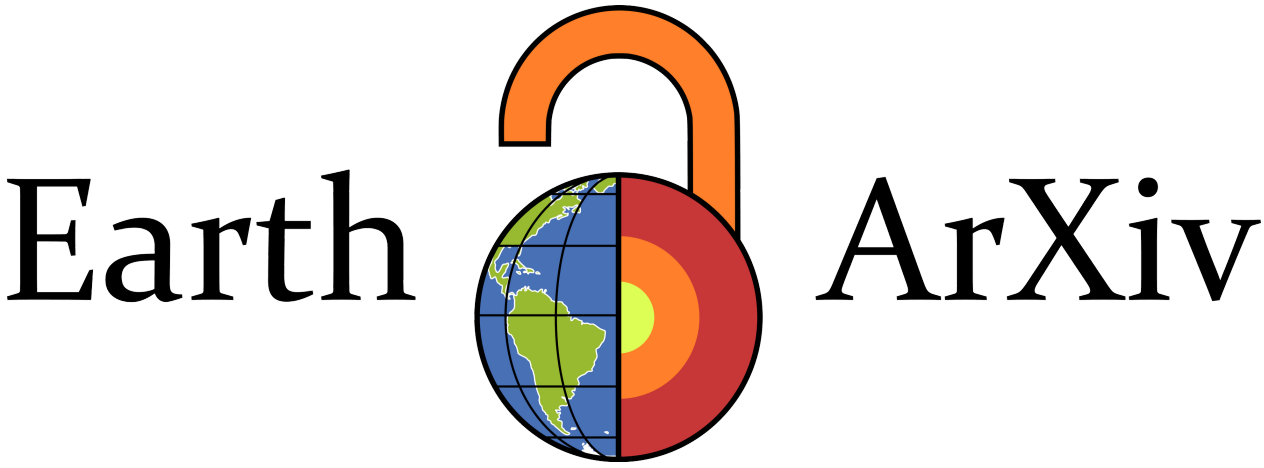


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Globally expanding lithium mining could threaten endemic species in biodiversity hotspots

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Abstract

Electric vehicles (EVs) are widely framed as a technological solution to the climate crisis. However, the mineral extraction supplying EV battery production can cause serious environmental damage, threatening ecosystems and biodiversity from local to global scales. Lithium, a key EV battery component, is experiencing an enormous mining boom, which could drive species population declines and eventual extinctions. In this work, we developed and tested an enhanced method for assessing the extent to which 400 operational and prospective lithium mines, located across 41 countries, could threaten Red List species with global extinction. Our results indicate that mines occurring within biodiversity hotspots could pose the greatest species extinction risks. More specifically, we identify degree of local species endemism as a key determinant of the threats posed by lithium mines, acknowledging the shortcomings of both the Red List and biodiversity hotspot assessments in comprehensively capturing these threats. At the regional level, our findings indicate priority attention should be given to ecosystems near lithium mines in southwest Australia, Chile and Argentina's portions of the Lithium Triangle, southeast China, and the western United States to prevent species extinctions. The species facing the greatest risks in these regions are predominantly plants, reptiles, and freshwater invertebrates.

Introduction

Electric vehicles (EVs) are widely framed as a technological solution to the climate crisis because they produce fewer lifecycle carbon emissions than internal combustion engine (ICE) vehicles[1]. With growing renewable energy adoption, EV carbon footprints are being further reduced[1]. However, viewing EVs through a carbon-centric lens omits other important aspects of their overall sustainability. Notably, the mineral supply chains feeding EV battery

production are frequently associated with serious environmental and social harm, a topic that is gaining traction in energy transition discourse[2,3,4]. The vast majority of EVs utilize lithium-ion batteries, which require numerous mineral inputs including lithium, nickel, cobalt, manganese, graphite, iron, and phosphorus[5]. These minerals are obtained by mining them from the Earth's crust, a process that can cause severe negative impacts to local people, ecosystems, and biodiversity[6,7]. With EVs expected to account for over 70 % of new car sales in 2040, many new mines could be built, alongside expansion of existing projects, to fuel battery production[8,9]. This is raising substantial concerns that mining-induced socio-ecological harm will intensify and spread to new frontiers as the EV industry continues its rapid growth[10,11,12].

Lithium in particular is experiencing an enormous mining boom to keep up with demand, which could increase at least five-fold by 2040[8]. Lithium mining's expansion rate is exceptional in that it exceeds that of virtually all other EV battery minerals[8]. This is a product of lithium's historic use being mostly limited to batteries for smaller scale technologies, namely portable electronics[13]. With EVs requiring lithium in far greater quantities than cell phones or laptops, existing lithium mine supply is unlikely to be sufficient to meet current EV deployment projections[8,14]. As a result, hundreds of new lithium extraction projects are being prospected globally[15]. The implications of the advent of EVs are further evident in their share of global lithium demand, which could increase from ~10 % in 2015 to over 80 % by 2040[13,16,17]. In addition to EVs, portable electronics are expected to continue being a downstream driver of expanding lithium mining, alongside grid-scale energy storage and emerging applications like combat drones[17,18].

Lithium is primarily mined via two methods: open pit mining and brine extraction. These methods share some similarities but also marked differences, both in their operational principles and their ecological impact mechanisms. Open pit lithium mining involves digging pits in the ground to access lithium-containing minerals located below the surface. It is typically used to extract hard rock and clay lithium deposits. In general, open pit mining's ecological pressures can range from being localised, in the form of land use change and deforestation, to extending over potentially hundreds of kilometres, through air, water, and soil pollution[6,7]. These pressures can result in a number of adverse impacts to surrounding species[19]. For instance, land use change and vegetation clearing for mine pit construction can cause direct loss and/or fragmentation of critical vertebrate habitat[20]. Mine pollutant dispersal, on the other hand, can cause heavy metals and sediment to enter local watercourses, potentially presenting serious developmental and toxicity risks to aquatic

species[21]. Additionally, particulate matter released in the form of dust has been found to adversely affect both plant and animal health[22].

In brine extraction, lithium-rich brine contained in underground aquifers is pumped into large surface ponds where the water is evaporated off, leaving lithium salts behind. Similar to open pit mining, lithium brine extraction can cause habitat loss for local species from evaporation pond construction[23,24]. It can also pose toxicity risks to species through the release of chemical contaminants and highly saline waste products[6,25]. The most notable ecological pressure associated with lithium brine extraction, however, is arguably groundwater depletion. As many brine mines are located in sensitive arid or wetland environments, hydrological disruptions can negatively affect the species relying on these water sources, particularly freshwater organisms[26,27]. In recent years, direct lithium extraction (DLE) has been extensively touted as a more sustainable way to harvest lithium brines because it could reduce the need for evaporation ponds[28]. However, the ecological risks associated with DLE are poorly understood, namely those related to its freshwater consumption and its reliance on the re-injection of contaminated brine back into exploited aquifers[28,29].

Regardless of the method used, lithium mining can cause significant harm to the species living near extraction sites, potentially driving population declines and heightening the extinction risk of those that are already threatened and/or endemic[30,31]. Species population declines, local extinctions, and eventual global biodiversity loss can have serious ramifications[32,33]. Species and ecosystems provide critical contributions to human well-being including food production, carbon sequestration, natural hazard regulation, nutrient cycling, and many others[34]. In addition to the material benefits they provide, many species and ecosystems also have intrinsic, cultural, and spiritual value to people around the world[35]. It is therefore urgent and imperative that the potential species-level ecological consequences of lithium mining are fully understood before, rather than after, more mines are built.

To the best of our knowledge, no study to date has attempted to audit how expanding lithium mining could threaten species from local to global scales. Most prior work on this topic has been limited to impacts on individual species or regional-level analyses[23,36,37,38]. However, several studies have developed methodological frameworks for assessing the global biodiversity threats of mining and other industries that could be applicable to a lithium-focused analysis[39,40,41]. The most pertinent of these methods is the Species Threat Abatement and Restoration (STAR) metric. Utilizing the IUCN Red List, the most comprehensive global threatened species database, the STAR metric aims to identify

regions containing large percentages of Red List species' habitats[42]. Initially proposed for setting conservation targets, the STAR framework can also be adapted to quantify the species-level threats posed by extractive projects[43]. However, the metric in its current form has several shortcomings that limit its ability to thoroughly capture lithium mining's potential ecological impacts. For one, at present, STAR does not incorporate threats to freshwater species which, as previously stated, can be especially vulnerable to mining-induced ecological pressures[44,45]. Additionally, the metric does not consider potential impacts to Data-Deficient Red List species, despite many of them predicted to be threatened with extinction[46]. Finally, STAR does not consider future threats to species beyond those that have already been reflected in the Red List, a significant hinderance to proactively assessing the ecological risks of prospective lithium mines.

Building on the STAR method's limitations, we developed an enhanced metric to quantify the extent to which 400 operational and prospective lithium mines could threaten their surrounding species, with the initial aim of highlighting regions where lithium extraction could pose disproportionately high species extinction risks. Additionally, we built a global list of species that could face the greatest extinction risks from potential lithium mining impacts, considering various scenarios for future mine construction. Using the Red List's categorization criteria, we also identified endemic species that are in danger of being driven to more severe threat categories than they are currently classified in, further illuminating the highest risk lithium mining locations. Our hope is that this study's findings will be used to better understand and communicate the biodiversity loss risks associated with globally expanding lithium mining while supporting bigger picture conversations about what truly responsible decarbonization should look like.

Methods

Mine data collection and preparation

A leading battery supply chain market intelligence provider (name withheld at their request) supplied us with a comprehensive list of names of operational and prospective lithium mines. Totalling 400, these mines encompass the provider's projections of the most likely lithium sources for the next one to two decades. The provider collects global lithium mine supply data from a variety of sources including publicly available information (company filings, reports, etc.), industry contacts, and proprietary estimates. Once an operational or prospective lithium mine is identified through these sources, the provider develops a detailed asset model for the facility reflecting its current/planned costs and production volume. The provider then categorizes these mines according to their operational feasibility. These

categories are: “operational” (mines actively producing lithium today), “highly probable” (mines that have passed necessary approvals and are expected to be producing within 24 months), “probable” (mines that have secured considerable funding and could be producing within five years), and “possible” (early-stage mines that have only secured a small amount funding and likely require five years or more to become operational).

We identified these mines’ coordinate locations through company websites, annual reports, feasibility studies, academic publications, and news articles. An exhaustive list of references is provided in the **Supporting Databook.** Using these publicly available sources, we were able to confirm the existence of all 400 mines; however, the level of granularity to which we could estimate each one’s location varied on a site-by-site basis. Mine coordinates were straightforward to determine for operational sites, as we could confirm visible pits or evaporation ponds using satellite imagery. For mines that have yet to be built, we relied on a combination of maps and project location descriptions published by their operator companies to triangulate each one’s probable future location (e.g., The Lake Johnston lithium mine is located 450 km east of Perth, Western Australia). In a small number of cases, where mines had exceptionally vague or minimal publicly available information, we narrowed down the likely site locations as far as possible, such as to the nearest county or town, before approximating representative coordinates. Where available, we also extracted the mines’ mineral resource estimates (MREs), reflected in terms of their measured, indicated, and/or inferred resources (in tonnes of lithium). All mine MRE information is provided in the **Supporting Databook**.

Though the data provider had already suggested potential feasibility categories for the mines, we opted to develop our own categorization methodology relying on more consistent criteria to increase the reproducibility and transparency of our work. Thus, we instead grouped the mines into three operational status categories: “Active,” “Under Development,” and “Exploratory”. For the “Active” category, we included all operational and near operational mines. For the “Under Development” and “Exploratory” categories, we relied on whether the mines have MREs published to gauge how far they have progressed. Typically, mine operators only publish MREs once they have conducted substantial geological analyses and feasibility studies[47]. Therefore, we assumed that future mines with MREs available are more likely to be constructed than those without. Accordingly, we classified all future mines with MREs into the “Under Development” category and those without into the “Exploratory” category.

Using QGIS (version 3.34.15) and R (version 4.5.2), we created point vectors for each mine, with the points located in the approximate centre of the mines' existing sites ("Active" mines) or their likely future sites ("Under Development" and "Exploratory" mines). For the operational mines, we also manually measured the active mining areas of each in km^2 by drawing polygons around the sites and using the st_area() function ("sf" package)[48]. For the operational hard rock / clay mines, we assumed active mining areas include all mining pits, tailings ponds, and processing units on site. For the operational brine mines, we assumed that all evaporation ponds and visible pumping / piping infrastructure constituted the mining area, although the latter was significantly more challenging to discern from satellite imagery. We note that previous studies, namely Maus *et al.* (2022), have already derived mining areas for tens of thousands of sites globally with reproducible methodologies[49]. However, a majority of the operational lithium mines in our study, ~75 %, do not appear to be mapped in the Maus *et al.* dataset. Therefore, to provide the most up-to-date view on active lithium mining areas, it was necessary to manually delineate these mines' footprints. We also manually drew the footprints of mines that are already included in the Maus *et al.* dataset to maintain consistency between sites and account for recent mine expansions. For the sites common to both studies, we found that our measured footprint areas were closely aligned with those determined by Maus *et al.* (**Table S4**).

IUCN Red List data preparation

We used the Red List to assess how each mine could threaten its surrounding species. The Red List is a globally harmonised database containing detailed information on the extinction risk of over 170,000 animal, plant, and fungi species[42]. Extant Red List species are classified as Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), and Critically Endangered (CR), increasing in severity of extinction risk. Vulnerable, Endangered, and Critically Endangered species are considered "threatened" due to their exceptionally high extinction risk. Species that have insufficient population distribution data to be placed in one of these categories are classified as Data-Deficient (DD). To qualify for classification as Vulnerable, Endangered, or Critically Endangered, species must meet the quantitative thresholds of at least one of the Red List's five criteria, named Criteria A – E[50]. We focused on Criteria B (geographic range area) and E (extinction probability) based on data availability and relevance to the study.

We obtained all available species range map polygons (i.e. where species are geographically known to occur) from the Red List database for the following taxonomic / species groups: mammals, amphibians, reptiles, plants, freshwater fish, and other

freshwater species (crabs, crayfishes, molluscs, odonata, and shrimps). We obtained bird range maps from BirdLife International, the Red List's authority for birds[51]. After filtering, the species selected for analysis totalled 67,050 (5,872 mammals, 7,730 amphibians, 9,999 reptiles, 10,097 birds, 10,593 plants, 13,711 freshwater fish, 9,048 other freshwater species).

Mine impact area model development

We developed a hybrid model for approximating the area over which lithium mines could threaten their surrounding species' ranges, with distinct methodologies for terrestrial and aquatic species, respectively. For the terrestrial species, we assumed that a 50 km radius around each mines' centre point was representative of the total area within which direct (e.g. deforestation, habitat loss, groundwater consumption, pollution) and indirect (e.g. ancillary infrastructure, roads, etc.) mining impacts could negatively affect them. First developed by Sonter *et al.*, 50 km buffers allow for rapid, global assessment of the potential terrestrial biodiversity impacts of mining projects and have been used in other related studies[52,53]. This buffer distance is also recommended by the Integrated Biodiversity Assessment Tool (IBAT) Alliance and has been used by mining companies to record threatened species prevalence near their assets[54,55].

It is important note that applying buffers around a singular point does not capture variance in the mines' land use footprints. However, a point-based method is the only feasible option for assessing "Under Development" and "Exploratory" mines as it is unclear exactly what these mines will look like. Therefore, we applied the same approach across all mines, including the "Active" mines with known footprints, to maintain consistency. We also analysed how using the "Active" mines' physical geometries to generate 50 km buffers extending from their edges rather than generalized 50 km buffers around their centre points would cause their threat scores to change.

For the aquatic species, as the dominant mode by which they are likely to be threatened is sediment and metal pollutant transport down local watercourses, we developed a directional drainage impact model largely based on Braz Pires *et al.'s* method[44,45,56]. We first used the HydroRIVERS dataset (version 1.0) to identify the river segments that each lithium mine's pollutants would be most likely to enter, assuming a 10 km buffer around the site[57]. We then assumed that the pollutants would propagate downstream through the affected river segments, during which they could harm local aquatic species. This would continue until an attenuation threshold, the distance at which pollutant concentrations become dilute enough

to likely no longer be harmful, was reached. Braz Pires *et al.* assumed upper and lower bound attenuation distances of 45.6 km and 6.5 km based on mine metal pollutant concentration models developed by Macklin *et al.* for river systems[56]. These values corresponded to the longest (arsenic) and shortest (zinc) river reach distances over which the study's models projected metal concentrations could remain above Dutch Intervention Limit (DIL) safety thresholds. However, as DIL thresholds are defined as the metal concentrations below which only 50% of the species in an ecosystem are likely protected from negative effects, they do not account for the totality of potential species impacts in a polluted river system[58]. Therefore, we chose to amend Braz Pires *et al.*'s thresholds to better capture the full extent to which lithium mine pollutants could threaten aquatic species. Macklin *et al.*'s models suggest that arsenic and zinc concentrations approach the typical background levels observed in unpolluted rivers at distances of ~100 km and ~10 km, respectively[59,60,61]. We therefore deemed these to be more suitable upper and lower bounds at which aquatic species could be more safely assumed to not face adverse impacts.

After mapping each mine's potentially affected river segments under the two attenuation distance scenarios, we assessed their overlap with the HydroBASINS dataset (version 1). This allowed us to identify which broader drainage basins, and corresponding species' ranges, the affected segments are contained within. We utilized a Pfafstetter level 8 basin resolution to align with the IUCN's range mapping recommendations for freshwater species[62]. Once we identified each mine's affected basins, we combined them using the st_union() ("sf" package) tool and assumed the aggregate area was representative of the mine's total aquatic species impact area. The directional drainage model is visualized for the Greenbushes mine in the **Supporting Information**.

All extinction threat score results (described in next section) presented in the main text are based on a 50 km terrestrial buffer / 100 km aquatic attenuation model. We also conducted a sensitivity analysis with three additional scenarios using the lower bound 10 km attenuation distance as well as a 10 km terrestrial buffer to reflect more conservative mine impact assumptions (**Supporting Information**). These additional model scenarios are: 1) 50 km terrestrial buffer / 10 km aquatic attenuation, 2) 10 km terrestrial buffer / 100 km aquatic attenuation, and 3) 10 km terrestrial buffer / 10 km aquatic attenuation.

Mine extinction threat scores

Building on the STAR metric's philosophy, we developed an enhanced threat metric that considers both the amount of species' ranges overlapping with mine impact areas and the species' extinction probabilities. First, we identified which Red List species could be impacted by each mine, applying the previously described terrestrial and aquatic models to the corresponding taxa. We then quantified the proportion of the species' ranges coinciding with the mine's impact area, from 0 to 1. Next, we translated each species' Red List threat category into an extinction probability. The Red List categories inherently incorporate extinction risk (Criterion E), with the IUCN stating that extinction probabilities are ≥ 50% in 10 years for Critically Endangered species, ≥ 20% in 20 years for Endangered species, and ≥ 10% in 100 years for Vulnerable species. However, as these time windows vary significantly, it is difficult to compare species' extinction risks across categories. Additionally, the Red List does not provide extinction probabilities for Near Threatened and Least Concern species.

We therefore utilized extinction probabilities developed by Gumbs *et. al* for the EDGE2 species prioritization protocol[63]. Assessed for a uniform 50-year time window, Gumbs *et. al* identified Critically Endangered species as having an extinction probability of 0.97, with probabilities then halving as categories descend (Endangered = 0.485; Vulnerable = 0.243; Near Threatened = 0.121; Least Concern = 0.0606). While extinction risk time windows can be subjective, Gumbs *et. al* chose 50 years as a suitable time frame to drive conservation action, being neither too far nor too near into the future. This is also well-aligned with the expected lifetimes of lithium mines, which can be decades. For Data-Deficient species, we assumed their possible weightings could range from 0.0606 (Least Concern) to 0.97 (Critically Endangered), with a median weighting of 0.243 (Vulnerable). Note that the extinction probabilities consider the cumulative impact of all anthropogenic threats a species may currently be facing, not solely documented mining-related threats.

We then multiplied each species' mine-range overlap fraction by its extinction probability to compute an extinction threat score, normalising to the maximum possible score (0.97) and yielding values between 0 and 1. Finally, we summed the mine's species' individual extinction threat scores to get a total extinction threat score for the mine.

Our total mine extinction threat score metric is summarised with the following formula:

$$TET_i = \sum_{j}^{n} \frac{O_{i,j} * E_j}{1.0 * 0.97}$$

Where TET_i is the total extinction threat score of a mine *i*, $O_{i,j}$ is the overlap fraction of mine *i* 's impact area with a species *j* 's range (from 0 to 1), E_j is the extinction probability of species *j* based on its Red List category (from 0.0606 for Least Concern to 0.97 for Critically Endangered), and *n* is the total number of species coinciding with the mine's impact area. The methodology is visualized in **Fig. 1** and a sample calculation is provided in the **Supporting Information (Extended Methods)**.

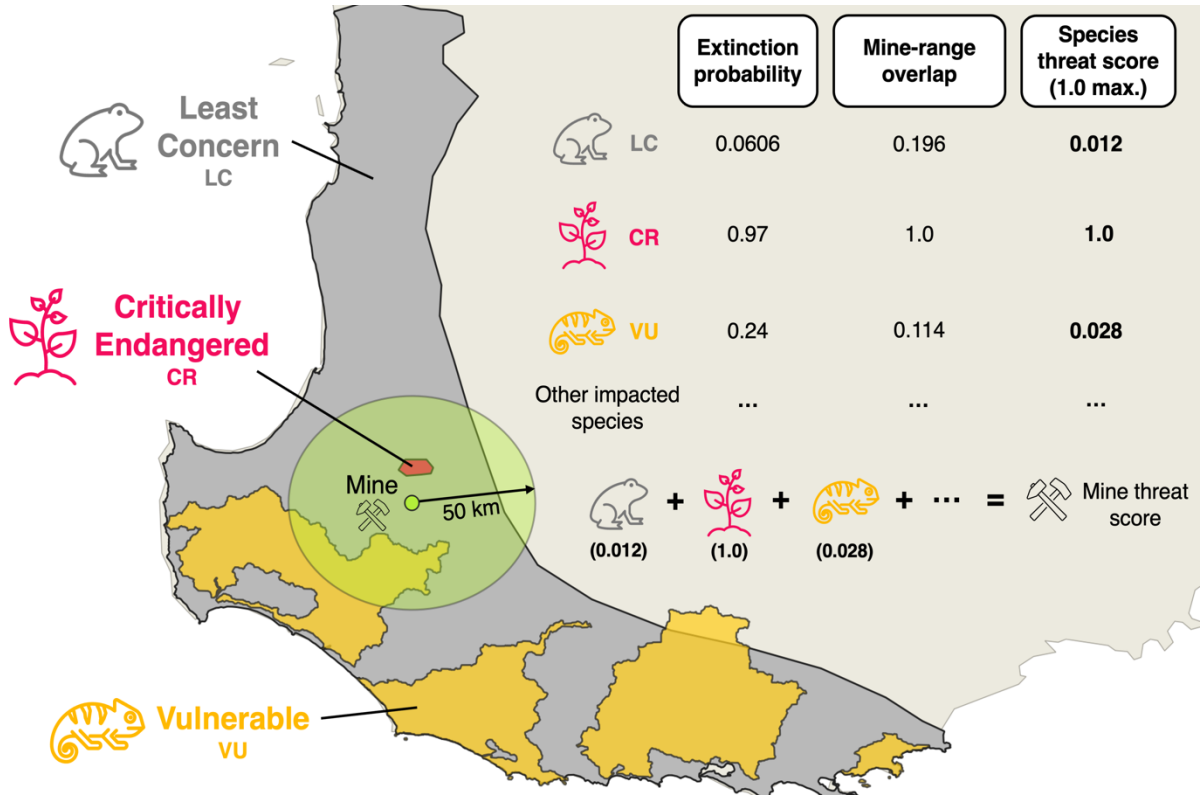


Figure 1 | Species threat metric methodology. Our methodology for computing species-level and mine-level threat scores is illustrated for a hypothetical active lithium mine (indicated in green with a 50 km terrestrial impact buffer) in Western Australia. The grey, yellow, and red regions indicate each corresponding species' range. Species threat scores are normalised to the maximum score of a Critically Endangered species (0.97) to yield values between 0 and 1. "Other coinciding species" refers to all possible Red List species that could be in proximity to the mine, other than the three explicitly shown. It is important to note that this illustration only depicts the methodology for terrestrial species. Aquatic species' threat scores are computed the same way but using a directional drainage mine impact area model rather than 50 km buffer.

We also developed a complementary metric to convey the average extinction threat per species potentially impacted by each mine. The aim of this metric is to account for the total extinction threat score's potential bias against mines located in regions with fewer documented Red List species, whether for reasons of inherent variation in species richness or data availability limitations.

Our per species mine extinction threat score metric is summarised with the following formula:

$$SET_i = \frac{TET_i}{n}$$

Where SET_i is the per species extinction threat score of a mine *i*, TET_i is the total extinction threat score of mine *i*, and *n* is the total number of species potentially coinciding with mine *i* 's impact area.

Cumulative species threat scores

In addition to the total and per species mine-level threat scores, we developed a global list of individual species that could face the greatest extinction risks. For this analysis, we considered not just the impact of individual mines on a species, but the combined impact of multiple mines distributed across the species' range (i.e. a cumulative threat score). We developed three scenarios, accounting for the varying likelihood of prospective lithium projects being constructed. The first scenario, "Scenario 1", assumes that only mines in the "Active" category are / become operational. The second scenario, "Scenario 2", assumes that both "Active" and "Under Development" mines are / become operational. The third scenario, "Scenario 3", assumes that all 400 mines across the "Active", "Under Development", and "Exploratory" categories are / become operational.

We computed cumulative threat scores for each species per scenario, ranging from a minimum of 0 to a maximum of 1. We used the st_union() function to combine each scenario's mines' impact areas, accounting for their potential overlap with each other and avoiding duplicative counting (**Fig. S2**).

Our cumulative species threat score metric is summarised with the following formula:

$$CT_j = \frac{(A_{i,j} - A_{i,self}) * E_j}{R_j * 1.0 * 0.97}$$

Where CT_j is the cumulative threat score of a species *j*, $A_{i,j}$ is the overlap of all scenario *i* mines' impact areas with species *j* 's range in km^2, $A_{i,self}$ is the overlap of all scenario *i* mines' impact areas with each other in km^2, E_j is the extinction probability of species *j* based on its Red List category, and R_j is species *j* 's range area in km^2.

Many Red List species, particularly those with wide distributions, have little overlap with lithium mining areas and thus low cumulative threat scores. As including all of these species in our global species lists would be excessive, we introduced a score cut-off threshold to

focus attention on the species facing the most significant extinction risks. We hereafter refer to these as “high-risk” species. We selected a cumulative threat score of 0.125 as our “high-risk” threshold to ensure all species scoring above the threshold are Vulnerable (max. score 0.25), Endangered (max. score 0.5), or Critically Endangered (max. score 1.0) species with considerable portions of their ranges threatened. Full lists of these “high-risk” species by scenario can be found in **Tables S8 – S10**. We acknowledge that adopting such a threshold could understate potential risks to any narrow-ranging Least Concern (max. score 0.0625) or Near Threatened species (max. score 0.125) that overlap significantly with mine impact areas. We have attempted to address this issue in the next section.

Future species category shift assessment

A significant number of the species we assessed are currently categorized as Least Concern or Near Threatened but have large portions of their ranges within the potential impact areas of lithium mines. Severe mining impacts, such as pollution or habitat fragmentation, could cause these species’ ranges to become uninhabitable and their populations to decline, dramatically shifting them from being of minimal concern to facing serious risk of local and/or global extinction. With this in mind, we conducted a future projection of species that could shift to more severe threat categories, using Red List Criterion B to re-designate species as the appropriate level of endangerment if they become impacted by mining activities.

For a species to qualify for a “threatened” category under Criterion B, it should 1) have an area of occupancy (AOO) less than 10 km^2 (Critically Endangered), 500 km^2 (Endangered), or 2,000 km^2 (Vulnerable) and/or an extent of occurrence (EOO) less than 100 km^2 (Critically Endangered), 5,000 km^2 (Endangered), or 20,000 km^2 (Vulnerable) and 2) be experiencing significant fragmentation, fluctuation, and/or continuing decline in its AOO, EOO, and/or population size. We assumed that negative mining impacts would cause the second condition to be met for all species. We also assumed that if a species’ range coincides with mine impact areas, the entirety of the overlapping area would become unsuitable for the species. However, we acknowledge this assumption could be too extreme in some cases. Therefore, we also considered an additional scenario, in which mining impacts would not be severe enough to cause species’ ranges to be entirely lost but would nevertheless cause their populations to go into decline, potentially still qualifying them for a “threatened” Red List designation (**Fig. S12**).

Since Criterion B only has thresholds for EOO and AOO rather than range, our only available species distribution data, we chose to apply the AOO thresholds to the species’

range areas to identify if they could qualify for categorization as “threatened”. The difference between AOO, EOO, and range, and the implications of selecting AOO thresholds for the analysis are explained in the **Supporting Information (Extended Methods)**. We have also included results using EOO thresholds in the **Supporting Databook** to show a different perspective.

To assess which species could shift to more severe threat categories, we first calculated the species’ current range polygon areas in km^2. We then subtracted the total mine overlap area from each species’ range and re-assessed what category the species would be in based on the Criterion B thresholds. We did not include Data-Deficient species in this analysis, as we already assumed their categorizations could range from Least Concern to Critically Endangered. In addition to identifying Least Concern or Near Threatened species that could shift to “threatened” categories, we used the same approach to identify species that are already classed as Vulnerable or Endangered but could still qualify for more severe categories. Finally, we quantified how mine threat scores could increase in the future because of species shifting categories. A comprehensive list of all species at risk of shifting to more severe categories is provided in the **Supporting Databook**.

Results

Table 1. Definitions of the key threat scoring metrics presented in the Results. Note that the metrics are primarily aggregated at the country-level throughout this section but are described below as they are applied at the individual mine-level, with the exception of “high-risk species”.

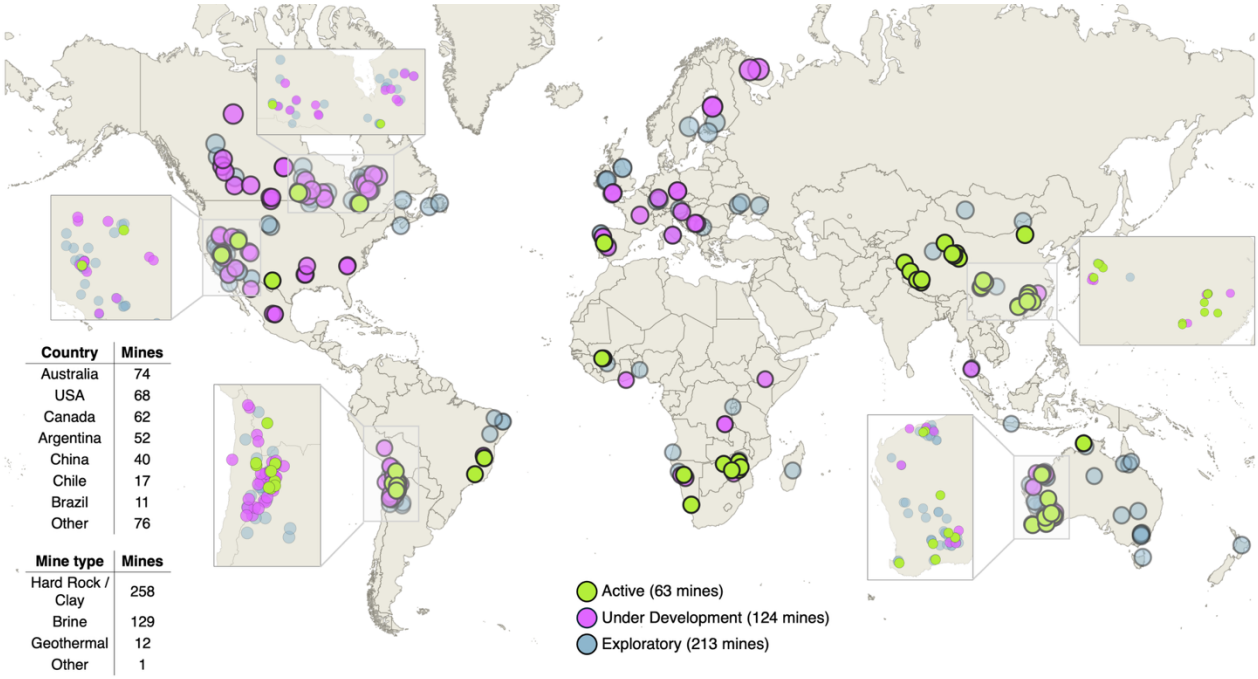
scoring metric	definition
total extinction threat score	sum of each mine’s individual extinction-probability-weighted species range overlap values
per species extinction threat score	average extinction threat per species potentially impacted by each mine
high-risk species	species with cumulative threat scores $>$ 0.125 (out of 1.0); corresponds to Vulnerable, Endangered, or Critically Endangered Red List species with significant portions of their ranges impacted by mining areas
species shifting to more severe threat categories	range-restricted species that each mine’s impacts could push to more severe threat categories than the Red List currently designates them as
species category shift fraction	fraction of Red List species potentially coinciding with each mine that could shift to a more severe threat category

Mine overview

The 400 lithium mines are dispersed across 41 countries, with Australia (74), USA (68), Canada (62), Argentina (52), China (40), and Chile (17) containing nearly 80 % (**Fig. 2a**). Approximately 65 % of the mines are hard rock or clay (258), with the remainder primarily brine (129). The hard rock mines include spodumene, petalite, and lepidolite ores, and the brine mines include both evaporative and direct lithium extraction projects. Fifty-six of the mines are operational and 7 are likely to become operational in the next two years – we categorized these 63 mines as "Active". We classed 124 as "Under Development" and the remaining 213 as "Exploratory" based on whether or not they have mineral resource estimates published.

Mine size varies significantly between the operational hard rock / clay and brine lithium mines. The median active mining area of the hard rock / clay mines is ~2 km^2 whereas it is ~120 km^2 for the brine mines, approximately 60-fold greater. This difference in scale is clearly visible in two representative mines' satellite images shown in **Fig. 2b**. Regardless of mine type, the active mining area represents a small share of the broader inferred impact area throughout which the mines could harm surrounding terrestrial species. For a median hard rock / clay mine, the active mining area represents ~0.03 % of the mine's total potential terrestrial impact area. For the larger brine mines, this value increased to only ~1.5 %.

(a)



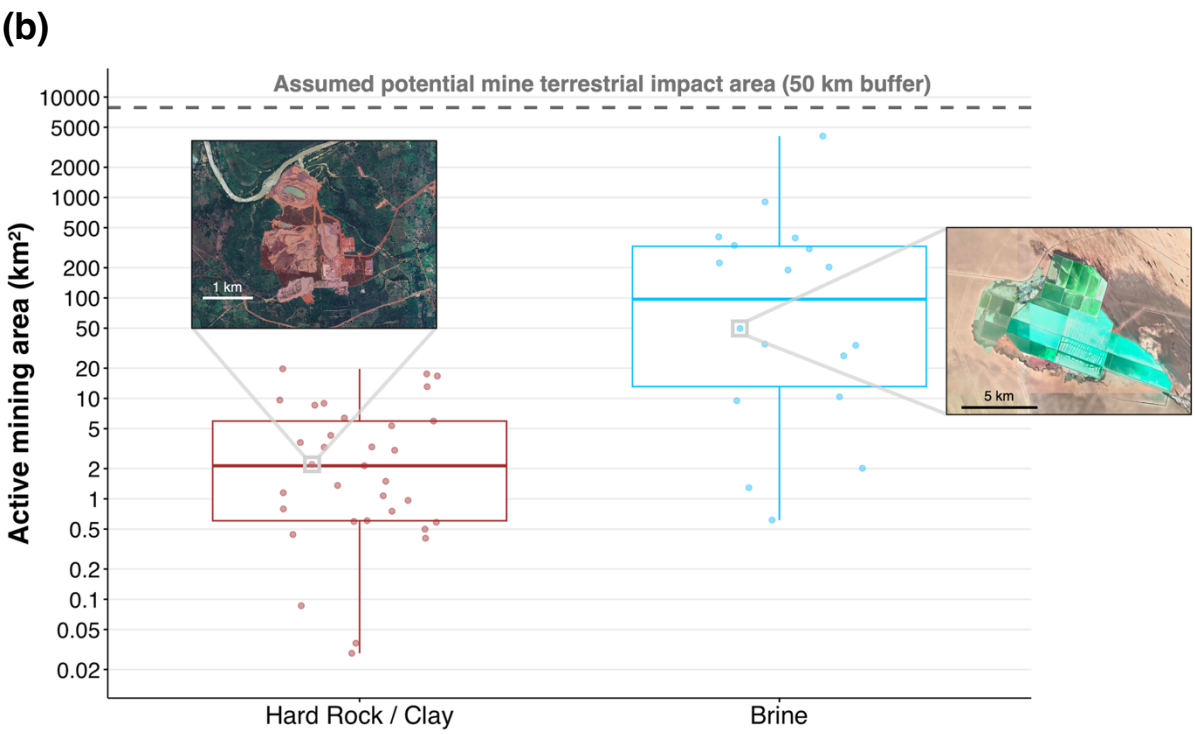


Figure 2 | A summary of the lithium mines assessed in this study. (a) A map of the 400 lithium mines considered in this study is depicted along with their respective categories. **(b)** The active mining areas of all operational lithium mines for which mining areas could be located (33 hard rock/clay, 18 brine) is shown, along with satellite images of two representative mines of close to median size for each mine type. The total terrestrial species impact area assumed for all the mines based on a 50 km buffer is shown as a dashed grey line. Brine mines include both evaporative and DLE technologies, with several sites likely incorporating a combination of the two at present.

Extinction threat scores

Across all 400 mines, the mean and median total extinction threat scores were 0.533 and 0.206, respectively (**Fig. 3a**). The Pegasus hard rock mine ("Exploratory") in Australia had the highest total extinction threat score (11.01), its potential impact area strongly coinciding with numerous Vulnerable (6), Endangered (9), and Critically Endangered (3) species' ranges. The Mythril hard rock mine ("Exploratory") in Canada had the lowest total extinction threat score (0.0052; ~ 2000-fold less than Pegasus), its potential impact area minimally overlapping with any Red List species. Sixty-seven mines have at least one Vulnerable, Endangered, or Critically Endangered species with 50% or more of its range within the mine's potential impact area.

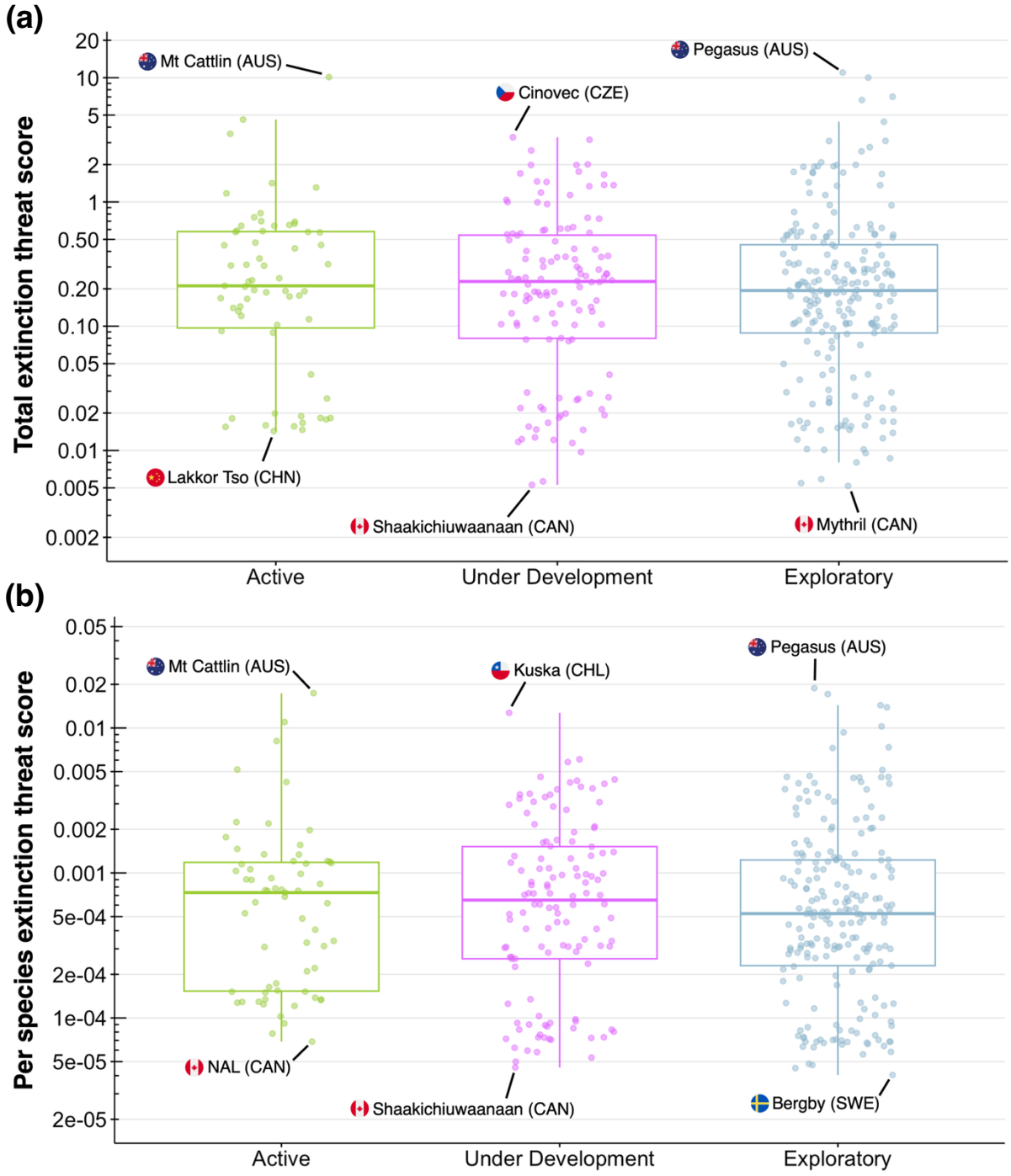
The highest total scoring mines tend to be concentrated in Australia, including seven of the top 10 and 24 of the top 50. Most of these mines are located in the state of Western Australia. This trend is also clearly reflected when considering country-level scores, with Australia having an overall total extinction threat score of 48.3, nearly six times greater than

the 2nd highest scoring country, Chile (8.54) (**Fig. 3c**). After Australia and Chile, the next highest scoring countries are China (8.05) and the United States (7.63), respectively. In general, we found that countries with more mines have greater total extinction threat scores. However, this is not always the case. Canada, for example, ranks 3rd for total active and prospective lithium mines (62) but only 20th for total extinction threat score (1.38). Its score is between those of Spain and Zimbabwe, which only have four and eight total lithium mines, respectively.

Across all the mines, the mean and median per species extinction threat scores were 0.00133 and 5.62×10^{-4}, respectively (**Fig. 3b and 3d**). The seven highest scoring Australian mines by total extinction threat score remained in the top 10 on a per species basis. Two Chilean mines, Kuska and Yapuckuta, also entered the per species top 10 after scoring 14th and 27th by total extinction threat score, respectively. At the country-level, Chile ranked 1st for per species extinction threat score (0.019), followed by Australia (0.018).

Our mine impact area sensitivity analysis exhibited similar trends to those above despite relying on more conservative terrestrial buffer and aquatic attenuation distance assumptions. Under all three alternative scenarios, Australia remained the highest overall scoring country by total extinction threat. Chile remained the highest overall scoring country by per species extinction threat in two of the three alternative scenarios, the only exception being the 10 km terrestrial buffer / 100 km aquatic attenuation case where it ranked 2nd after Austria (**Fig. S6-S11).**

We also found that the “Active” mines’ total threat scores did not meaningfully change when using 50 km terrestrial buffers incorporating each mine’s geometry rather than generalized 50 km terrestrial buffers around the mines’ approximate centres. We’ve provided this threat score comparison for the top 25 scoring “Active” mines in **Fig. S5**.


(a)
Total extinction threat score
20
10
5
2
1
0.50
0.20
0.10
0.05
0.02
0.01
0.005
0.002
Mt Cattlin (AUS)
Pegasus (AUS)
Cinovec (CZE)
Lakkor Tso (CHN)
Shaakichiuwaanaan (CAN)
Mythril (CAN)
Active
Under Development
Exploratory
(b)
Per species extinction threat score
0.05
0.02
0.01
0.005
0.002
0.001
5e-04
2e-04
1e-04
5e-05
2e-05
Mt Cattlin (AUS)
Kuska (CHL)
Pegasus (AUS)
NAL (CAN)
Shaakichiuwaanaan (CAN)
Bergby (SWE)
Active
Under Development
Exploratory

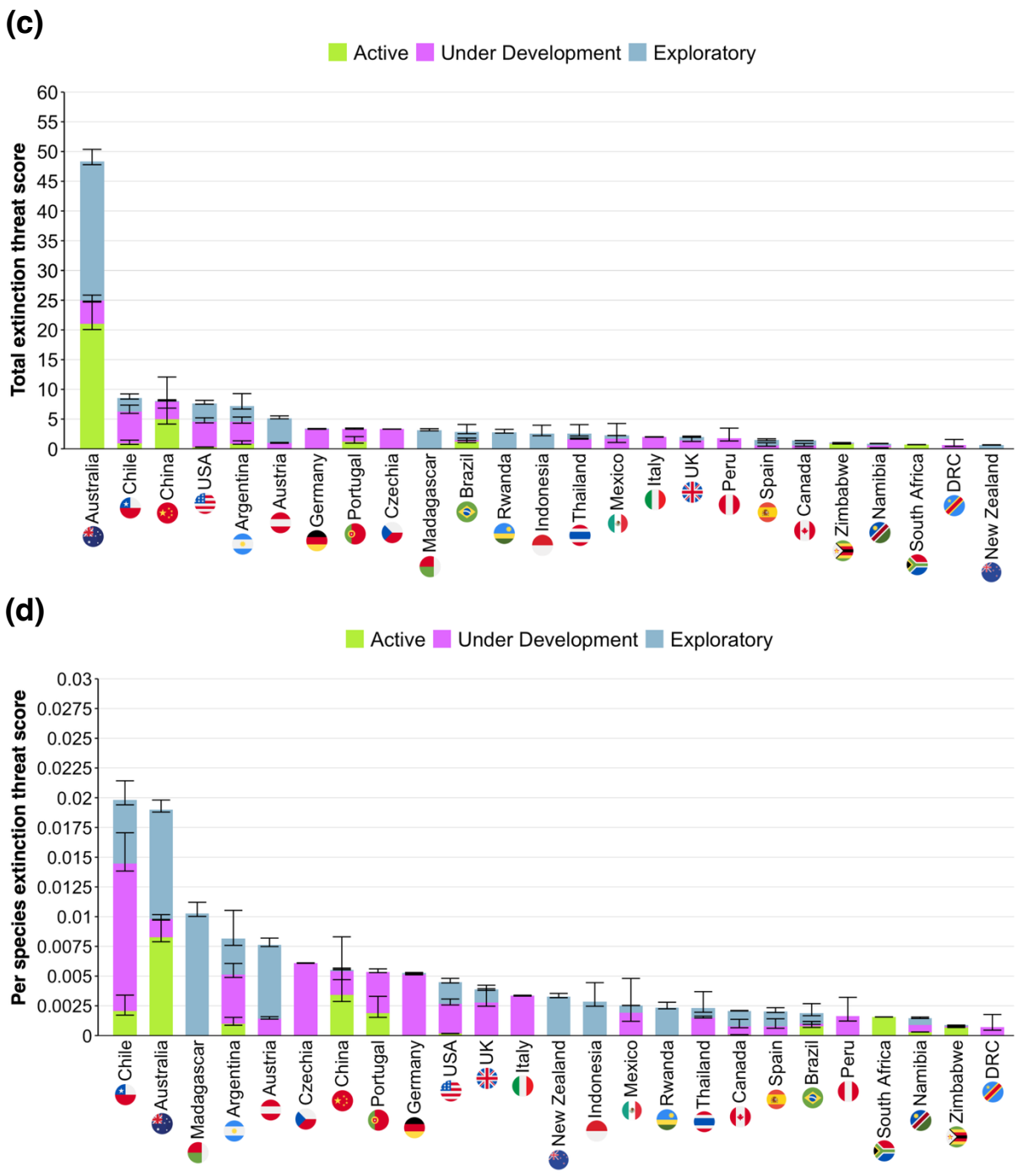


Figure 3 | Mine and country-level extinction threat scores. (a) Boxplot of total extinction threat score for all 400 mines, grouped by mine development category, (**b)** Boxplot of per species extinction threat score for all 400 mines, grouped by mine development category, **(c)** Top 25 countries by total extinction threat score, **(d)** Top 25 countries by per species extinction threat score. Values are for a 50 km terrestrial buffer / 100 km aquatic attenuation model. Score bars assume Data-Deficient species are equivalent to Vulnerable species. Error bars show the upper and lower bounds for Data-Deficient species – lower bound assumes all Data-Deficient species are Least Concern, upper bound assumes all are Critically Endangered. Colour coding indicates mine category. Per species extinction threat scores were calculated by dividing each mine's total extinction threat score by the number of Red List species potentially occurring within the mine's impact area. Flag icons reprinted with permission from www.flaticon.com. A comprehensive list of mine-by-mine and country level extinction threat scores can be found in the Supporting Databook.

Species at the greatest risk of extinction

At the global level, we identified 43 (Scenario 1) to 180 (Scenario 3) “high-risk” species. Many of these species are located in Australia (32-78) and the majority are plants (30-95). Approximately 36-57 % of these plant species are from the *Eucalyptus* or *Grevillea* genera. Reptiles and invertebrate freshwater species (“Freshwater other”) make up the next two taxonomic groups facing the greatest threats, with up to 25 and 23 “high-risk” species, respectively. The invertebrate freshwater species are distributed across a number of countries, and the reptiles are predominantly concentrated in Australia and the Chilean and Argentinian portions of the Lithium Triangle. Up to 14 species (Scenario 3) received the maximum threat score of 1.0, indicating they would face the most extreme risk of global extinction. A detailed list of all “high-risk” species is provided in **Tables S8-S10.**

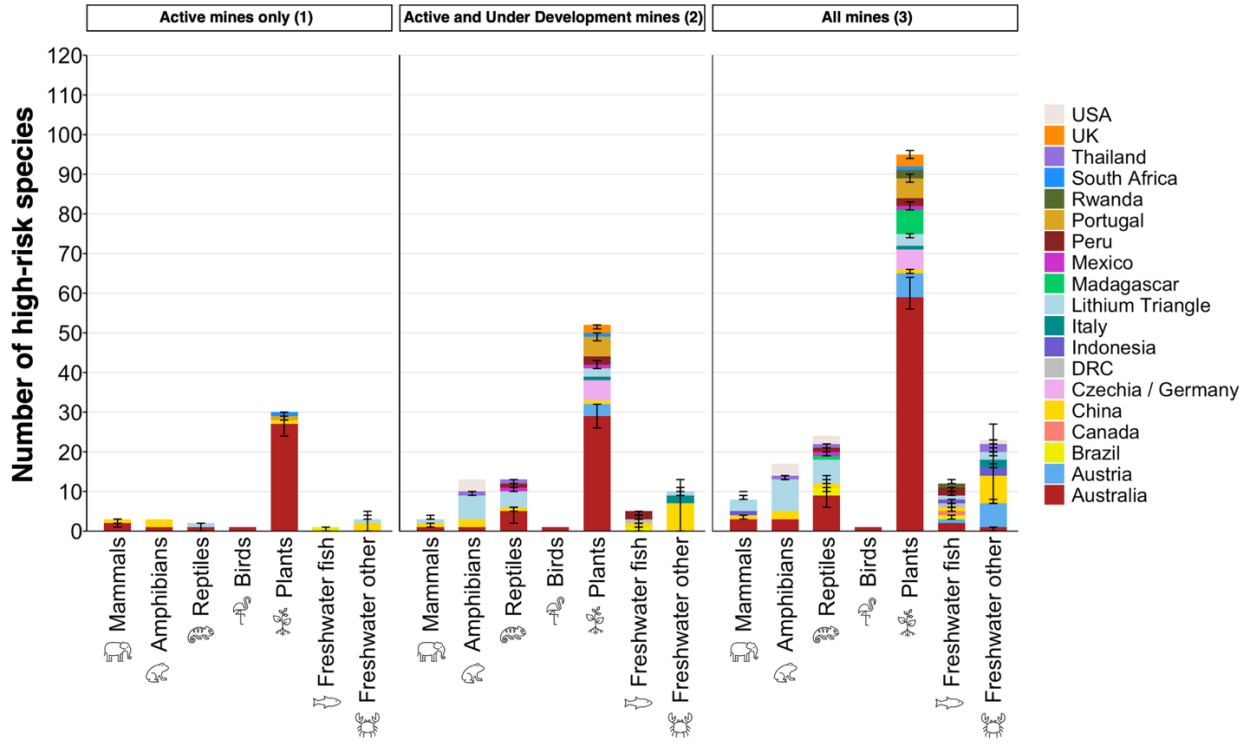


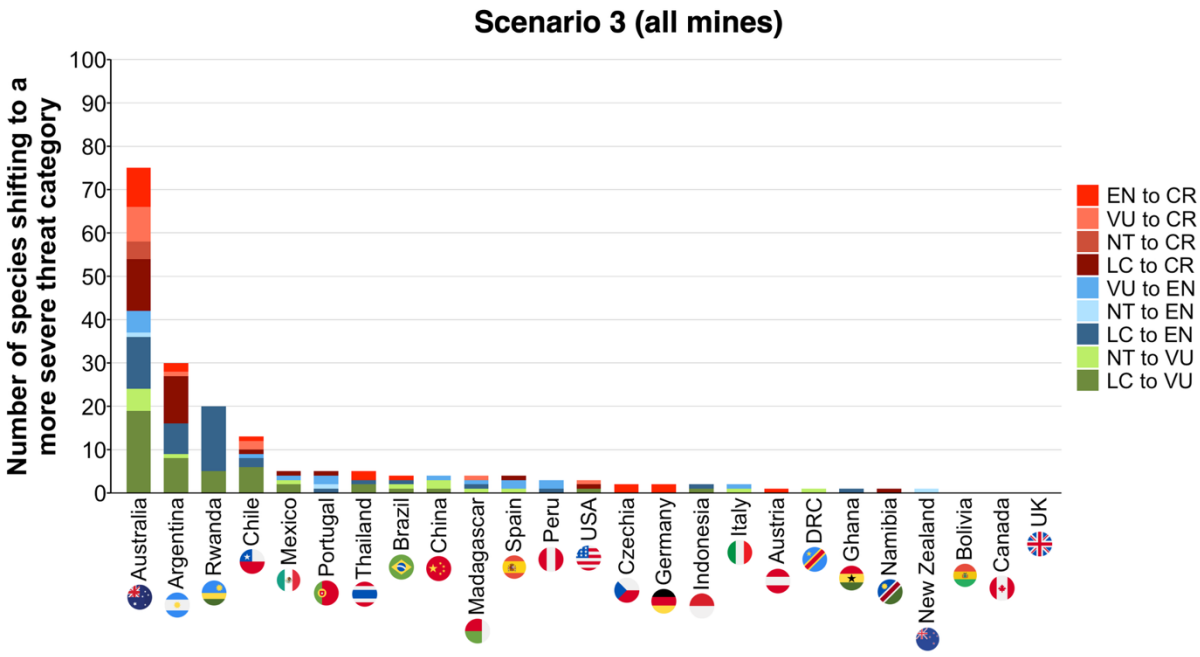
Figure 4 | **“High-risk” species by taxonomic group and country.** The number of “high-risk” species (cumulative threat score > 0.125) per taxonomic group and broken down by country. Values are for a 50 km terrestrial buffer / 100 km aquatic attenuation model. Scenario name and number are indicated above each set of corresponding results. Freshwater other includes crabs, crayfishes, molluscs, odonata, and shrimps. Chile, Argentina, Bolivia mines are aggregated into one stack called “Lithium Triangle” to avoid double counting species impacts as many of these mines have overlapping mine impact areas. Czechia and Germany shown as one stack because the at-risk species are threatened by mines from both countries.

Future species category shift

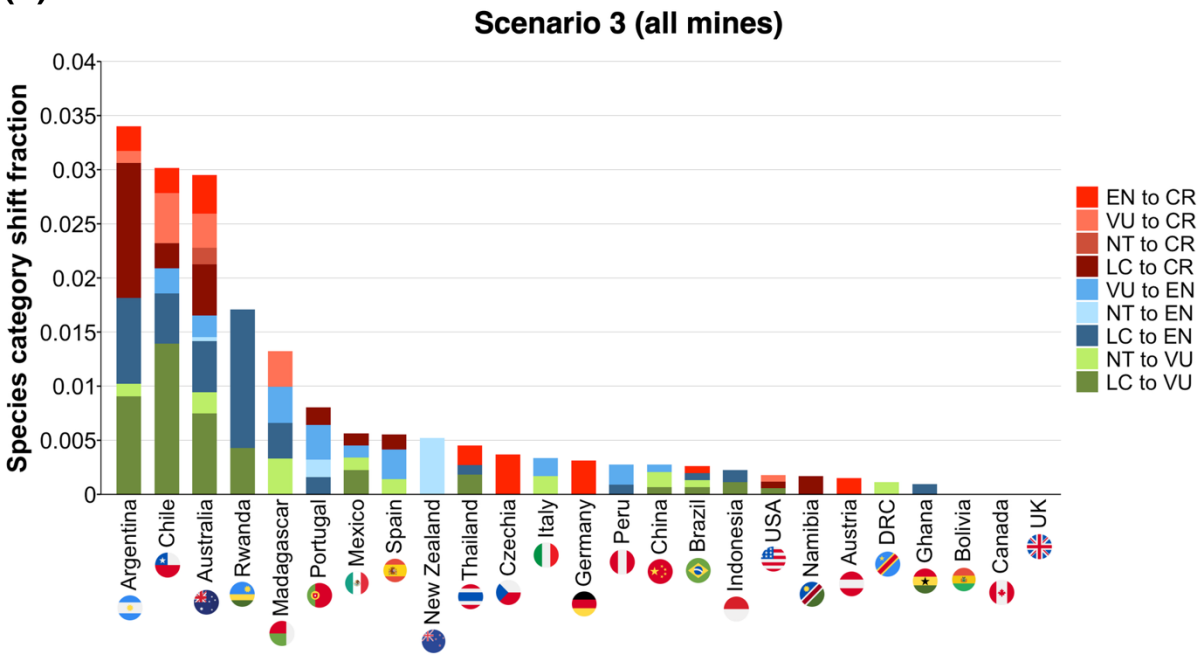
Across all three mine construction scenarios, at least 178 endemic species could be at risk of being pushed to more severe threat categories if negatively impacted by lithium mining. The majority of these species are plants (63-80 %) and reptiles (7-24 %) (**Fig. S15**). A considerable number of these species could dramatically shift from Least Concern to Endangered (9-43 species) or even Critically Endangered (5-28 species). 34-41 % of the plant species that could shift to more severe categories are from the *Eucalyptus* genus. The majority of the reptiles are lizard species from the *Liolaemus* genus (53-75 %). By country, Australia has the greatest number of species that could shift categories (75 in Scenario 3), with 33 species (44 %) that could become Critically Endangered. Argentina follows behind Australia, with potentially 30 species in danger of shifting to more severe categories. We found Argentina to have the highest fraction of potentially impacted species that could shift categories (~0.034), the majority of these from Least Concern to Critically Endangered. Chile and Australia follow closely behind, with species category shift fractions of ~0.03 and ~0.029, respectively.

We found Australian lithium mines to exhibit the largest potential future threat score increase, their combined total extinction threat score rising from ~48 at present to potentially ~80, over 1.5-fold greater. The threats posed by Argentinian and Chilean lithium mines could also become significantly greater in the future, with their total extinction threat scores increasing from ~7 to ~21 and ~9 to ~13, respectively. On a per species threatened basis, similar trends are observed, with Australia having the greatest future per species extinction threat score (~0.032). Chile and Argentina follow closely behind at ~0.029 and ~0.024, respectively.

(a)


Scenario 3 (all mines)
Number of species shifting to a more severe threat category
100
90
80
70
60
50
40
30
20
10
0
Australia
Argentina
Rwanda
Chile
Mexico
Portugal
Thailand
Brazil
China
Madagascar
Spain
Peru
USA
Czechia
Germany
Indonesia
Italy
Austria
DRC
Ghana
Namibia
New Zealand
Bolivia
Canada
UK
EN to CR
VU to CR
NT to CR
LC to CR
VU to EN
NT to EN
LC to EN
NT to VU
LC to VU

(b)


Scenario 3 (all mines)
Species category shift fraction
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Argentina
Chile
Australia
Rwanda
Madagascar
Portugal
Mexico
Spain
New Zealand
Thailand
Czechia
Italy
Germany
Peru
China
Brazil
Indonesia
USA
Namibia
Austria
DRC
Ghana
Bolivia
Canada
UK
EN to CR
VU to CR
NT to CR
LC to CR
VU to EN
NT to EN
LC to EN
NT to VU
LC to VU

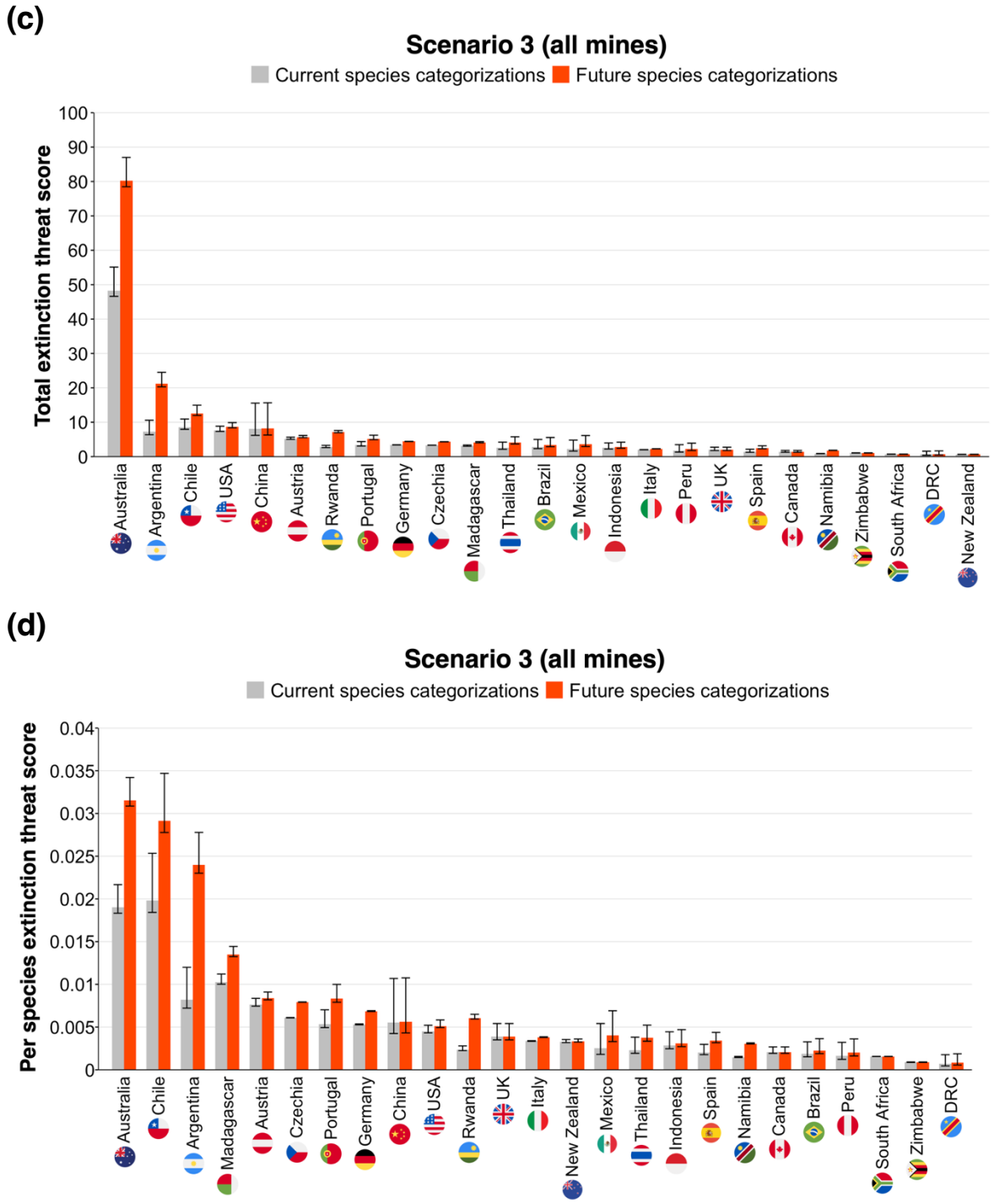


Figure 5 | Future species Red List category shift and extinction threat scores in Scenario 3 (all mines). (a) Number of species at risk of shifting to a more severe threat category per country, **(b)** Fraction of Red List species potentially coinciding with each country's mines that could shift to a more severe threat category, **(c)** Top 25 future country total extinction threat scores, assuming all species that could shift to a more severe threat category do, **(d)** Top 25 future country per species extinction threat scores, determined by dividing country total future threat score by number of Red List species potentially impacted by the country's mines. Values are for a 50 km terrestrial buffer / 100 km aquatic attenuation model. Flag icons reprinted with permission from www.flaticon.com. Species category shift analyses for Scenario 1 ("Active" mines only) and Scenario 2 ("Active" and "Under Development" mines) can be found in the Supporting Information.

Discussion

Biodiversity hotspots as indicators of high-risk lithium mines

We attribute the acute extinction threat posed by the highest scoring mines, particularly those in Australia, Chile, and Argentina, to a common phenomenon – their co-location with biodiversity hotspots. Biodiversity hotspots are regions containing exceptionally large numbers of endemic species that are also heavily threatened by habitat loss[64]. At present, there are 36 such designated regions around the world[65].

All seven of the Australian lithium mines that rank in the top 10 mines by total extinction threat score exist within the Southwest Australia biodiversity hotspot, where over 50 % of local plant species are found nowhere else[66]. Taking the Mt Cattlin mine as an example, 95 % of the mine's total threat score is from plant species. A large share of these plants are extremely range-restricted species from the *Eucalyptus* genus (43%).
E. purpurata is the most severely confined of these species, having only one known locality and a very narrow range (~70 km^2) that is entirely covered by the mine's potential impact area[67]. Mining-induced population decline could further increase the *Eucalyptus* species' risk of both local and global extinction.

Numerous Australian mines' occurrence in a biodiversity hotspot also helps explain Australia's large number of species potentially shifting to more severe threat categories and high future threat score. As many species in the region are range-restricted, even those that are not currently listed in high severity Red List categories could still face dramatically elevated extinction risks from adverse mining impacts. This is evident for the Mt Cattlin mine, which coincides with up to 14 endemic *Eucalyptus* species currently categorized as Least Concern or Near Threatened that could be pushed to Endangered or Critically Endangered if they begin to experience population or habitat instability. These 14 species' category shift would alone be responsible for over 50 % of Mt Cattlin's potential future score increase.

To the best of our knowledge, this result is the first time the potentially severe ecological threats posed by Australian lithium mining have been articulated. Cabernard *et al*. identified the potential for bauxite, gold, and coal mining in southwest Australia to cause biodiversity loss, however their results do not include the impacts of lithium mining in the region[68]. Yu *et al*. acknowledged that demand for clean energy technologies and concurrent lithium mining in Australia could increase biodiversity loss risks, though their analysis similarly focuses on other metal mines such as coal and copper[69].

Chilean lithium mines' ecological threat is not immediately clear when considering total extinction threat values, in which Australia scores over five times higher than Chile. However, Australia also has nearly six times more published Red List species than Chile, a product of both Australia's greater inherent species richness and potential biases in the Red List data collection process itself[70,71]. Additionally, Australia has over four times more total lithium mines than Chile, meaning the area over which its species could be impacted is significantly larger. As a result, Australian lithium mines could cumulatively overlap with 2,937 Red List species' ranges, compared to 437 for Chile. Chile's higher per species threat score therefore indicates that, while Chilean lithium mines could impact fewer total species than Australian lithium mines, the average extinction threat each of these species faces is greater in Chile than it is in Australia. Including this more nuanced perspective is crucial to avoid solely focusing attention on regions with many mines or large numbers of species, which risks glossing over potentially serious risks to rare and/or endemic taxa in other geographies.

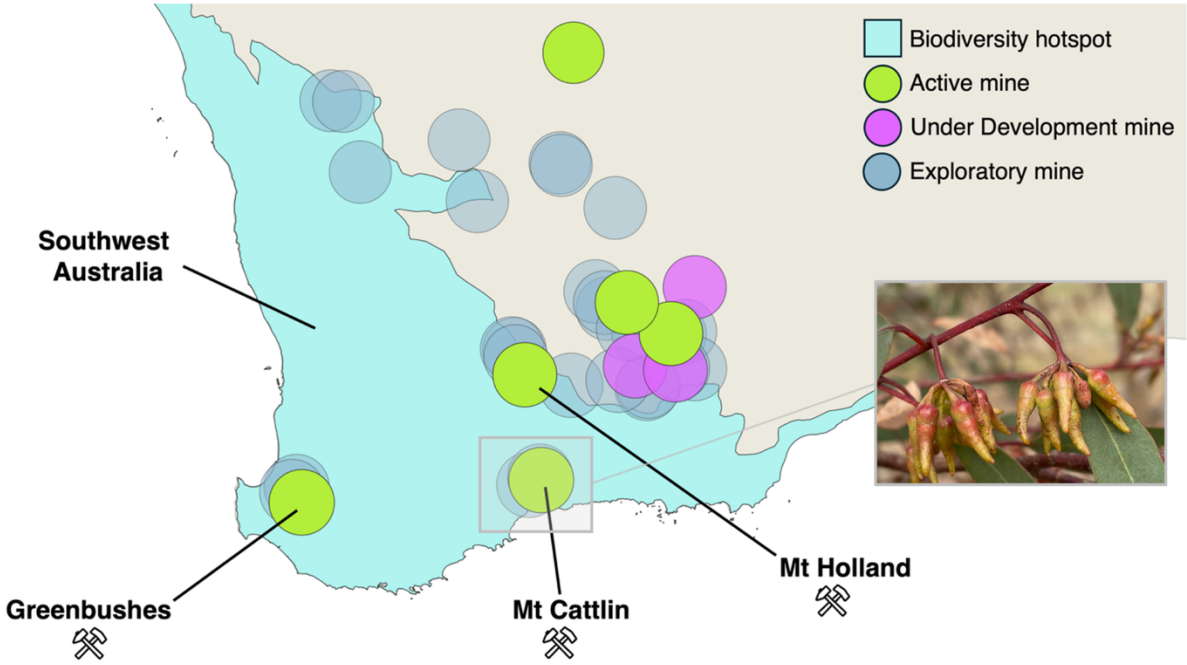
All 17 operational and prospective Chilean lithium mines are located within the Tropical Andes and/or Chilean Winter Rainfall-Valdivian biodiversity hotspots. Similar to Southwest Australia, both of these hotspots are known for their abundance of endemic plant species[65]. However, plant species ultimately contribute only ~ 10 % of Chile's total extinction threat score, with reptiles and amphibians contributing much larger shares (~ 70 % combined). This is because, although biodiversity hotspots are often defined based on their local plant species, the endemic richness observed in plants in these regions is also generally thought to be similar for other terrestrial taxonomic groups[72,73]. It is therefore important to consider that lithium mines in biodiversity hotspots such as those in Chile could threaten non-plant endemics in addition to plant species. *Liolaemus,* a genus of lizards accounting for three-quarters of the reptiles in the Chilean Winter Rainfall-Valdivian hotspot, is one such example[74]. We identified a total of six "high-risk" *Liolaemus* species that could be significantly threatened by Chilean mines and up to seven that could potentially be pushed to more severe Red List categories.

Including Argentinian mines, which also coincide with numerous *Liolaemus* species, this total could increase to 23 species potentially shifting categories – close to 10 % of the genus' known species. As with *Eucalyptus* in Australia, many of the *Liolaemus* species that could shift categories are currently listed as Least Concern but could qualify as Endangered or Critically Endangered if impacted by mining activities. This also helps explain Argentina having the highest fraction of species at risk of shifting categories and the 2nd highest total

future threat score. ~70 % of Argentina's potential future threat score increase can be attributed to category shift from range-restricted *Liolaemus* species. Like Chile, nearly all the Argentinian lithium mines are also located within a biodiversity hotspot (Tropical Andes).

Our observations surrounding Canadian lithium mines offer another perspective on the relationship between mine overlap with biodiversity hotspots and extinction threat. As stated in the **Results**, Canada has a disproportionally low total threat score relative to its abundance of lithium mines. All Canadian mines also have identical current and future threat scores, indicating they are unlikely to cause Red List species to shift to more severe threat categories. Canada is starkly different from the high scoring Australian and South American lithium mining regions in its ecological makeup; it contains no biodiversity hotspots and has relatively low endemic and threatened species richness[75]. This provides additional evidence that degree of local species endemism is a key determinant of a mine's threat score. Lamb *et al.* raised a similar point, concluding that hotspot regions with high endemism face heightened vulnerability to biodiversity loss from mineral extraction[40].

(a)



(b)

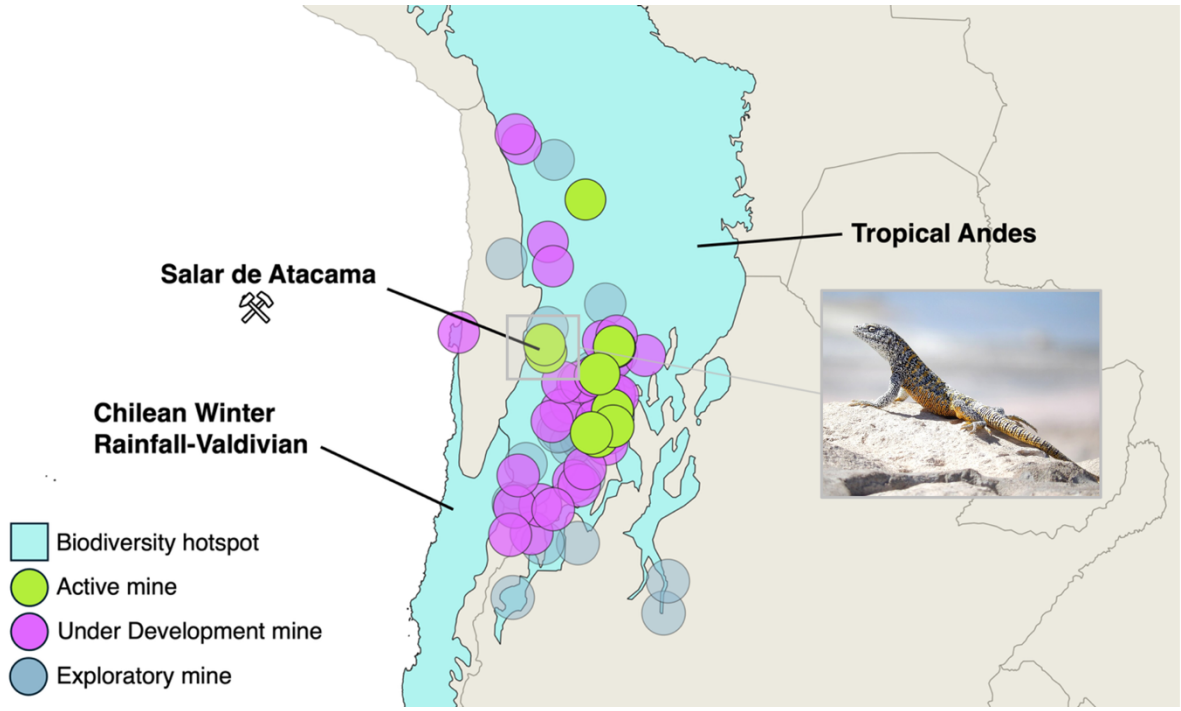


Figure 6 | The co-location of Australian, Chilean, and Argentinean lithium mines with biodiversity hotspots. (a) The Southwest Australia biodiversity hotspot overlapping with Australian lithium mines across the three mine categories. The operational Mt Cattlin, Greenbushes, and Mt Holland mines are also labelled. *Eucalyptus purpurata*, which occurs within the Mt Cattlin mine impact area, is shown. The image was reprinted with credit to Dean Nicolle under CC BY-NC 4.0 and is available at https://www.inaturalist.org/photos/268603015, **(b)** The Tropical Andes and Chilean Winter-Rainfall Valdivian biodiversity hotspots overlapping with Chilean and Argentinian lithium mines across the three mine categories. The operational Salar de Atacama mine in Chile is also labelled. *Liolaemus fabiani*, which occurs within the Salar de Atacama mine impact area, is shown. The image was reprinted with credit to Daniel Colas under CC BY 4.0 and is available at https://www.inaturalist.org/photos/349230384.

Potential drawbacks of global biodiversity assessments

While lithium mine co-location with biodiversity hotspots is a strong indicator of outsized extinction risks, mines outside of these regions can also coincide with and threaten endemic species. This is apparent for the mines driving China's total threat score, the 3rd highest overall after Australia and Chile. Our results show that lithium mines in China's southeastern regions, despite not falling within designated biodiversity hotspots, could significantly threaten several endemic species, particularly freshwater invertebrates (**Fig. S16**). One explanation for this discrepancy is the tendency of freshwater ecosystems to be underrepresented in global biodiversity assessments (including hotspots), which are mostly centered around terrestrial species[76]. Furthermore, regions of terrestrial and freshwater endemism are often incongruent, meaning they cannot be assumed to be proxies for one another[77]. Lithium mine overlap, or lack thereof, with normative biodiversity hotspots is therefore unlikely to be indicative of the magnitude of threats local freshwater species may

face. An additional barrier to accurately capturing potential lithium mining impacts on freshwater ecosystems is that many Red List freshwater species (~ 25 %) are currently categorized as Data-Deficient, meaning there is insufficient information available to estimate their extinction probabilities[78]. This is also true of the most significantly threatened freshwater invertebrates we identified in China, with the seven highest scoring species all currently considered Data-Deficient. Due to the lack of clarity surrounding their extinction risks, Data-Deficient species are often excluded from biodiversity monitoring and typically receive far less attention than classified threatened species in conservation interventions[79]. Compounded with freshwater species' already marginalized status in biodiversity assessments, this suggests there is significant risk of the ecological threats of lithium mining in southeast China and other regions with similar species characteristics being improperly understood and addressed.

Like China, the USA also contains several lithium mines, namely those in Nevada, North Carolina, and California, that are not located within biodiversity hotspots but could nevertheless threaten multiple endemic, endangered Red List species (**Fig. S17**). Two previous studies on the potential biodiversity impacts of lithium mines in the USA broadly support this finding, with both identifying numerous species included on federal and/or state-level endangered lists that could coincide with proposed sites in Nevada and California[37,38]. Furthermore, a deeper examination of the species noted in these studies in comparison to those identified in our work reveals that, alongside the limitations of biodiversity hotspot co-location approaches, sole reliance on the Red List to comprehensively capture the species extinction threats posed by lithium mines can be insufficient. *Eriogonum tiehmii* (Tiehm's buckwheat), a rare buckwheat species found in Nevada, exemplifies this point. In their study, Clifford *et al.* flagged Tiehm's buckwheat as facing a high risk of extinction from lithium mining because of its extremely narrow range – the species' sole population is restricted to an approximately 10-acre area (0.04 km^2) located directly on the site of the planned Rhyolite Ridge mine[80]. The mine's potential ecological consequences are also well-understood locally, with community and environmental groups raising strong opposition to the project on the basis of its existential threat to the plant[81]. However, despite the buckwheat's imperilled status being known, it is not currently included in the Red List and therefore not reflected in our calculated threat score for Nevada. This is because, whilst the Red List is undoubtedly the best global database currently available, it ultimately only covers 8 % of the world's described species, and an even smaller fraction of the species thought to exist on Earth[70]. This suggests that, not only could our threat scores be underestimates for the Rhyolite Ridge

mine and Neveda more broadly, but they could also be for any other projects with endemic or threatened species in their vicinities that are not on the Red List.

Recommendations and Broader Perspectives

Our study's focus on the species facing the greatest threats of extinction from lithium mines, while indeed crucial, should not be considered in isolation. Species exist within deeply complex ecosystems and their survival often requires a vast collection of other species to be present for food, habitat, pollination, etc. This is particularly relevant in biodiversity hotspots where non-focal species, including those that are currently undescribed, are likely to be narrow-ranging and endemic to similar extents as well-documented Red List species in these regions[82]. Exclusively focusing on a small number of rare species can be problematic when aiming to prevent wider ecological degradation, unless the species also act as important "umbrella" species (those whose conservation could, in turn, protect other local species) and/or "flagship" species (well-known, charismatic animals that generate public interest) that sustain broader ecosystem integrity[83,84]. The species underpinning our analysis should therefore be thought of as "canaries in the coal mine" that indicate where lithium mining could pose outsized risks of contributing to species extinctions and hopefully spur further investigation into these sites. This further investigation should involve use of a more robust framework for capturing the totality of species-level mining impacts, include a deeper mechanistic understanding of the effects of habitat loss and metal pollution on species population declines as a precursor to local, regional, and global biodiversity loss. Additionally, as global datasets like the Red List and biodiversity hotspots do not exhaustively represent all species/regions that could be adversely affected by lithium mining, this framework must prioritize incorporating local ecological knowledge, obtained through consultation with communities, NGOs, and government agencies.

Future threat evaluation methodologies should also be designed to help better inform the Red List's species assessments, along with national and regional species conservation lists. While we found reasonable alignment between our results and the species the Red List have classified as facing ongoing threats from mining, there were still several potentially threatened species we identified whose threats are not represented in the database – some with ranges coinciding with direct mining areas (**Fig. S4**). Nimmo *et al.* similarly concluded that mining-related threats to threatened species are frequently underestimated and insufficiently recognized in the Red List's assessments[85]. Comprehensive identification and reporting of lithium mining threats to species is especially critical for those with restricted

ranges that are not currently considered threatened. Given that these species could face unexpectedly high extinction risks from lithium mining impacts, it is crucial that any future frameworks enable more detailed, proactive identification of potential threats they may face before, rather than after, they start being negatively affected.

Globally expanding lithium mining ultimately presents a sustainability paradox. Decarbonized transportation is urgently needed for combatting the climate crisis, itself a major driver of species extinctions, and EVs are a viable technology for helping accomplish that. However, if the mineral extraction supplying EV battery production leads to extensive biodiversity loss, the consequences for both human well-being and global ecological integrity could be severe. At the same time, fossil fuel extraction causes much of the same environmental harm as mining at a larger scale, while also fuelling the climate crisis[86,87]. Therefore, a future that preserves the status quo is not acceptable either. Ultimately, a responsible decarbonization pathway ensuring carbon emissions can be eliminated while protecting ecosystems and biodiversity is necessary. Our results provide support for this pathway by highlighting regions where priority attention is needed to prevent lithium-mining-induced species extinctions. Southwest Australia, Chile and Argentina's portions of the Lithium Triangle, southeast China, and the western United States all stand out in this regard. Our findings could also serve as an evidence base for the establishment of mining "No-Go" zones – where extraction is off-limits – within high-risk areas such as biodiversity hotspots and locations with exceptional species endemism more broadly[88]. Finally, though not directly evaluated in this work, it is crucial to reiterate that surging downstream demand is the fundamental driver of lithium mining and its consequent ecological threats. Achieving responsible decarbonization therefore also requires interrogating the core assumptions underpinning future lithium and EV demand projections, along with seriously considering ways to limit lithium mining without hindering climate action. This could involve reducing lithium consumption alongside carbon emissions through behavioural and policy changes, including decreased personal vehicle ownership, smaller vehicle sizes, increased public transportation, and mandated metal recycling[89].

Limitations and Outlook

It is very important to acknowledge that this work's scope and framing, which center the ecological aspects of expanding lithium mining, offer only one lens into a complex and multifaceted issue. As stated in the Introduction, mineral extraction can not only cause serious harm to local species but also to local people. Therefore, the social and human rights implications of lithium mining must also be thoroughly understood alongside those

related to ecosystems and biodiversity. One example is the disproportionate impacts Indigenous peoples are facing, and could continue to face, due to increasing mineral demand[90]. Several of the lithium mines in this study alone, namely those in Australia, Argentina, Chile, and the U.S.A, are directly on or near Indigenous peoples' territories[91]. Under international law, Indigenous communities must be consulted and provide consent before, during, and after any extractive projects take place on their ancestral lands[92]. Future efforts should prioritize improving cohesion between approaches for assessing the human and ecological dimensions of lithium mining impacts to inform more holistic solution frameworks.

This study also has several methodological limitations, alongside those previously mentioned, that should be improved upon. In particular, several aspects of the generalized 50 km buffer used to assess potential impacts to terrestrial species warrant refinement. For one, this method does not account for site-to-site variation in how impacts could propagate, which may vary drastically based on each mining area's environmental conditions. The 50 km radius also does not consider that different lithium mine types will likely have different impact mechanisms, as mentioned in the Introduction. Finally, the 50 km radius does not offer insight into how much species' ranges are affected by direct mining areas compared to broader mine impacts. For example, a species with a mine-range overlap fraction of 1.0 (100% of its range within the 50 km buffer) that occurs directly where a mine's pits are is treated the same as a species with an overlap fraction of 1.0 that is located away from the direct mine site, but still within the 50 km buffer area. While predicting the physical footprints of pre-operational mines is difficult, future efforts should nevertheless aim to develop enhanced methods of delineating indirect and direct mining impacts to better inform conservation efforts.

The three mine constructions scenarios are another methodological limitation of our study. Many factors including downstream demand, government policies, regulatory feasibility, and commodity prices influence a mine's likelihood of becoming operational. Given the uncertainty inherent to each of these factors, there is a possibility that a significant number of prospective lithium mines, particularly those in the "Exploratory" category, are never built. Therefore, our results for the full mine deployment scenario (Scenario 3) in particular should be viewed as indicative rather than definitive. Additionally, future studies should incorporate a wider range of criteria to better estimate the number of new lithium mines that could be built.

The Red List also has limitations that should be acknowledged, several of which we have already discussed. One significant additional limitation is that Red List species' extinction statuses are typically only reassessed every 5-10 years. It is therefore possible that species' populations or habitats have deteriorated further than their Red List categorizations indicate and our extinction threat scores are not reflective of their current states. Furthermore, it is possible that species located near active lithium mines may already be facing detrimental impacts to their populations that will not be recorded by the Red List until the species' next reassessment. In terms of the Red List species selected for this analysis, it is also worth noting that we excluded the dataset's marine species, since all the mines studied are in terrestrial environments. However, as mine pollution can travel downstream through rivers and eventually reach the ocean, future work should incorporate potential impacts to marine ecosystems.

Supporting Information

Additional information related to this study can be found in the Supporting Information and Supporting Databook. Supporting Information: Mt Cattlin mine *Eucalyptus* species (Extended Discussion S1); *Telmatobius* frog species in South America (Extended Discussion S2); difference between AOO, EOO, and range (Extended Methods S1); example threat score calculation (Extended Methods S2); IUCN Red List Criteria B (Extended Methods S3); threat score ranges by Red List category (Extended Methods S4); operational mines areas compared to Maus *et al*., 2022 (Extended Methods S5); combining mine polygons for cumulative impact analysis (Extended Methods S6); freshwater species impact model visual (Extended Methods S7); comparison of measured species threats with those reflected in the Red List for two mines (SI "Ground truthing" analysis); comparison of our threat score and STAR metric for two mines (SI STAR metric comparison); mine threat scores with and without mine footprint included (Figure S5); sensitivity analysis on buffer and attenuation distances (Figures S6-S11); future threat scores for "no AOO loss" scenario (Figure S12); species category shift for scenarios 1 and 2 (Figures S13 and S14); species category shift by taxa for scenario 3 (Figure S15); biodiversity hotspot overlap for China and USA mines (Figures S16 and S17); "high-risk" species by scenario (Table S8-10). Supporting Databook: mine information (S1 Mine info); threat scores by mine (S2 Threat scores – indiv.); threat scores by country (S3 Threat scores – country); global list of at-risk species not including Data-Deficient species (S4 Species list by mine – no DD species); global list of at-risk Data-

Deficient species (S5 DD species list by mine); list of species shifting to a more severe threat category assuming AOO thresholds (S6 Species category shift – AOO thresholds); list of species shifting to a more severe threat category assuming EOO thresholds (S7 Species category shift – EOO thresholds).

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Data Availability

The list of 400 lithium mines was provided by a leading battery supply chain market intelligence provider (name withheld at their request). A summary of the mines' names, types of lithium resources, coordinate locations, and mineral resource estimates (if available), along with the references for each, can be found in the **Supporting Databook**. IUCN Red List species range polygons (with the exception of birds) can be downloaded from https://www.iucnredlist.org/resources/spatial-data-download. Bird range polygons can be downloaded from https://datazone.birdlife.org/. Biodiversity hotspot polygons can be downloaded from https://www.cepf.net/our-work/biodiversity-hotspots/hotspots-defined.

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