South Africa. Vulnerable; threatened by mining (Rampartab, 2015).

Species has 45% of highly suitable habitat (1095 km²) within mining areas, including 9 operational mine sites targeting platinum (to north) and coal (to south).

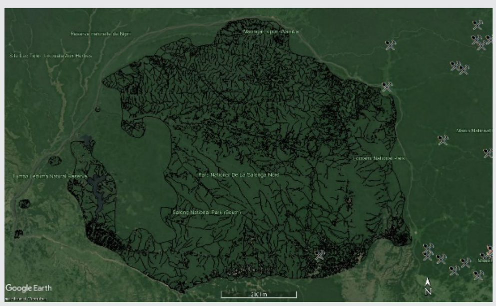


e. ***Habromys schmidlyi*** (Schmidly's Deer Mouse), Mexico. Critically Endangered; not threatened by mining (Álvarez-Castañeda et al., 2018).

Species has 86% of highly suitable habitat (50.5 km²) within mining areas, including operational silver mines.

f. ***Pan paniscus*** (Bonobo), DRC Endangered; threatened by mining (Fruth et al., 2016).

Species has 0.02% of highly suitable habitat (369,008 km²) within mining areas. Large habitat requirement; mining listed as future risk to minority of the population.



Note: Google Earth images often represent a combination of dates. Here, we include the most recent images as of February 2022.

Figure 4). Surprisingly, only 17 species were common to both lists (Table S2). To understand these results and determine whether they represent systematic issues with data and methods, we examined Red List assessment notes for key mammal species.

We found that 72% of tmammals listed by IUCN as threatened by mining had <10% of their habitat within mapped mining areas and 30 species had no overlap whatsoever. In some cases, our data may have been unable to detect the threats identified by Red List assessments. For example, our mining maps ignore small-scale artisanal mining, illegal mining activities, and quarries—all known threats to species, their habitat and biodiversity (e.g., Clements et al., 2006; Siqueira-Gay & Sánchez, 2021).

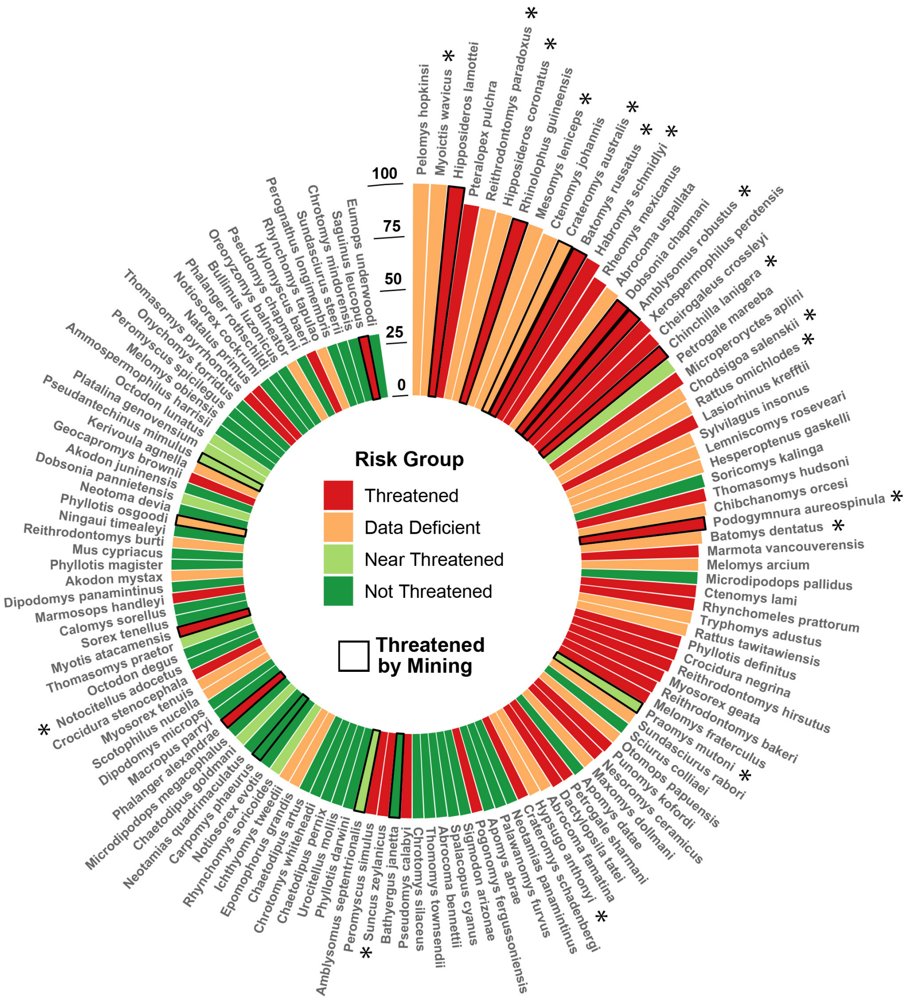


FIGURE 4 Mammal species with >30% habitat within mining areas, color-coded according IUCN Red List categories (Threatened = Critically Endangered, Endangered, and Vulnerable). Asterisks (*) indicates the 17 species that also have >30% habitat within operational mining areas. Black boxes around columns indicate the 17 species listed by IUCN Red List as directly threatened by mining and quarrying. Species are ordered based on proportional overlap (height of the histogram bars) to show that species with greater overlap also trend to be threatened with extinction or data deficient.

This indeed explained the lack of overlap for *Hipposideros hypophyllus*, a critically endangered bat imperiled by illegal granite mining nearby its only known roost (Chakravarty et al., 2016). Threat assessments need to utilize multiple datasets—although many of these do not yet exist at a global scale (Joppa et al., 2016)—along with expert and local knowledge to determine the actions that will most effectively conserve habitat critical for their survival. This is particularly important for artisanal mining, given that their biodiversity losses often go unmitigated and do not always occur nearby large-scale industrial mining (World Bank, 2019).

In other cases, the extent of overlap between mining areas and species habitat measured in our study may be a poor indicator of mining impact. This may be true for species where mining plays only a small role in the cumulative threats to a species. For example, *Pan paniscus*—the Endangered Bonobo from the Democratic Republic of the Congo—was listed as primarily threatened by poaching, residue from civil warfare, habitat loss and alteration (from logging and agriculture), and housing development and disease largely due to human population growth and migration; mining activities were listed to potentially add to these other threats in future (Fruth et al., 2016; Table 1). Further, mining infrastructure (e.g., roads, waste storage and processing facilities) that does not cause extensive direct habitat loss, may contribute to landscape-scale habitat fragmentation. This was particularly true for primate species (Table S2), such as *Aotus miconax* (Shanee et al., 2020), with severely fragmented habitats. These results illustrate the importance of understanding local context in identifying threats and their severity.

We also found 39 Near Threatened and threatened species (Vulnerable, Endangered, or Critically Endangered) with >30% of their habitat within mapped mining areas that were not listed by IUCN as threatened by mining. Most ($n = 36$) of these species had a large proportion of habitat within 10 km of a mineral exploration site, suggesting a lack of consideration of potential current or future mining threats (Joppa et al., 2016). The other three species had >30% habitat within 10 km of an operational mine, including the species with the greatest overlap: *Habromys schmidlyi*, a critically endangered rodent with

86% of its habitat within 10 km of a large silver mine in Mexico (Table 1). *H. schmidlyi* was listed as directly threatened by habitat loss due to Biological Resource Use (logging and wood harvest) (Álvarez-Castañeda et al., 2018) and, while the motivation of this logging and wood harvest was not listed, it is possible some of this land would then be subsiquently utilized for mining. Similar results were found for 11 of the other 20 species with >10% habitat within 10 km of an operational mine site, although the assessment notes for one species (*Atopogale cubana*; Kennerley et al., 2018) did mention mining as a key threat of habitat loss without explicitly listing mining as a threat in the classification.

4.2 | Implications of missing threat data for conservation planning and practice

Many conservation initiatives aiming to assess and manage threats to biodiversity draw on information from the IUCN Red List of Threatened Species. Misclassifying or failing to detect some threats could thus affect conservation actions implemented by multiple stakeholders. One key tool used by industry is the Integrated Biodiversity Assessment Tool (IBAT; UNEP-WCMC 2020). Mining companies and decision makers use this tool to identify biodiversity risks and opportunities within or close to a project boundary. While data deficiencies on species populations and trajectories may affect identification of those species threatened by proposed projects, errors in threat mapping and classification will also influence decisions around conservation actions by companies. In turn, poorly designed mitigation efforts may affect the quality of corporate reports on biodiversity performance—a key benefit of the IBAT tool for business operations.

The recently published Species Threat Abatement and Restoration (STAR) metric also relies on IUCN Red List assessments (Mair et al., 2021). STAR is used by the international conservation community to inform and deliver on conservation targets and goals at different scales and, in 2021, STAR was integrated into the IBAT to allow organizations, such as mining companies, to measure their relative contributions toward reducing species extinction risks. The STAR metric quantifies contributions that abating threats and restoring habitats in specific places offers toward reducing extinction risks, for individual species and across geographies. But for STAR to be effective, it needs to rely on accurate threat information and the relative contribution each threat makes toward species' risk of extinction. Given that mining threats appear to sometimes be missed or misclassified, it is not surprising that recent analyses show the threat of mining is the smallest contributor to aggregated species extinction risk globally (Mair et al., 2021). We argue that capturing the true scale of abatement opportunities will require moving toward a systematic approach to classifying mining threats to species, and several key remaining data gaps in Red List assessments. This will ensure tools like the STAR metric will be utilized to their full potential.

4.3 | A more systematic approach to capture mining threats to species

The IUCN Red List classifies the direct threats to species (IUCN, 2012), defined as "proximate human activities or processes that have caused, are causing, or may cause the destruction, degradation and/or impairment of biodiversity targets" (Salafsky et al., 2008). The scope, severity and timing of each threat is recorded and used to determine remaining knowledge gaps and appropriate conservation actions designed to ensure species persistence. However, only a small proportion of mining threats emerge through direct processes (Sonter et al., 2018) and, as described in the previous section, failing to comprehensively capture the role of mining in threat assessments limits the role these data play in conservation action. Here, we make three recommendations to broaden the treatment of mining threats in Red List assessments, to capture indirect threats and interactions among threats. Threat assessment for some species already implement these recommendations; however, clearer guidance and a more systematic process will help improve conservation outcomes.

Recommendation 1: **Record when current direct threats are driven by future mining operations.** Mineral demand and mining operations indirectly drive other non-mining threats to species through indirect processes. In some cases, other non-mining proximate causes of habitat loss may take place in the lead up to a planned mine development. Vegetation cleared prior to mining, for example, is sometimes harvested for its resource value and this may become a more common practice in future (Annandale et al., 2021). However, it is currently a judgment call as to whether this deforestation and habitat loss be classified as Threat 3.2 'Mining and Quarrying' or Threat 5.3 'Biological Resource Use' (IUCN, 2012). We suggest that both threats be recorded, particularly if their interactions over time will undermine a species recoverability post-mining. This information could either be recorded as the motivation for Threat 5.3, or by simply recording both threats with different timings (Threat 5.3 current/ongoing, Threat 3.2 future).

Recommendation 2: **Capture interactions among multiple current threats.** The operation of mine sites will often be linked to other direct threats to biodiversity. Current guidance is to record the most direct threat

(IUCN, 2012), where, for example, sediment or toxic chemical runoff from mining should be classed as Threat 9.2. 'Industrial and Military Effluents', rather than due to the emergence of the mine itself. Again, as above, we suggest that both threats be recorded, and their interactions noted. Reviewing the 17 mammal species with >30% habitat within mapped mining areas and listed as threatened by mining revealed that all but two species (*Bathyergus janetta; Phyllotis osgoodi*) had more than one threat listed, some of which may indeed be linked; however, none of the assessments explicitly mentioned these potential links. In addition to links among threats already identified in IUCN guidance, many others may exist, such as Threat 7.2. 'Dams & Water Management/Use' (Northey et al., 2016).

Recommendation 3: Consider future threats facilitated by current mines. Mining operations and their associated infrastructure can themselves facilitate future threats to species (Sonter et al., 2018). Some assessments attempt to capture these indirect threats. For example, *Allochrocebus lhoesti* is listed as threatened by mining, given the effect it may have on opening up formerly remote areas to exploration, leading to more habitat loss, bushmeat trade and poaching in the future (Ukizintambara et al., 2019). The current lack of knowledge about when, where and how mining operates as a driver of future land use change may limit operationalizing this recommendation; however, previous research does suggest that mining can facilitate or amplify Threat 1. 'Residential and Commercial Development' (Owen & Kemp, 2017), Threat 2. 'Agriculture and Aquaculture' (Pijpers, 2014), and Threat 5.1. 'Hunting' (Edwards et al., 2014). Thus, we urge threat assessment teams to keep these threats in mind for those species currently listed as threatened by mining and quarrying.

4.4 | Opportunities to overcome remaining data deficiencies

Thirty-three mammal species with habitat exposed to mining activities were listed as Data Deficient (Figures 2 and 4) and some may be at imminent risk of extinction (Bland et al., 2017). Filling these gaps is important for conservation action; without new information, these species may be ignored in environmental impact assessments and thus unknowingly vanish if mining pushes them beyond critical thresholds. This is particularly important for mining threats, given that this threat has the least number of datasets out of any IUCN threat category that are available at an appropriate spatial resolution (Joppa et al., 2016). Generating new spatial data on mining will help fill these gaps; however, other opportunities to engage industry and society exist too.

Our analysis can inform where to target data collection efforts and our results suggest large knowledge gains could be made by a relatively small effort. Collecting data on only 33 species would overcome all known data deficiencies for IUCN listed mammals with >30% habitat within mining areas (Table S2). Given that many of these are dominated by small-bodied mammals, which receive less attention in research and action (Kennerley et al., 2021), filling these gaps could have a significant impact on conservation action. Mining companies are well placed to finance scientific efforts to fill these gaps, given they already operate in these regions and are typically required to conduct surveys as part of environmental licensing conditions. It is not unprecedented for companies to provide data to the Red List (Bennun et al., 2018), nor is it unusual for industry to lead the discovery of new species (e.g., Lehr et al., 2021). The costs to fill these gaps are increasingly well understood (Stewart et al., 2021) and thus could be budgeted for by companies and in mine site feasibility assessments. To enhance these opportunities, though, companies need better access to what information is missing in sites they are operating in (or plan to operate in) and, in instances where new information reveals additional threats, governments must provide clarity on reporting requirements. Such efforts could be integrated within existing tools, such as IBAT, to enable companies to identify opportunities (UNEP-WCMC 2020).

Other uncertainties exist in the data we used to identify mammal habitat within mining areas. Mining maps from Sonter et al. (2020) were constructed from the SNL Metals & Mining database (SNL 2020). Despite being considered one of the most comprehensive datasets available, it is not perfect. As already mentioned, this dataset does not capture artisanal and illegal mining or quarrying activities. SNL also underestimates mineral extracted from China for most commodities and, while African countries are well reported, gold extraction from DR Congo is only 60% that reported elsewhere (Maus et al., 2020). These two countries contain habitat for 1098 mammal species (China = 607 species; DRC = 491) and, although they tend to have lower-than-average data deficiencies (9% in both China and DRC, compared to average of 14% across all countries), incomplete data underestimates the number of species threatened and opportunities to address uncertainties and improve conservation outcomes.

Mapping global species distribution is also associated with issues of bias and uncertainty. Here we considered the geographic distribution of mammals in the IUCN Red List, which are often considered to overestimate species distributions. We limit this issue by using habitat suitability models, specifically the AOH method, which represents only the suitable portion of each species ranges and exclude areas less likely to be occupied (Brooks et al., 2019; Rondinini et al., 2011). It is also possible that IUCN maps exclude some area from species ranges that are occupied, but this can only be corrected for a limited number of species with accurate and representative point locality data (Boitani et al., 2011). However have no reason to believe uncertainty around species mapping depends on the presence of mining areas, hence any uncertainty in the underlying biodiversity data should not introduce biases in our results.

4.5 | Mining and the broader global conservation agenda

Achieving global conservation goals (UNEP, 2021) will require nations to seriously consider mining threats to biodiversity in national plans and policies. Some countries have mining areas tightly correlated with important habitat for threatened species and some mammals are particularly exposed to mining activities. Improving methods to detect, assess, and characterize mining threats to species will become even more important in future, particularly as mineral demand grows to support a green energy transition (Sovacool et al., 2020). Indeed, we found evidence that mammal species tend to have larger proportions of habitat within mining areas that target materials needed for an energy transition (Figure 3).

Despite these ongoing and emerging threats to biodiversity, mining is still permitted in many sites considered vital for species conservation (Sonter et al., 2020) and there is little evidence to suggest current management approaches achieve no net biodiversity loss (zu Ermgassen et al., 2019), let alone the net gain targets evident in the UN Convention on Biological Diversity (CBD) Global Biodiversity Framework (UNEP, 2021). Several efforts have already made significant progress on engaging industry to improve practice in this space, including an international expert workshop and report on "Biodiversity Mainstreaming in the Sectors of Energy and Mining, Manufacturing and Processing and Infrastructure" (CBD, 2018a) and the related decision adopted by Parties at COP14 to establish an Informal Advisory Group on Mainstreaming of Biodiversity (CBD, 2018b). Despite this, the draft post-2020 Global Biodiversity Framework provides little guidance on how to make decisions when minerals vital for sustainable development will negatively affect species and, as revealed by our analysis, further progress is needed to improve the characterization of mining threats within IUCN Red List assessments and related tools, such as IBAT and STAR, which utilize this valuable data.

AUTHOR CONTRIBUTIONS

Laura J. Sonter conceived the idea, Laura J. Sonter and Thomas J. Lloyd analyzed the data, all authors interpreted results and wrote the manuscript.

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DATA AVAILABILITY STATEMENT

This study uses secondary datasets, which can be sourced from their primary source, as referenced.

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REFERENECES

Álvarez-Castañeda S. T., Lacher T., & Vázquez E. (2018). *Habromys schmidlyi*. p. e.T136616A22376358. The IUCN Red List of Threatened Species.

Annandale, M., Meadows, J., & Erskine, P. (2021). Indigenous forest livelihoods and bauxite mining: A case-study from northern Australia. *Journal of Environmental Management*, *294*, 113014.

Bebbington, A. J., Humphreys Bebbington, D., Sauls, L. A., Rogan, J., Agrawal, S., Gamboa, C., Imhof, A., Johnson, K., Rosa, H., Royo, A., Toumbourou, T., & Verdum, R. (2018). Resource extraction and infrastructure threaten forest cover and community rights. *Proceedings of the National Academy of Sciences*, *115*, 13164–13173.

Bennun, L., Regan, E. C., Bird, J., van Bochove, J. W., Katariya, V., Livingstone, S., Mitchell, R., Savy, C., Starkey, M., Temple, H., & Pilgrim, J. D. (2018). The value of the IUCN Red List for business decision-making. *Conservation Letters*, *11*, e12353.

Bland, L. M., Bielby, J., Kearney, S., Orme, C. D. L., Watson, J. E. M., & Collen, B. (2017). Toward reassessing data-deficient species. *Conservation Biology*, *31*, 531–539.

Boitani, L., Maiorano, L., Baisero, D., Falcucci, A., Visconti, P., & Rondinini, C. (2011). What spatial data do we need to develop global mammal conservation strategies? *Philosophical Transactions of the Royal Society B: Biological Sciences*, *366*, 2623–2632.

Brooks, T. M., Pimm, S. L., Akçakaya, H. R., Buchanan, G. M., Butchart, S. H. M., Foden, W., Hilton-Taylor, C., Hoffmann, M., Jenkins, C. N., Joppa, L., Li, B. V., Menon, V., Ocampo-Peñuela, N., & Rondinini, C. (2019). Measuring terrestrial area of habitat (AOH) and its utility for the IUCN Red List. *Trends in Ecology & Evolution*, *34*, 977–986.

Bull, J. W., & Strange, N. (2018). The global extent of biodiversity offset implementation under no net loss policies. *Nature Sustainability*, *1*, 790–798.

CBD. (2018a). CBD/MS/WS/2018/1/4: *Report of the international expert workshop on mainstreaming biodiversity in the sectors of energy and mining, infrastructure, manufacturing and processing*. Convention on Biological Diversity. Sharm El-Sheikh, Egypt: CBD Secretariat. https://www.cbd.int/doc/c/64e1/803b/0cf178a44f3e95b87e51953f/ms-ws-2018-01-04-en.pdf

CBD. (2018b). CBD/COP/DEC/14/3: *Decision adopted by the conference of the parties to the convention on biological diversity*. Convention on Biological Diversity. Sharm El-Sheikh, Egypt: CBD Secretariat. https://www.cbd.int/doc/decisions/cop-14/cop-14-dec-03-en.pdf

Chakravarty R., Srinivasulu B., & Srinivasulu C. (2016). *Hipposideros hypophyllus*. The IUCN Red List of Threatened Species 2016: e.T10138A22092730.

Clements, R., Sodhi, N. S., Schilthuizen, M., & Ng, P. K. L. (2006). Limestone karsts of Southeast Asia: Imperiled arks of biodiversity. *Bioscience*, *56*, 733–742.

Crooks, K. R., Burdett, C. L., Theobald, D. M., King, S. R. B., di Marco, M., Rondinini, C., & Boitani, L. (2017). Quantification of habitat fragmentation reveals extinction risk in terrestrial mammals. *Proceedings of the National Academy of Sciences*, *114*, 7635–7640.

Di Marco, M., Venter, O., Possingham, H. P., & Watson, J. E. M. (2018). Changes in human footprint drive changes in species extinction risk. *Nature Communications*, *9*, 4621.

Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Agard, J., Arneth, A., Balvanera, P., Brauman, K. A., Butchart, S. H. M., Chan, K. M. A., Garibaldi, L. A., Ichii, K., Liu, J., Subramanian, S. M., Midgley, G. F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., … Zayas, C. N. (2019). Pervasive human-driven decline of life on earth points to the need for transformative change. *Science*, *366*, eaax3100.

Edwards, D. P., Sloan, S., Weng, L., Dirks, P., Sayer, J., & Laurance, W. F. (2014). Mining and the African environment. *Conservation Letters*, *7*, 302–311.

Erskine, P., Van der Ent, A., & Fletcher, A. (2012). Sustaining metal-loving plants in mining regions. *Science*, *337*, 1172–1173.

Fruth, B., Hickey, J. R., Andre, C., Furuichi, T., Hart, J., Hart, T., Kuehl, H., Maisels, F., Nackony, J., Reinartz, G., Sop, T., & Thompson, J. (2016). *Pan paniscus*. p. e.T15932A102331567. The IUCN Red List of Threatened Species.

Gerrie, R., & Kennerley, R. (2017). *Rattus omichlodes*. p. e.T136785A22442966. The IUCN Red List of Threatened Species 2017.

Giljum, S., Maus, V., Kuschnig, N., Luckeneder, S., Tost, M., Sonter, L. J., & Bebbington, A., J. (2022). A pantropical assessment of deforestation caused by industrial mining. *Proceedings of the National Academy of Sciences of the United States of America, 119 (38), e2118273119*.

Harfoot, M. B. J., Tittensor, D. P., Knight, S., Arnell, A. P., Blyth, S., Brooks, S., Butchart, S. H. M., Hutton, J., Jones, M. I., Kapos, V., Scharlemann, J. P. W., & Burgess, N. D. (2018). Present and future biodiversity risks from fossil fuel exploitation. *Conservation Letters*, *11*, e12448.

ICMM. (2020). *Mining principles: Performance expectations*. International Council on Mining and Metals.

IFC. (2012). *Performance Standard 6: Biodiversity conservation and sustainable management of living natural resources*. International Finance Corporation.

IUCN. (2012). *IUCN—CMP unified classification of direct threats (version 3.2)*. International Union for Conservation of Nature.

IUCN. (2020). *IUCN Red List categories and criteria (version 3.1)*. International Union for Conservation of Nature.

IUCN. (2021). *The IUCN Red List of Threatened Species (version 2021-3)*. International Union for Conservation of Nature.

Jaffé, R., Prous, X., Zampaulo, R., Giannini, T. C., Imperatriz-Fonseca, V. L., Maurity, C., Oliveira, G., Brandi, I. V., & Siqueira, J. O. (2016). Reconciling mining with the conservation of cave biodiversity: A quantitative baseline to help establish conservation priorities. *PLoS One*, *11*, e0168348.

Johnson, C. J., Venter, O., Ray, J. C., & Watson, J. E. M. (2020). Growth-inducing infrastructure represents transformative yet ignored keystone environmental decisions. *Conservation Letters*, *13*, e12696.

Joppa, L. N., O'Connor, B., Visconti, P., Smith, C., Geldmann, J., Hoffmann, M., Watson, J. E. M., Butchart, S. H. M., Virah-Sawmy, M., Halpern, B. S., Ahmed, S. E., Balmford, A., Sutherland, W. J., Harfoot, M., Hilton-Taylor, C., Foden, W., Minin, E. D., Pagad, S., Genovesi, P., … Burgess, N. D. (2016). Filling in biodiversity threat gaps. *Science*, *352*(6284), 416–418.

Kennerley, R. (2017). *Batomys russatus*. p. e.T136394A22449489. The IUCN Red List of Threatened Species 2017.

Kennerley, R., Turvey, S. T., & Young, R. (2018). *Atopogale cubana*. e.T20320A22327125. The IUCN Red List of Threatened Species 2018.

Kennerley, R. J., T. E. Lacher, Jr., M. A. Hudson, B. Long, S. McCay, N. Roach, S. T. Turvey and Young, R. (2021). Global patterns of extinction risk and conservation needs for Rodentia and Eulipotyphla. *Diversity and Distributions*, *27*:1792–1806. https://doi.org/10.1111/ddi.13368

Lehr, E., Lyu, S., & Catenazzi, A. (2021). A new, critically endangered species of Pristimantis (Amphibia: *Anura: Strabomantidae*) from a mining area in the cordillera occidental of northern Peru (Región Cajamarca). *Salamandra*, *57*, 15–26.

Mair, L., Bennun, L. A., Brooks, T. M., Butchart, S. H., Bolam, F. C., Burgess, N. D., Ekstrom, J. M., Milner-Gulland, E. J., Hoffmann, M., Ma, K., & Macfarlane, N. B. (2021). A metric for spatially explicit contributions to science-based species targets. *Nature Ecology & Evolution*, *5*, 836–844.

Maus, V., Giljum, S., Gutschlhofer, J., da Silva, D. M., Probst, M., Gass, S. L. B., Luckeneder, S., Lieber, M., & McCallum, I. (2020). A global-scale data set of mining areas. *Scientific Data*, *7*, 289.

Newbold, T., Hudson, L. N., Hill, S. L. L., Contu, S., Lysenko, I., Senior, R. A., Börger, L., Bennett, D. J., Choimes, A., Collen, B., Day, J., de Palma, A., Díaz, S., Echeverria-Londoño, S., Edgar, M. J., Feldman, A., Garon, M., Harrison, M. L. K., Alhusseini, T., … Purvis, A. (2015). Global effects of land use on local terrestrial biodiversity. *Nature*, *520*, 45–50.

Northey, S. A., Mudd, G. M., Saarivuori, E., Wessman-Jääskeläinen, H., & Haque, N. (2016). Water footprinting and mining: Where are the limitations and opportunities? *Journal of Cleaner Production*, *135*, 1098–1116.

Owen, J. R., & Kemp, D. (2017). Social management capability, human migration and the global mining industry. *Resources Policy*, *53*, 259–266.

Pijpers, R. (2014). Crops and carats: Exploring the interconnectedness of mining and agriculture in Sub-Saharan Africa. *Futures*, *62*, 32–39.

Rampartab, C. (2015). *Amblysomus robustus*. p. e.T62008A21284697. The IUCN Red List of Threatened Species 2015.

Rodrigues, A. S. L., Pilgrim, J. D., Lamoreux, J. F., Hoffmann, M., & Brooks, T. M. (2006). The value of the IUCN Red List for conservation. *Trends in Ecology & Evolution*, *21*, 71–76.

Rondinini, C., di Marco, M., Chiozza, F., Santulli, G., Baisero, D., Visconti, P., Hoffmann, M., Schipper, J., Stuart, S. N., Tognelli, M. F., Amori, G., Falcucci, A., Maiorano, L., & Boitani, L. (2011). Global habitat suitability models of terrestrial mammals. *Philosophical Transactions of the Royal Society B*, *366*, 2633–2641.

Salafsky, N., Salzer, D., Stattersfield, A. J., Hilton-Taylor, C., Neugarten, R., Butchart, S. H. M., Collen, B., Cox, N., Master, L. L., O'Connor, S., & Wilkie, D. (2008). A standard lexicon for biodiversity conservation: Unified classifications of threats and actions. *Conservation Biology*, *22*, 897–911.

Shanee, S., Cornejo, F. M., & Mittermeier, R. A. (2020). *Aotus miconax* (amended version of 2019 assessment). *The IUCN Red List of Threatened Species* 2020: e.T1802A164046186.

Sigwart, J. D., Chen, C., Thomas, E. A., Allcock, A. L., Böhm, M., & Seddon, M. (2019). Red listing can protect deep-sea biodiversity. *Nature Ecology & Evolution*, *3*, 1134.

Siqueira-Gay, J., & Sánchez, L. E. (2021). The outbreak of illegal gold mining in the Brazilian Amazon boosts deforestation. *Regional Environmental Change*, *21*, 28.

SNL. (2018). *Metals and mining database*. S&P Global Market Intelligence.

Sonter, L. J., Ali, S. H., & Watson, J. E. M. (2018). Mining and biodiversity: Key issues and research needs in conservation science. *Proceedings of the Royal Society B: Biological Sciences*, *285*, 20181926.

Sonter, L. J., Dade, M. C., Watson, J. E. M., & Valenta, R. K. (2020). Renewable energy production will exacerbate mining threats to biodiversity. *Nature Communications*, *11*, 4174.

Sonter, L. J., Herrera, D., Barrett, D. J., Galford, G. L., Moran, C. J., & Soares-Filho, B. S. (2017). Mining drives extensive deforestation in the Brazilian Amazon. *Nature Communications*, *8*, 1013.

Sovacool, B. K., Ali, S. H., Bazilian, M., Radley, B., Nemery, B., Okatz, J., & Mulvaney, D. (2020). Sustainable minerals and metals for a low-carbon future. *Science*, *367*, 30–33.

Stewart, C. L., Watson, J. E. M., Bland, L. M., & Tulloch, A. I. T. (2021). Determining ranges of poorly known mammals as a tool for global conservation assessment. *Biological Conservation*, *260*, 109188.

Ukizintambara, T., Olupot, W., & Hart, J. 2019. *Allochrocebus lhoesti*. The IUCN Red List of Threatened Species 2019: e. T4220A92345122.

UNEP. (2021). *First Draft of the Post-2020 Global Biodiversity Framework*. CBD/WG2020/3/3 Convention on Biological Diversity, UN Environment Programme.

UNEP-WCMC. (2020). IBAT Annual Report. Available at: https://www.ibat-alliance.org/pdf/ibat-annual-report-2020.pdf

United Nations. (2015). *Transforming our world: The 2030 agenda for sustainable development*. United Nations.

Werner, T. T., Mudd, G. M., Schipper, A. M., Huijbregts, M. A. J., Taneja, L., & Northey, S. A. (2020). Global-scale remote sensing of mine areas and analysis of factors explaining their extent. *Global Environmental Change*, *60*, 102007.

Woolley, P. (2016). *Myoictis wavicus*. p. e.T136829A21945185. The IUCN Red List of Threatened Species 2016.

World Bank. (2019). *Forest-smart mining: Identifying factors associated with the impacts of large-scale mining on forests*. World Bank.

World Bank. (2020). *Minerals for climate action: The mineral intensity of the clean energy transition*. World Bank.

zu Ermgassen, S. O. S. E., Baker, J., Griffiths, R. A., Strange, N., Struebig, M. J., & Bull, J. W. (2019). The ecological outcomes of biodiversity offsets under "no net loss" policies: A global review. *Conservation Letters*, *12*, e12664.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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