Global Environmental Change 69 (2021) 102303

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Surge in global metal mining threatens vulnerable ecosystems

Sebastian Luckeneder [a,*], Stefan Giljum [a], Anke Schaffartzik [b], Victor Maus [a,c], Michael Tost [d]

[a] Institute for Ecological Economics, Vienna University of Economics and Business (WU), Austria
[b] Institute of Social Ecology, University of Natural Resources and Life Sciences, Vienna, Austria
[c] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
[d] Chair of Mining Engineering and Mineral Economics, Montanuniversität Leoben, Austria

ARTICLE INFO

Keywords:
Mining
Natural resources
Raw material extraction mapping
Socio-environmental impact

ABSTRACT

Mining activities induce profound changes to societies and the environment they inhabit. With global extraction of metal ores doubling over the past two decades, pressures related to mining have dramatically increased. In this paper, we explore where growing global metal extraction has particularly taken effect. Using fine-grain data, we investigate the spatial and temporal distribution of mining of nine metal ores (bauxite, copper, gold, iron, lead, manganese, nickel, silver and zinc) across approximately 3,000 sites of extraction worldwide between 2000 and 2019. To approach the related environmental implications, we intersect mining sites with terrestrial biomes, protected areas, and watersheds categorised by water availability. We find that 79% of global metal ore extraction in 2019 originated from five of the six most species-rich biomes, with mining volumes doubling since 2000 in tropical moist forest ecosystems. We also find that half of global metal ore extraction took place at 20 km or less from protected territories. Further, 90% of all considered extraction sites correspond to below-average relative water availability, with particularly copper and gold mining occurring in areas with significant water scarcity. Our study has far-reaching implications for future global and local policy and resource management responses to mitigate the negative effects of the expected expansion of metal mining.

1. Introduction

Mining plays an ambiguous role for society. It has become indispensable to the model of economic growth currently pursued in industrialised, mineral-based societies. But it is also among the most environmentally and socially hazardous human activities. Its harmful consequences for the environment and its catalysing association with social conflicts are well-documented (Scheidel et al., 2020; Conde, 2017; Bebbington et al., 2008; Bridge, 2004). Unprecedented and rapidly growing extraction of metals and minerals during the past two decades (Schandl et al., 2017; Schaffartzik et al., 2014) and the projected increase in material demand (UN IRP, 2019; OECD, 2019) are alarming signs that associated impacts will intensify in the future.

The surge in global metal mining signifies an increased production of metal commodities through establishing new mining projects, physical expansion of existing sites and intensifying and optimising the extraction process. It is part of an overarching trajectory of globally increasing resource use, referred to as the Great Acceleration (Steffen et al., 2015), which is pushing the global economy's metabolism up against Planetary Boundaries (Rockström et al., 2009). Differences in growth dynamics of the extractive sector are apparent, with countries and regions unequally contributing to this global trajectory (Dorninger et al., 2021; Schaffartzik et al., 2016). Local mining expansion and intensified production, as well as related impacts in the immediate surroundings of the sites of extraction, are closely coupled to overarching global change, calling for a "multilevel perspective" (Gibson et al., 2000) to understand the environmental and social implications of mining's worldwide growth. By studying the local expressions of the global surge in mining in a spatially explicit manner, we seek to advance the empirical understanding and conceptual framing across levels of scale.

This paper presents and contextualises a detailed assessment of how metal mining volumes are distributed across almost 3,000 mining projects worldwide, covering nine metal ores (bauxite, copper, gold, iron, lead, manganese, nickel, silver and zinc) in the period 2000–2019. We explore whether the development of global metal mining has particularly affected vulnerable ecosystems around the world and identify hotspots of raw material extraction and ecosystem impact. We assume extraction gains to be associated with additional pressures, because production volumes are likely related to the areal extent of mining sites (Werner et al., 2020) and intensified use of heavy machinery. Based on

* Corresponding author at: Vienna University of Economics and Business (WU), Welthandelsplatz 1, 1020 Vienna, Austria.
E-mail address: sebastian.luckeneder@wu.ac.at (S. Luckeneder).

https://doi.org/10.1016/j.gloenvcha.2021.102303
Received 11 December 2020; Received in revised form 8 April 2021; Accepted 13 May 2021
Available online 3 June 2021

our large-scale empirical assessment, we discuss the environmental implications of the expected increase in mining activities. We pave the way for in-depth local studies and future assessments of the cumulative magnitude and transmission of impacts, and summarise how mining companies and policies can contribute to impact mitigation.

In order to gauge the potential impact of mining on ecosystems, we focus on ecosystem vulnerability. Vulnerability has been debated in sustainability science under definitions such as "the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or a stress/stressor" (Turner et al., 2003, p. 8074). In their extensive review, Weißhuhn et al. (2018) suggest the term ecosystem vulnerability as being preferable to ecological, environmental, or other notions of vulnerability and propose a framework with "exposure", "sensitivity", and "adaptive capacity" defining the degree of vulnerability. They stress that such a perspective on vulnerability is biocentric (Birkmann and Wisner, 2006) rather than anthropocentric, because it understands environmental systems as being affected by natural and anthropogenic drivers, instead of being sources of hazards that influence human systems. In employing this concept in the context of intensified mining, we investigate whether the acknowledgement of ecosystem vulnerability deters extraction.

For the purposes of this paper, we assume that mining activities exert pressure on all ecosystems, but that certain areal characteristics can be identified which are considered to signal particular vulnerability. Our study uses three spatial layers as proxy indicators for ecosystem vulnerability: terrestrial biome categorisations, protected areas, and water scarcity. Subsequently, we connect these layers with spatio-temporal patterns of extraction at the mine level. In doing so, we combine approaches from previous work dealing with single environmental layers and their respective links to mining. Murguía et al. (2016) and Sonter et al. (2018) demonstrate how mining relates to biodiversity loss. Durán et al. (2013) find that metal mining activities undermine the role of protected areas as a key policy tool for conservation. Regarding an intersection of mining sites with water scarcity indicators, Northey et al. (2017) find that the exposure of areas to water risk is especially high in the case of copper mining. Recently, studies have also investigated the areal extent of mines, either based on estimations, such as Tost et al. (2020), or by the use of satellite imagery (Maus et al., 2020; Werner et al., 2020). These studies focus on cross-sectional analyses of a specific selection of metals, such as four key metals in Durán et al. (2013) or of the locations of base metal resources in Northey et al. (2017). Our study builds upon these approaches to provide the first fine-grained assessment of metal mining regions on a worldwide scale, covering nine major metal commodities across a 20-year period.

We find that the rapidly expanding mining sector exerts increasing pressures on ecosystems recognised as vulnerable. Our results show that there is a substantially skewed distribution in terms of extraction volumes, i.e. extraction per mine is not evenly distributed around a certain value, but a minority of mines reports much higher figures than the mass. Further, regional hotspots of mining growth have emerged during the observed time period, in particular in Latin America, Central Africa, India, and Western Australia. Due to the multilevel approach, our findings have substantial implications for future global and local policy responses, supporting calls for a stricter set of rules for accessing primary resources.

2. Material and methods

2.1. Mining data and environmental spatial layers

We utilised mine-specific production data from the SNL Metals and Mining Database[1] (SNL, 2020). Projects were considered for which SNL reported any mining of bauxite, copper, gold, iron, lead, manganese, nickel, silver or zinc within the time period 2000–2019, in total summing up to 2935 individual mines. Focusing on the 21st century obviously presents a limitation, but it allows to cover the entire period of what might be considered the "second great acceleration" (Görg et al., 2020) of resource use at the global level.

Except for bauxite, iron and manganese, which are listed as ores (gross weight), metal production is reported as metal content (net weight). In order to construct a homogeneous measure of extracted crude ore that is used as an input from the natural environment to the economic system, we applied country- and commodity-specific conversion factors from UNEP's Global Material Flow Database (UN IRP, 2017) to all net weight commodities. This measure, referred to as "extraction" or "metal ore" in the following, corresponds to the actual amount of extracted material exerting pressure on the environment instead of a final product after several processing steps.[2] Fig. 1 provides a summary of the data and illustrates variations in extraction volumes and increasing extraction rates for the nine metal ores. For more detail, see S 1.1 and 1.2 in the supplementary material.

We considered this set of base and precious metals in our study because of their extensive industrial use. Next to construction materials, coal and crude oil, iron, bauxite and copper ore feature the highest extracted mass among mineral resources (Murguía et al., 2016). Schaffartzik et al. (2016) name iron and aluminium (we consider bauxite) being quantitatively most important. Together with other metals in smaller amounts including lead, manganese and copper they form the "skeleton of industrial development" (ibid.: 103). Similar selections are made, for example, by Durán et al. (2013) and Northey et al. (2017), additionally including zinc and nickel. We furthermore consider the precious metals gold and silver, because of the high prevalence of such mining facilities (Murguía et al., 2016) and persistent exploration expenditure due to high market value (Ali et al., 2017). Other metals with growing demand, such as cobalt or rare earth metals, were not covered in our analysis as they were poorly reported in the database at hand.

We are aware that assuming national averages as ore grades introduces uncertainty in the data. As a validation of coverage and quality, we compared annual metal extraction according to our dataset (based on reports of production from individual mines) with official UNEP IRP statistics (based on national accounts). In the supplementary material, we demonstrate that our extraction data provides reliable coverage, mimicking extraction trends reported by other sources (S 1.3.1). Largest gaps between our modified SNL aggregates and UNEP IRP figures occur because of country-level irregularities, most notably regarding China. For the case of iron, approximately 1,500 Megatonnes (Mt) of Chinese iron ore extraction in 2017 is missing in the SNL data compared to UNEP IRP. Moreover, we illustrate that assumptions about ore grades influence extraction estimates for individual mines (S 1.3.2). For comparison, we considered copper mines of four countries and mine-specific ore grades available from Mudd and Jowitt (2018). The exercise suggests that assumed national averages are conservative, as they rather lead to under-estimating extraction, and that estimates from both approaches correlate well. However, we must also note that we found substantial deviations for some extraction countries, such as Peru, where estimates of the considered sample sum up to 350 Mt when utilising individual ore grades while they only amount to 90 Mt using the UNEP average grade.

[1] This database, offered by Standard and Poor's (S&P) Market Intelligence, provides extensive operative and financial information on thousands of mining projects based on company reports.

[2] Waste rock is excluded because this information is not yet available for global analyses, but it would be extremely valuable to researchers and policy makers. We expect that an inclusion of over- and interburden might allow for a better approximation of the potential disruption to the local system.

Fig. 1. Global extraction of bauxite, copper, gold, iron, lead, manganese, nickel, silver and zinc ores based on SNL (2020) and UN IRP (2017) conversion factors. Please note the differences in scale on the y-axes. See Table S2 in the supplementary material for underlying data.

Difficulties to fully consider artisanal and informal mining on a global scale impose a limitation, again suggesting that the data we used represent under- rather than over-estimations of material extraction. The environmental pressures related to small-scale mining will be at least as strong and possibly farther-reaching compared to larger mines considered in our study (Asner et al., 2013; Caballero Espejo et al., 2018).

Exposure to environmental complexity was assessed by spatially intersecting extraction data with terrestrial biome categorisations (accessed from Resolve, 2017 based on Dinerstein et al., 2017). Biomes are defined as communities of plants and animals occurring together under certain climate conditions (Resolve, 2017). They systematically subsume the richness of an area's ecosystem in terms of variety in and number of species. As another proxy for anthropocentrically recognised rich, special, or endangered biodiversity, we considered a spatial layer on protected areas (UNEP-WCMC, 2020). We calculated the distance to the closest protected area for each mine. Third, we considered the Available Water Remaining (AWARE) index (WULCA, 2019) as an indicator for water risk exposure (annual average at watershed level). It represents water availability after the demand of ecosystems and humans is met. While a variety of spatial water indices exists with each providing a somewhat different perspective on the interactions between water resources and mining (Northey et al., 2017), we chose this index for two main reasons. First, it provides spatial coverage for the entire set of considered mines except for Nalunaq mine in Greenland. Second, the AWARE index was designed to reflect potential water deprivation by other users of water – a suitable indicator given that mines utilise water in a number of processes. The index further features a convenient interpretation: It is limited between 0.1 and 100, where 1 corresponds to the world average and 10, for instance, represents water availability that is ten times less than the world average.

2.2. Approaches to analysing global distribution and extraction trends

We implemented three analytical steps in order to evaluate the surge in global metal mining between the years 2000 and 2019. We first assessed annual spatial distribution and concentration of global metal ore extraction. Second, we performed spatial overlay analyses to determine the extent to which increased production particularly occurs in recognisably sensitive areas with regard to species richness, need of protection, and water availability. In doing so, we also addressed differences in extraction patterns across the nine commodities. Third, to detect the most critical developments and based on our findings from the layer analyses, we performed an assessment of hotspots among the three environmental layers. An illustration of our workflow is provided in Fig. 2.

To facilitate visual interpretation, we aggregated annual metal mining into 1×1 degree cells (corresponding to approximately 110 km at the equator) by summing up the total ore extraction across all nine metals. This simplification serves as an initial, high-level picture of the spatial distribution of global metal ore extraction. It cannot point out potential environmental impacts that occur in direct and up to only a few km proximity to mines, nor does it reflect the actual number and specifics of mining projects such as type and scale within each grid cell. However, recent studies show that assuming biodiversity (Sonter et al., 2020) and deforestation (Sonter et al., 2017) effects within at least a 50 km wide radius around mines is reasonable, and hence the map provides a first estimate of potentially negatively affected areas and indicates the corresponding extraction volumes (for a more conservative grid of 0.5 and 0.1 degrees see supplementary material S 1.5). In order to intersect mining activities with regional environmental structure, we overlaid all mine sites with the three different spatial layers mentioned above and aggregated annual extraction volumes into the respective layer categories.

Trends in the extraction volumes were estimated employing a geographically weighted regression (GWR) model, modelling log-transformed extraction at the mine level as a function of time (see supplementary material S 2 and Brunsdon et al. (1996) for more detail regarding GWR). GWR captures the spatial structure within the data and yields spatially varying parameter estimates. In contrast to estimating a trend for each single spatial observation, GWR incorporates the information of surrounding mines weighted by geographical distance and hence reflects potential compound effects of mining on the environment in areas where multiple sites are close to each other. Extractive industries can have different relationships across regions such as networks of mines expanding in emerging mining regions, regional boosts in investment and new technologies or multiple mines being closed in certain areas as a consequence of decreased (economic) feasibility of mining.

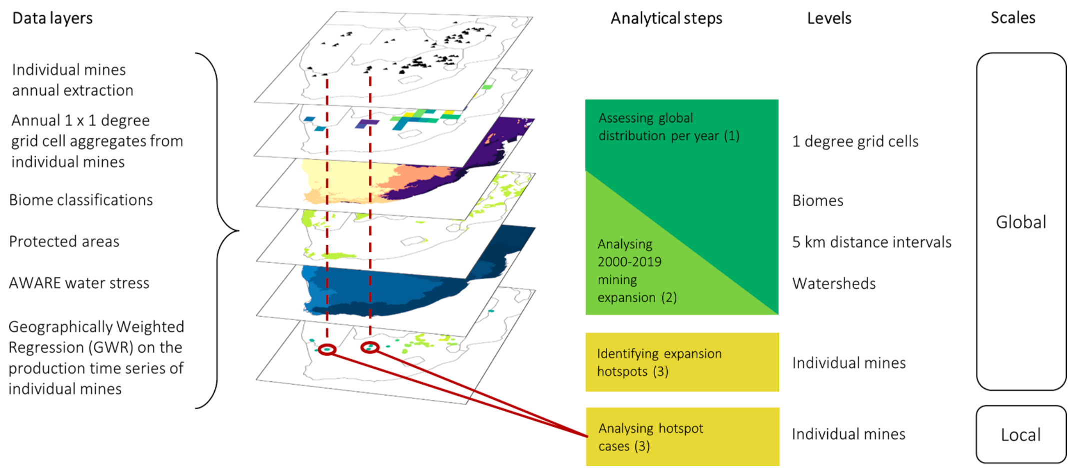

Fig. 2. Workflow of this study, highlighting utilised spatial data, analytical steps 1–3, and respective operational level and scale of each stage. Dashed red lines represent links across layers, and solid red lines indicate syntheses of information.

While the GWR approach makes it possible to depict sub-national densification clusters by reflecting heterogeneity within countries, it comes at the cost that it smooths over individual outlier cases within the clusters (using spatial weights assigned to proximate mining projects) that might also have critical impacts on the environment.

3. Results

The main findings of our study include global spatially explicit extraction volumes, the distribution of mining sites, and their intersection with terrestrial biomes, distance to protected areas and water risk classifications over the period 2000–2019. We also identify particular hotspots of mining intensification and expansion.

3.1. Spatial distribution of metal mining

Relative to the total earth surface, only a small area is used for mining. In a recent paper, Maus et al. (2020) estimated the global mining area at around 57,300 km^2, approximately the size of Croatia or Togo. In Fig. 3, we show all mining activities projected into 1 × 1 degree cells.[3] Among the mining cells, we observe strong heterogeneity regarding extraction volumes and a highly skewed distribution, i.e. a small fraction of mining areas reporting very large extraction volumes and vice versa. For 2019, about 95% of all mining areas indicate less than 25 Mt and half of the observations less than 1.3 Mt of extraction per cell, while a small fraction of cells yields extraction of up to 279 Mt.

Mining activities are spatially concentrated in Western Australia, Southern Africa, and along the Andes and into the Central and North American ranges of the American Cordillera. Furthermore, we find significant activities in Brazil, West Africa, India, China and Southeast and Central Asia. For China, we observe a considerable number of mining sites, but we also find that almost 80% of the observed cells show extraction volumes not larger than 2 Mt. Maus et al. (2020) also highlight that mining in China is characterised by many – on average smaller – mining areas, while Australia reaches a comparable total areal extent with fewer, but larger mining sites. Certain clusters appear in strong concentrations within countries, such as in Brazil or along the Zambian and Congolese border. This fact is vital to consider for the discourse about mining and its impacts, as well as for global material flow analyses. Sizeable copper flows, for example, originate from the DR Congo, with extraction occurring only in a few mines in the very south of the country. Likewise, in Brazil, 90% of all iron ore extracted in 2019 can be attributed to only ten mining sites within the states of Pará and Minas Gerais.

The unequal distribution of extraction intensity across all mining regions shows a similar pattern across commodities, but on different scales regarding volumes, the number of mining regions and the degree of concentration. For more detail, see supplementary material S 1.6, where we resampled extraction data to 0.25 degree resolution and ordered the cells by their extraction volumes for all nine metals.

In Figs. 4a-c, we map the three environmental layers and indicate how mining sites are distributed across them. With regard to terrestrial biome classifications, most mines are located in temperate broadleaf & mixed forests (627 observations), tropical & subtropical moist broadleaf forests (594) and deserts & xeric shrublands (448), while only 39 sites lie in the tundra biome. The histogram in Fig. 4b illustrates that 92% of all mines are located within a distance of 250 km to a protected area. More than a third of the 2935 mines are in a range of 20 km, and 4.2% of all mining sites (i.e. 123 mines) are located within designated protected territories. Lastly, we detect that, on the one hand, only 280 mines, i.e. 9.5% of our full sample, are located in watersheds of above-average water availability. On the other hand, 13% of mines lie within areas of an index score higher than 60 (corresponds to 4.1 on the figure's logarithmic scale), i.e. within high water risk regions such as various Central and Eastern Asian deserts, the Chihuahuan Desert, and Southeast Australian temperate forests and savannas.

3.2. Surge in global metal mining in environmentally vulnerable regions

Having explored the uneven distribution of mining activities across the globe, we evaluated the intensification and expansion of mining against the backdrop of perceivable regional vulnerability to the harmful consequences of extractive practices. Fig. 5 illustrates how extraction volumes have developed in relation to the regional characteristics of the area in which they occur. It is important to note that "regional" in this sense refers to a wider understanding than specific localised features in the immediate surroundings of mines. Heterogeneity in space that occurs at more granular levels is not assessed here. Not only extraction volumes (see Section 3.1) but also biomes exhibit notable variation in size: the Mediterranean forests, woodlands & scrub biome extends over only 1.5% of global land surface while boreal forests/taiga are the largest biome covering 12%. We hence evaluated both absolute numbers (left panels in Fig. 5; in Mt) and relative trends (right panels; using 2000 as the base year) for the three spatial layers.

Fig. 5a shows that, in absolute values, deserts and xeric shrublands

[3] 2000, 2010, 2015 and 2019 maps separate by metal are available in the supplementary material (see S 3). For an evaluation of how the counts of mining cells have changed per commodity, see supplementary material S 1.4.

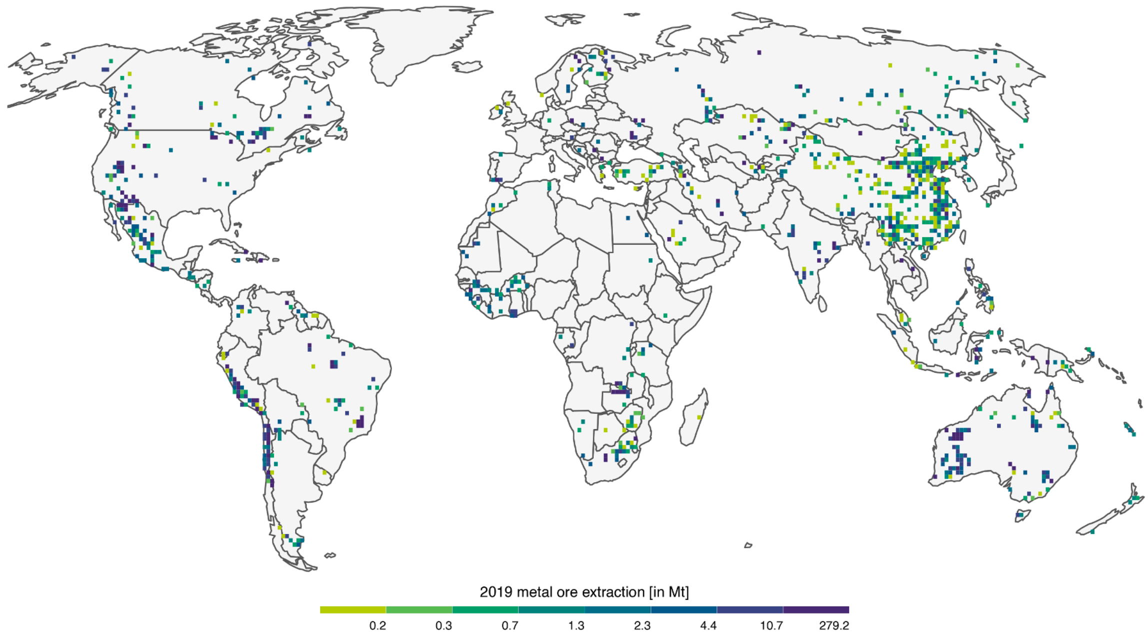

Fig. 3. Global 2019 metal ore extraction (in Mt) grouped by 8 quantiles on a 1 degree resolution (i.e. about 110 *km* × 110 *km* at the equator) using a Robinson map projection. Based on SNL (2020) and UN IRP (2017) conversion factors.

(DesXS) were the most exploited terrestrial biome during the past twenty years. In 2019, 2,241 Mt of metal ores were mined there, followed by tropical and subtropical moist broadleaf forests (TropSubMBF, 911 Mt) and temperate broadleaf and mixed forests (TempBMF, 614 Mt). Upon ranking all biomes according to their richness in species[4], we find that five of the six most complex terrestrial biomes jointly were the origin of 79% of total metal ore extracted in 2019. Next to the three biomes mentioned above, these five include montane grasslands and shrublands (MontGS) and tropical and subtropical grasslands, savannas and shrublands (TropSubGSS). While this pattern has not altered over the past twenty years and the ranking across biomes remained mostly unchanged since 2000, we see that extraction has changed in relative terms within biomes. The right panel of Fig. 5a shows that mining has intensified over time in all biomes except temperate conifer forests (TempCF) and MontGS. In TropSubMBF, the biome richest in species, metal ore extraction has increased by a factor of 2.1, due to, among others, the expansion of mining activities in the Central Range Papuan montane rain forests (New Guinea), the North Western Ghats moist deciduous forests and the Malabar Coast moist forests (India), and the Borneo lowland rain forests (Indonesia).

Nature reserves are a political instrument for protecting specific territories from anthropogenic environmental destruction. However, it is likely that the designation of conservation areas also accounts for current and potential future minerals extraction in some countries. As a second spatial layer, we examined the proximity of mining activities to protected areas. Fig. 5b depicts global extraction up to 50 km from such areas. In 2019, 50% of all global metal ore extraction took place within a 20 km boundary around protected territories, and 480 Mt (8%) were mined within officially protected zones. Similar to mining within biomes, we find that this is a pattern that has not changed fundamentally since 2000. But it has intensified. While the high concentration of metal ore extraction within a buffer of 20 km around protected areas appears to be a stable finding for the period considered in our study, it is the mining *within* protected areas that surged. Over the twenty-year period, mining in protected areas has risen from 225 Mt to 480 Mt, a 113% increase. Further, the figure suggests that there was a significant surge in mining in the 10–15 km range from protected areas.

The large increase of mining activities in protected areas is partly explained by new sites. Over the full period analysed in this study, 123 mines were detected within protected zones. The number of mining sites in such zones increased from 55 in 2000 to a peak of 96 in 2012 and since then oscillated between 80 and 90. One prominent example of a new project within a protected area is the expansion of mining in the Carajás National Forest in the state of Pará, Brazil, located in the Xingu-Tocantins-Araguaia moist forests ecosystem. In 2016, the Brazilian multinational corporation Vale opened the Serra Sul (also known as S11D) mine as the largest project in the company's history (Vale, 2016). In 2019, 73 Mt of iron ore were mined at this site. Other mines within the area, which was declared national forest of the state Pará in 1998, have already existed longer, yet increased their extraction significantly at the beginning of the 21st century. For example, the N5 iron ore mine increased its production from 11 Mt in 2001 to 54 Mt in 2013 and the N4W mine from 15 Mt in 2001 to almost 40 Mt in 2012.

Some mines are not located within, but directly border on protected areas. The Indonesian Grasberg copper and gold mine, one of the world's largest mining projects, is such an example. Its concession area immediately neighbours Lorentz National Park, designated World Heritage Site in 1999. The mine is related to the pollution of rivers and lakes in that area due to riverine tailings disposal (Martinez-Alier, 2001). Lorentz National Park is the largest national park in South-East Asia. It has an outstanding biodiversity and comprises a number of fragile ecosystems, such as subalpine areas, tropical rainforest, and mangroves (UNESCO, 2020).

Supporting the choice of terrestrial biomes as one category indicating ecologically complex and vulnerable regions, nine out of the ten largest extraction projects that lie within protected areas (identified by accumulated mined volumes) are located in TropSubMBF or TropSubGSS. Only the Grasberg mine in Indonesia belongs to the MontGS biome. Eight of these nine mines in tropical regions are located in Brazil (seven of which are iron ore mines and one is a bauxite mine).

The third layer intersection was conducted with regard to water stress, using the normalised AWARE index with a score of 1 representing the available water remaining in a watershed as corresponding to world

[4] We based the ranking on the Millennium Ecosystem Assessment (2005), where species richness (the number of species in a given area) is referred to as the most common measure of biodiversity.

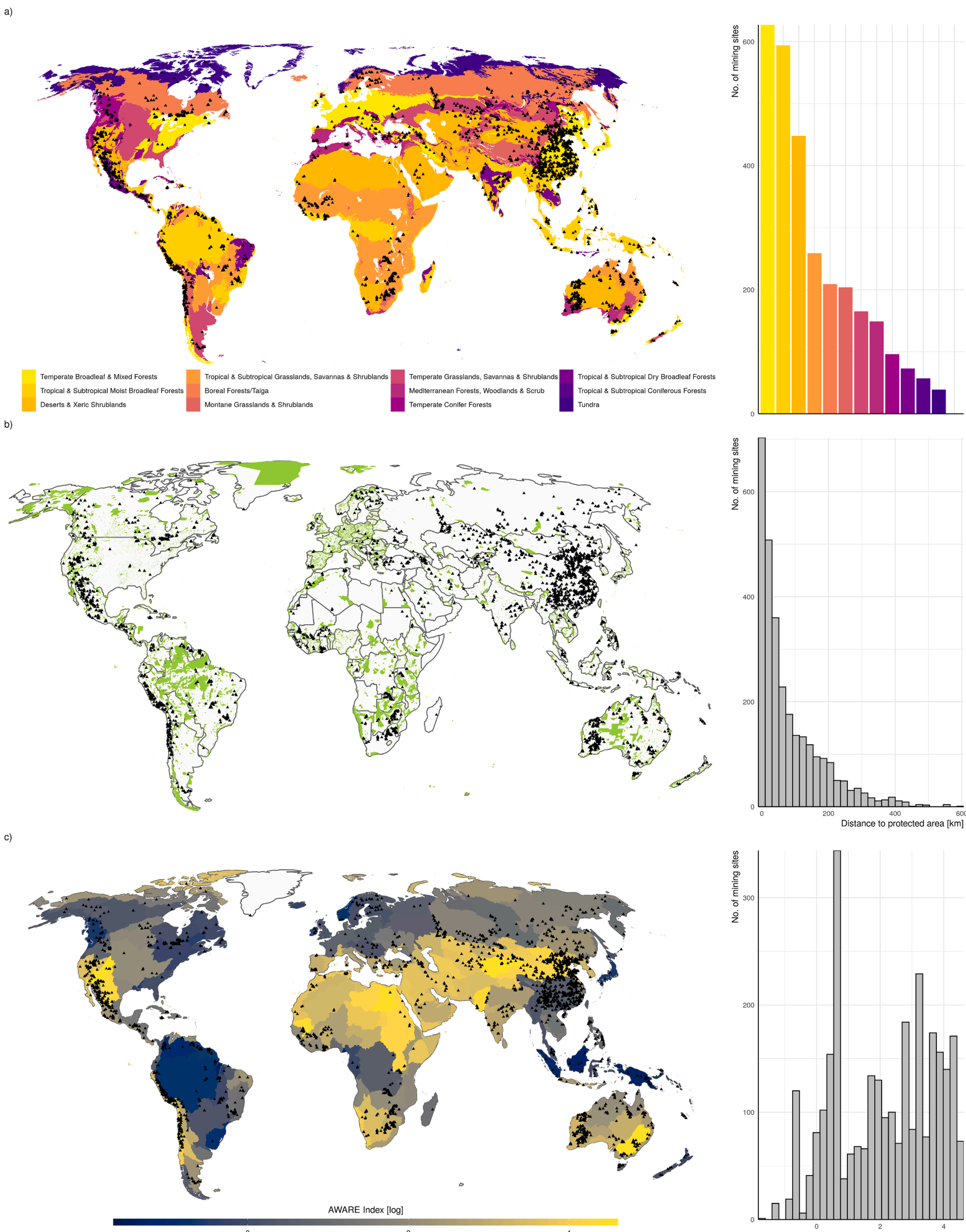

Fig. 4. Mining sites considered in this study (based on SNL, 2020) and their distribution across a) terrestrial biomes (based on Resolve, 2017), b) protected areas (based on UNEP-WCMC, 2020), and c) AWARE water stress index classifications (log-transformed, based on WULCA, 2019) using Robinson map projections.

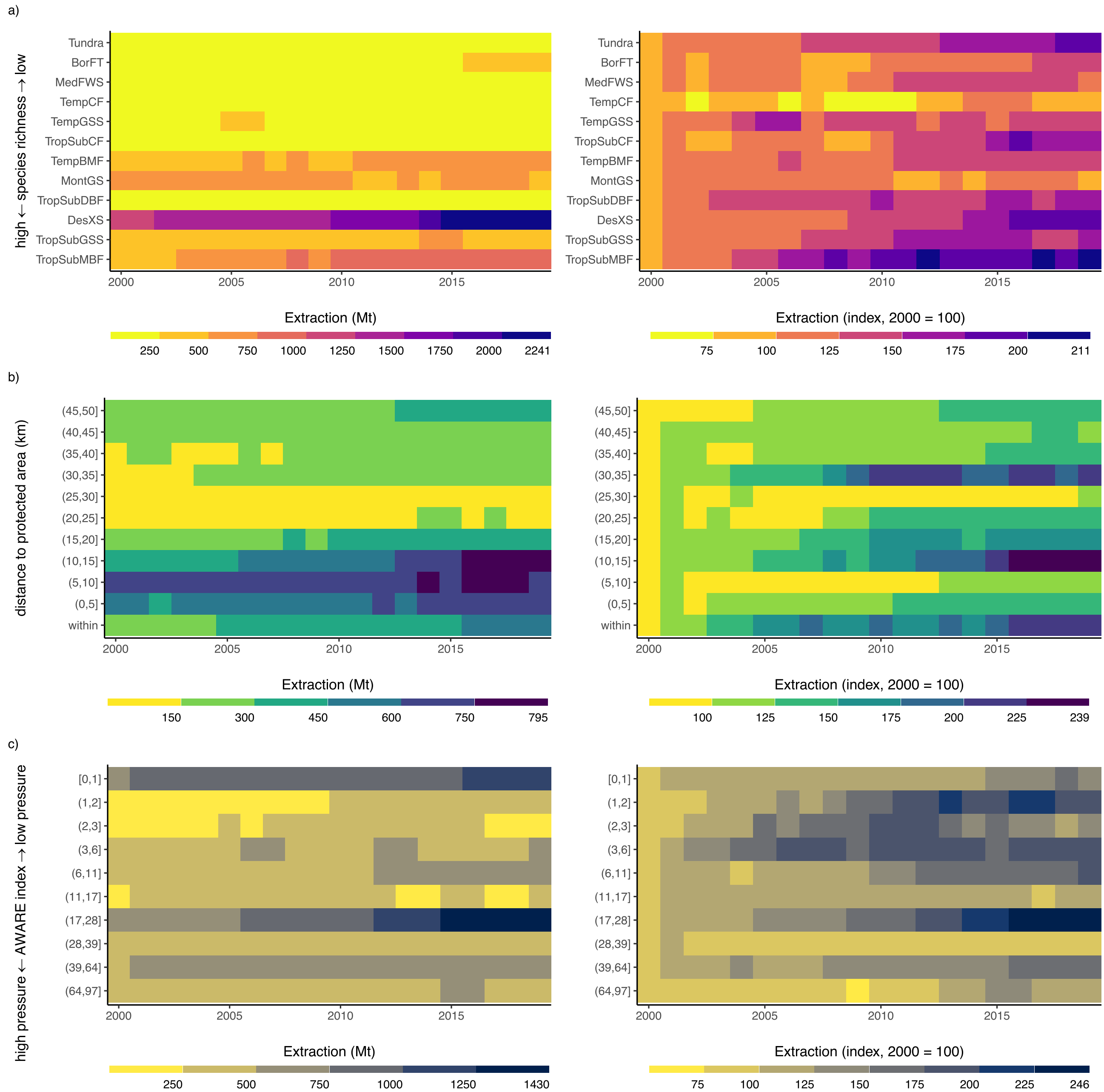

Fig. 5. Total (left) and relative (right) extraction volumes within a) biome classifications, b) 5 km proximity buffers to protected areas, and c) available water remaining (AWARE) decile intervals; 2000–2019; based on SNL (2020) and UN IRP (2017) conversion factors.

average and scores above 1 corresponding to less water availability relative to the global average. Fig. 5c illustrates annual extraction in Mt at the AWARE decile level. While in 2019, 1,080 Mt (18 %) of metal ore were extracted in the decile with high relative water availability, i.e. watersheds with an AWARE score smaller or equal to 1, 90% of all considered extraction sites are located within watersheds that have below-average relative water availability. Considering that the consumption-weighted average AWARE index is 43, meaning that the majority of economic activity and water consumption affects regions where the index exceeds 1, we find that 1,034 Mt (17 %) were extracted in watersheds with an AWARE score higher than this weighted average. In the most critical category, the 64 to 97 decile, 472 Mt were mined in 2019, of which approximately one third was mined in the Chihuahuan desert in Mexico and the United States. Largest extraction volumes and highest growth rates are measured for watersheds with AWARE scores between 17 and 28. These include major mining hubs such as the Escondida copper mine in the Chilean Atacama desert, iron ore production in the Australian Pilbara shrublands, and copper mining in the Kazakh semi-desert.

3.3. Differences across metal types

We next highlight differences across metals in Fig. 6. From top to bottom, this figure depicts the environmental layers and from left to right, it represents the nine metals considered in this study. We illustrate how the composition of extraction volumes per metal has developed between 2000 and 2019. Regarding biomes (6a), the five categories with highest species richness – TropSubMBF, TropSubGSS, DesXS, tropical and subtropical dry broadleaf forests (TropSubDBF) and MontGS – are separately shown while all other biome categories are aggregated as “other”. Charts in 6b show distance to protected areas in incremental steps of 5 km each up to 20 km proximity and remaining sites grouped

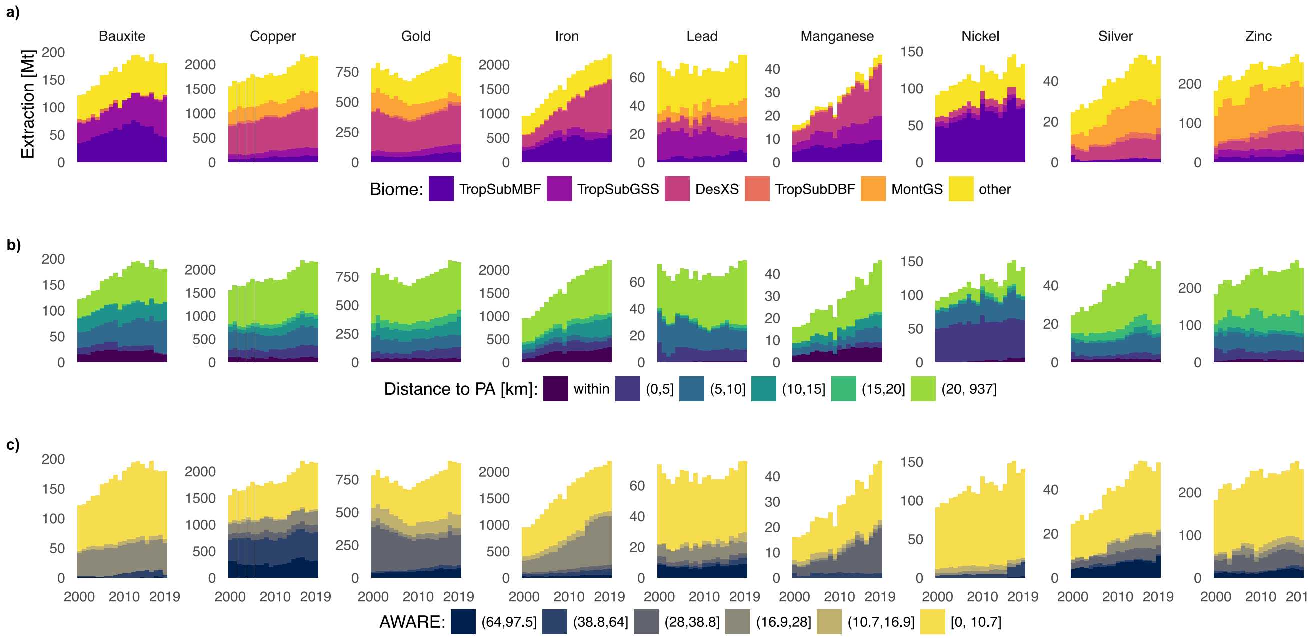

Fig. 6. Extraction volumes by commodity and a) selected biomes, b) distance to protected area, and c) AWARE index; 2000–2019; based on SNL (2020) and UN IRP (2017) conversion factors.

into a residual category. In 6c, AWARE index categorisations are depicted. We stress the five most critical water scarcity deciles and subsume the other half of all observations under AWARE scores between 0 and 10.7. Note that the levels of extraction volumes differ widely, with iron, copper and gold ore being mined in the largest amounts.

Highest increases in global extraction are reported for iron and manganese ores. In 2019, more than 75% of iron ore were mined either in TropSubMBF, TropSubGSS or DesXS biomes. This share has grown since 2000, when 60% were mined in these three categories, mostly (but not only) because of extraction gains in DesXS. Manganese, which is predominantly used as an input for steel production, reaches an even higher share of production stemming from these critical biomes of about 90%. This proportion has not significantly changed since 2000, but absolute volumes have risen from 16 Mt in 2000 to 46 Mt in 2019. Furthermore, similar to iron ore and bauxite, manganese ore is, to a notable extent, mined within protected areas. A prominent example are manganese mining operations at Groote Eylandt: Australia's fourth-largest island is entirely part of Anindilyakwa Indigenous Protected Area. Extraction volumes at Groote Eylandt have more than quadrupled between 2000 and 2019, and in 2019, the mine extracted about three quarters of Australian manganese ores.

Besides bauxite, iron, and manganese, nickel ores are most notably mined in TropSubMBF. While bauxite mining decreased in TropSubMBF from 76 Mt in 2012 to 45 Mt in 2019, and shifted to TropSubGSS (49 Mt in 2012 and 72 Mt in 2019), the mining of nickel ores in TropSubMBF has been increasing during the past two decades. In 2019, about 55% of global nickel ore extraction took place in the species-richest tropical biome, 66% of which can be attributed to only two mining sites in the Indonesian Sulawesi lowland rain forests, Sorowako and Pomalaa. Sulawesi island has been suffering from massive deforestation in recent decades, with nickel mining known as one among several significant drivers (Supriatna et al., 2020). In addition, nickel mining is almost entirely conducted within a 20 km distance to protected areas, and about half of all ore is extracted at 5 km or less from protected areas. However, in contrast to bauxite and iron ore mining, nickel is hardly mined *within* protected areas.

The world's largest copper and gold deposits are located in DesXS, and hence large mining projects are located in this biome, such as Escondida and Chuquicamata in Chile, or Morenci and Bingham Canyon mines in the USA. The fact that copper and gold ores are predominantly mined in desert ecosystems is reflected by water pressure indicators, as becomes evident in Fig. 6c. Approximately 40% of all copper ore is mined inside the two highest AWARE deciles. While gold ore extraction shows a decreasing trend in the third highest decile of scores around 30, iron ore extraction substantially increased for regions with AWARE scores between 17 and 28. These include several Australian iron ore mines located in the Pilbara shrublands, such as Hope Downs, the Sino-Iron project, and Roy Hill, which may have significant impact on groundwater and surface water in that area (WA Government, 2009). Nickel mining tends to affect mostly areas with low AWARE scores. However, we also notice a rapid increase in the second decile since 2016.

3.4. *Regional hotspots*

One of the innovations of our study is to show regional mining patterns over time based on spatially explicit accounts of metal ore extraction. In order to estimate regional trends, we conducted a GWR analysis. As noted in Section 2.2, the framework of a GWR considers both reported volumes for each mine and volumes for respective neighbouring mining sites, with more weight given to closer operations. We hence obtained trend estimates for each mining location not only accounting for the mine itself, but also for surrounding activities, enabling us to provide an overview of the trends across agglomerations of mining projects. In Fig. 7, we present all positive 2000–2019 trend estimates for total metal ore extraction. We limit results shown on the map to only positive coefficients in order to highlight hotspots of increased production, the focus of this study. A map including negative GWR trend coefficients and metal-specific maps are provided in the supplementary material (S 2). Table 1 lists selected hotspots with their respective GWR coefficients, biome, distance to the nearest protected area, AWARE score, and average annual extraction.

On the one hand, GWR results reveal global hotspots of densification, i.e. positive trend coefficients for mining regions where extraction volumes have on average increased. We find positive coefficients for 1272 site observations. The regions with the highest extraction growth rates (between 7% and 10% per year) are located in mining clusters in Peru, the DR Congo, Zambia, India, China, and in Western Australia. Highest

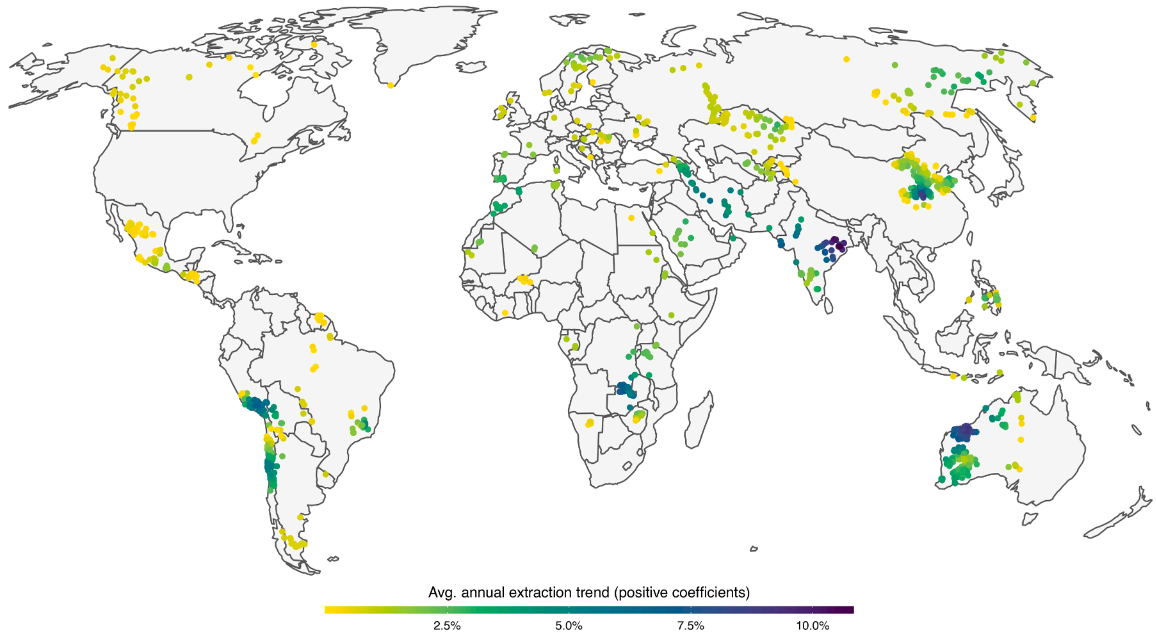

Fig. 7. Mining sites with positive trends in metal ore extraction between 2000 and 2019. The linear coefficients were estimated for each mining location using GWR. The map is a Robinson projection. Based on SNL (2020) and UN IRP (2017) conversion factors. Technical notes on GWR are provided in S 2 in the supplementary material.

average annual growth is reported for iron ore and bauxite sites in Odisha, Eastern India. On the other hand, 1659 site observations yield negative trend coefficients and can therefore be interpreted as regions with decelerating extraction. In the following, we highlight some examples, connecting to other findings from the previous sections.

Countries along the Andean Range tend to be strongly involved with mining. For Peru, we can identify mining intensification in the south of the country, whereas extraction volumes on average decreased in the north. The densification hotspots are represented in Table 1 by the example of the five mines with highest growth coefficients inside Peru. They are located in the Central Andean puna and Sechura desert ecoregions, and lie within areas reaching a particularly high AWARE score of 28.27. Significant mining intensification at these hotspots is cause for concern because Peruvian regions suffering from water scarcity are shown to be particularly vulnerable to ecological distribution conflicts related to mining and water competition (Salem et al., 2018; Bebbington and Williams, 2008).

For Brazil, we find substantial extraction growth in the state of Minas Gerais (up to 5% p.a.), while mining regions outside Minas Gerais stagnated on average. Four out of the five Brazilian mines with the highest growth coefficients are located no farther than 5 km away from natural reserves (e.g. Serra do Gandarela National Park). Furthermore, many projects of that hotspot are large-scale and situated in species-rich tropical biomes. One of the most serious threats to the environment and people in that region are tailings dam failures of large mining projects. Vale's Mina Córrego do Feijão, for example, gained notoriety due to the dam disaster near the municipality of Brumadinho in January 2019, releasing around 12 million cubic meters of tailings and killing at least 259 people (Freitas and Almeida, 2020). Brazil has hundreds of such tailings dams, most of them in the state of Minas Gerais (Fonseca do Carmo et al., 2017). Brucutu mine, extracting almost 18,000 Mt ore per year on average and with an average extraction intensification of 5.2%, is such an example, and it is located in proximity to the previous tailings dam failure. In 2019, as a response to the Brumadinho dam disaster, disposal of tailings at the Laranjeiras dam, part of Brucutu mine, was temporarily suspended due to safety concerns. In November 2015, Minas Gerais had already experienced a major environmental accident, when two dams at Samarco minining complex (4.9% average annual extraction expansion) collapsed, causing 19 casualties and far-reaching contamination of rivers, eventually spreading pollutants over more than 600 km (Fonseca do Carmo et al., 2017).

With average annual growth rates of approximately 7%, the strongest intensification of mining activities in Africa is found in the border region between Zambia and the DR Congo, known as the Central African Copperbelt. The highly mineralised region lies in the TropSubGSS biome, more precisely the Central Zambezian miombo woodlands. It is known for its vast copper deposits, but is also the habitat for a great variety of wildlife such as large mammals. The adverse effects of mining expansion in the Copperbelt, especially on forests and forest livelihoods, are evident. Moving millions of tonnes of earth, industrial copper mining has directly and indirectly caused significant environmental change due to extensive forest clearings, pollution of soil, air and water, and population pull effects of mining towns (Mwitwa et al., 2012; Peša, 2020). Our results show that Zambian mining hotspots are located in particularly close proximity to protected areas. Moreover, Lumwana mine with an average annual growth coefficient of 7.16% lies partly within Acres No. 105 National Forest.

The SNL (2020) data supports that metal mining has become a major industry in India. Growth rates of metal ore extraction such as bauxite and iron ore are exceptionally high in the eastern territories and the northwest. Yet, GWR results stress substantial extraction growth for some of the country's less prominent (and smaller in size) mining projects. While India's largest projects, such as the Chhattisgarh Group, Sesa Goa, and Noamundi iron mine, extract between 15 Mt and 25 Mt of metal ore per year (and results yield coefficients between 2% and 9%), average annual ore extraction for the mines listed in Table 1 lies between 0.01 and 1.3 Mt. Extraction volumes of these iron ore and bauxite sites, however, grow at remarkably swift rates of about 10%, i.e. the highest rates observed globally. They are located in the tropical East Deccan moist deciduous forests, which offer a spacious and rich habitat for a great number of species, including endangered large vertebrates (Wikramanayake et al., 2002). Extensive extraction gains in this area, as they are observed, hence endanger conservation of a still-intact habitat.

In the Global North, trend estimates for mines located in the Unites States and eastern Canada indicate an average decline of mining activities, while slight intensification is found for the Canadian Rocky

Table 1
Mines selected by highest five coefficients (β) from GWR (average growth p.a.) per hotspot country. Dist. PA indicates distance to nearest protected area, μ indicates average annual ore extraction based on SNL (2020) and UN IRP (2017) conversion factors. Empty cells in biome and AWARE column indicate constant characteristic for all five mines.

Country	Mine	β [%]	Biome	Dist. PA [km]	AWARE	μ [kt]
Peru	Ares	7.27	Montane Grasslands & Shrublands	19.80	28.27	1529.51
	Santa Rosa	7.19	Deserts & Xeric Shrublands	20.18		95.54
	Orcopampa	7.18	Deserts & Xeric Shrublands	21.52		2639.23
	Arcata	7.11	Montane Grasslands & Shrublands	4.89		729.17
	Shila-Paula	7.08	Montane Grasslands & Shrublands	53.93		295.81
Brazil	Brucutu	5.22	Trop. & Subtrop. Moist Broadleaf Forests	14.69	3.14	17958.33
	Sao Bento	5.12	Trop. & Subtrop. Moist Broadleaf Forests	4.08		367.65
	Gongo Soco	5.05	Trop. & Subtrop. Moist Broadleaf Forests	1.49		5464.29
	Samarco	4.87	Trop. & Subtrop. Grasslands, Savannas & Shrublands	1.92		17827.88
	Alegria	4.84	Trop. & Subtrop. Grasslands, Savannas & Shrublands	3.05		12720.52
DR Congo	Kamoto	7.21	Trop. & Subtrop. Grasslands, Savannas & Shrublands	18.15	1.67	2762.92
	Metalkol RTR	7.21		22.47		1846.24
	Mutoshi	7.20		33.32		248.28
	Kolwezi	7.20		24.66		1359.43
	Tilwizembe	7.16		48.99		48.87
Zambia	Trident - Sentinel	7.42	Trop. & Subtrop. Grasslands, Savannas & Shrublands	5.22	7.43	16301.33
	Lumwana	7.16		0.00		10431.14
	Kansanshi	6.85		10.77		21100.96
	Muliashi North	5.80		5.72		3224.72
	Baluba	5.78		4.50		1621.13
India	Malangtoli	10.83	Trop. & Subtrop. Moist Broadleaf Forests	59.15	16.90	573.33
	Silijora-Kalimati	10.71		50.01		87.10
	Unchabali	10.70		45.90		1284.75
	Dubna	10.62		50.85		11.86
	Khondbond	10.62		44.61		748.19
Australia	Spinifex Ridge	9.14	Deserts & Xeric Shrublands	88.89	27.19	765.14
	Corunna Downs	9.13		120.61		512.00
	Bamboo Creek	9.11		79.34		5.12
	Nullagine	9.06		147.96		1155.92
	Mt Webber DSO	8.97		78.24		3783.89

Mountains. For Europe, we find almost entirely positive trend coefficients, indicating growing metal extraction volumes within Europe, although at generally low levels of absolute extraction. A geographical divide is apparent in Australia. Large iron ore sites in Western Australia are the drivers for intensification rates up to almost 10% and make the region a global hotspot, while sites across the eastern half of the continent show an average decline by about 2.5% per year. Highest coefficients are reported for mines in Pilbara, which hosts some of the world's largest iron ore mines. Among others, Mount Webber direct shipping iron ore mine is located at that hotspot, with a growth coefficient of almost 9%. The large mining complex, opened in 2014, continuously increased annual extraction volumes and mined more than 7 Mt of ore in 2019. Australian mining activities also demonstrate that the movement of vast amounts of earth not only causes pollution and degradation of ecosystems and loss of biodiversity, but also destroys cultural and spiritual heritage. The mining expansion in Pilbara, for example, disturbs significant Indigenous sites. In May 2020, Anglo-Australian multinational Rio Tinto was blamed for destroying the Aboriginal heritage of 46,000 year old Juukan Gorge rock shelters in order to expand Brockman 4 mine (EJatlas, 2020).

4. Discussion

4.1. Mining's socio-ecological impacts

In contrast to other frameworks that conceptualise the socio-ecological crisis and possible responses at high levels of aggregation and abstraction (e.g. Rockström et al., 2009), our results demonstrate concretely *where*, from 2000 to 2019, the surge in global mining has been implemented. What we demonstrate in particular is that increased production occurs to a large extent in areas requiring protection. Almost 80% of global metal extraction in 2019 occurred in the world's most species-rich biomes, 90% of mining sites were in areas of relative water scarcity, and almost 50% of extraction occurred at less than 20 km distance or even within protected areas. By highlighting that these are especially vulnerable areas, it is not our intention to suggest that mining should be expanding "elsewhere", in areas that are supposedly less vulnerable. Instead, we interpret the degree to which mining occurred in areas that - by indirect or direct stipulation - *should* be protected to demonstrate the environmental unsustainability of the current mode of expansion.

The findings of this paper contribute to the literature by offering annual estimates and trends for the nine metals at hand, but they also compare well with previous, often cross-sectional, studies. Northey et al. (2017), for example, also find highest average AWARE scores for copper, medium water risks for lead–zinc resources, and nickel to be mined predominantly in areas that are exposed to less water risks. While the shares of copper, lead and zinc mining in critical categories are stable, we do, however, detect a recent surge in nickel mining for higher AWARE scores. Durán et al. (2013) find that 7% of mines in their sample overlap with protected areas and 27% lie within a 10 km boundary. Our findings are slightly more conservative, but just as alarming. We furthermore complement the findings of Durán et al. (2013) by the observation that extraction volumes have considerably increased within protected areas since 2000. A comparison with Murguía et al. (2016) shows that results are sensitive to the choice how to proxy biodiversity. Our findings are in line with their study regarding bauxite, while our approach does not support their conclusions that silver mining showed a high concentration in "high diversity zones" (ibid: 416).

The global approach applied in this study also entails some uncertainties and limitations. Using crude ore extraction estimates instead of often reported net-metal contents more accurately quantifies pressures that are exerted by the mining industry on the environment and hence our estimates also serve as better indicators with regard to potential impacts. A drawback to our crude ore approach is that assumptions on average ore grades place substantial variances around these estimates. However, we argue that such uncertainties affect the conclusions of this work less, because we can assume high correlation between our estimates and actual extraction volumes from conducted robustness checks. Introducing mine-specific conversion factors can thus be assumed to have level effects on our global-scale results rather than causing substantial changes of our findings on the distributional structure and trends of global mining activities.

Further, by keeping a global scope while utilising broad categories of associated vulnerability, we provide only a crude assessment about where environmental impacts may be more severe than elsewhere. This approach is beneficial as it serves as an early warning mechanism through a trend analysis of the global mining sector, helping to identify potential high-impact areas. Nevertheless, we need to stress that we can only illustrate threats to the environment in terms of *potential* impacts or a contextual risk. Estimating *actual* impacts would require more locally specific data such as actual mine practices and more precise information on (changes in) the mines' immediate surroundings. Species-richness, for instance, serves as broad indicator, while biodiversity and hence also impacts are heterogeneous across space within the same biome.

Our study thus provides signposts to where more in-depth local studies are needed that consider the interplay of regional circumstances at the site- and case level. On the one hand, we support efforts to evaluate the impacts of the global surge in mining based on investigations that are tied to specifically selected cases. On the other hand, there is great need for more quantitative studies on the magnitude of impacts induced by the entire mining industry. Any expansion of mining constitutes a trade-off for other human and non–human uses or values attached to land and resources. More accurate assessments of mining projects' propensities to exert additional pressures such as biodiversity loss, deforestation, water and air pollution as well as social conflicts could help constructing spatially varying impact measures. These indicators could then be used for global assessments of mining impacts and industry monitoring. Importantly, more knowledge is needed about the nature and the extent of the spatial transmission and the temporal persistence of mining-induced environmental change. Such improvements will help not only to anticipate the consequences of increased metal production, but also to evaluate current progress towards more sustainable technologies and better regulations, as well as to better consider competing stakeholder interests.

Our research points mostly towards the potential environmental impacts of mining expansion where it occurs. Simultaneously, designating land (and resources in a much wider sense) to be used for mining precludes many other human uses or the non-use of that land. Environmental justice movements opposing mining have raised numerous issues from the loss of land and water for subsistence uses to local air and water pollution and the destruction of cultural values (Martinez-Alier, 2001; Temper et al., 2015). The categories we utilised may often proxy the risk of social disruption just as much as they indicate environmental vulnerability. Conflicting use and pollution of water is a frequent cause for resistance of local communities against mining projects, even though mining operators insist that technologies would guarantee sustainable use of water resources and concrete water monitoring plans would already be in place at major mining projects (Bebbington and Williams, 2008). Geological conditions determine that the deposits of some metals are predominantly mined in areas where water is scarce. Our study illustrates the massive extraction of copper and iron ores in desert ecosystems and areas of below-average water availability, which inevitably raises questions about potential conflicting uses of water and strategies to prevent future social disruptions in affected regions. Similarly, protected areas secure livelihoods and cultural values for many indigenous populations. We did not distinguish between indigenous lands and other protected areas in this study and we did not consider informal mining, which is evidently affecting protected lands in many regions (see, e.g., Asner and Tupayachi, 2016). However, our results suggest that public resistance against mining operations may rise due to increased production within and close to protected areas and we hence highlight the need for investigating and monitoring social dynamics around such areas.

4.2. Implications for mining companies and policies

Accelerated global extraction of metals and minerals particularly threatens vulnerable ecosystems and selected regions emphasised in this study. To reduce associated risk in the short and medium term, the impacts of mining itself need to decrease. There is no doubt that the mining industry has already developed and implemented improvements in environmental management processes and impact mitigation systems, such as progressive rehabilitation throughout the life cycle of a mine. While considerable advancements were also made in regulatory systems (e.g. cumulative environmental impact assessment policies and improved regional planning), environmental minimum standards and better sustainability practises and performance must be realised at the mine sites (IRMA, 2020) and above and beyond corporate level commitments, as e.g. demanded by the International Council on Mining and Metals (ICMM, 2020).

Evaluating, challenging and improving this ongoing transition also includes critically reviewing and reforming national environmental regulations. Our work contributes to such a discourse by pinpointing regions with expansive dynamics and alarming developments such as a surge in extraction within protected areas. These insights could be used for more accurately targeting regional policies. As shown in Section 3.4, areas with highest extraction growth rates are, with the exception of Australia, located in low- and middle-income countries of the Global South including Brazil, the DR Congo, India and China. These countries score lower in the OECD Environmental Policy Stringency Index as compared to industrialised countries (OECD, 2021). However, according to this composite measure, nations such as China and India have put significant efforts in improving environmental standards, while the index stagnates at very low levels for Brazil. The Central African Copperbelt also marks a challenging region with substantial room for improvements at the policy and company level. Even though forms of protective laws and regulations were established in the 1990s in Zambia and in the 2000s in the DR Congo, this change in environmental management practices remained rather a change on paper, while mining companies intensified extractive operations based on a dominantly economic and technocratic rationale (Peša, 2020). Concrete opportunities for action include rethinking mining governance such that it avoids unnecessary large-scale infrastructure, averts opening up untouched spaces to settlement, considers cumulative impacts across space (such as watershed regions) and over time and involves most affected populations in the decision making (Bebbington et al., 2020). National and sub-national governments are integral parts of the International Resource Panel's "Sustainable Development Licence to Operate" framework (UN IRP, 2020), which makes a strong case for policy coherence along multiple levels that is grounded on robust laws and regulations: National governments have the opportunity to define broad national development goals and to require mining activities being aligned to these. They can do so, for instance, through the use of auctioning, given that government policy objectives are clarified and made publicly available well in advance of the auction. Sub-national and local governments, in turn, have the ability to actively collaborate in local development planning and to steer negotiations regarding trade-offs between the environmental, economic and social dimensions of mining operations.

The shared knowledge as to the distribution and the contextual risk of increased mining, to which we have contributed with our research, turns the decision to expand mining anywhere into an informed decision to inflict negative impacts on the environment and human communities.

Any expansion therefore arguably requires tight governance of which metals can be extracted, not just when and where, but also *for what purpose* and *by what means*. One possible solution how both of these aspects could be controlled better might be more vertical integration of mining in global supply chains, making these less complex and more transparent, which should be advantageous to consumer facing downstream companies, e.g. in the automotive or electronics sectors.

4.3. The global drivers of accelerated mining

While our results have clear implications for mining companies and related regulation, the global framework in which mining actors operate needs to be equally considered, when discussing options to reduce the socio-ecological impacts of mining. Given that any expansion of mining has detrimental environmental and social impacts, it seems straightforward to call for a halt to mining expansion, as has, in fact, been the request throughout various environmental justice movements (e.g. Temper et al., 2015). However, this claim is in stark contrast to expected future trends. Global demand for metal ores is expected to significantly increase in the coming decades (Elshkaki et al., 2018) mostly due to the build-up of global material stocks (Krausmann et al., 2017, 2020) and the expansion of low-carbon infrastructures, such as wind and solar energy and battery storage capacities (Elshkaki and Shen, 2019; Watari et al., 2020). It will be impossible to sustain increasing levels of consumption in those areas while simultaneously curbing the negative environmental and social impacts of metal mining.

The increasing metabolic inequalities of current growth trajectories also play an important role. Global supply and use chains currently direct the additional resources gained by metal mining to places of already high or rapidly increasing consumption and material wealth (Dorninger et al., 2021). High-income and some middle-income economies engage in net-appropriation of raw materials and without net-imports would not be able to pursue their models of industrialised growth. While the mature industrialised economies have largely exhausted their domestic resource base, countries in the earlier phases of capitalist industrialisation continue to hinge their economic “development” on extractivist agendas (Gudynas, 2010), taking on roles of global suppliers of primary commodities while foregoing the higher value added associated with refinement and manufacturing (UNCTAD, 2019). As a consequence, final consumers are in many cases geographically distant from resource extraction and the related impacts (Schaffartzik et al., 2016; Gudynas, 2010). Due to these “tele-connections” between production and consumption, the systemic character behind ecological distribution conflicts needs to be addressed from a global perspective, acknowledging pertinent patterns of ecologically unequal exchange (Dorninger et al., 2021; Xu et al., 2020).

5. Conclusion

To date, there is no reason to expect the expansion of metals and minerals extraction to halt in the near future. In contrast, the accelerated build-up of global material stocks and the development of new and supposedly more sustainable technologies will create growing markets for metal ores.

In this study, we investigated and contextualised metal ore extraction of the past two decades. We illustrated the types and amounts of commodities extracted, along with a detailed assessment of their geographical location. Backed by the rich empirical evidence that mining activities induce hazardous changes to the environment, we considered areas around mining sites to be more strongly at risk and reflected how severe mining pressures may impact ecosystems, in particular those already recognisable as vulnerable. It is remarkable that, compared to the total global surface, relatively few and small areas supply the metallic basis for the entire industrialised world. However, based on what we know so far about the impacts of minerals extraction on the environment and their spatial transmission, it seems highly likely that indirect effects distant from mines may be extensive. We found that the intensification of extraction shows distinct regional patterns, which increase the pressure on vulnerable ecosystems in several biomes across the globe. In order to preserve both livelihoods and habitats to many, often rare and endangered species, particularly tropical ecosystems of vast biodiversity require stronger protection from interference through mining. The increase of metal mining in vulnerable and protected areas shown in our study points to the challenge of reversing current unsustainable trends in resource extraction.

Metals are point resources and do not occur ubiquitously. Rather than implying that there is no choice but to mine them where they do occur, we have argued that this in fact supports an even stronger case for reducing resource consumption, first and foremost of the world’s wealthiest economies, in order to protect vulnerable ecosystems and their inhabitants. Further pursuing this agenda can be supported by the type of information we have sought to develop for this article, including the spatially explicit mapping, the historical contextualisation and the assessment of the status quo of resource development and its transformative potential. Aggregate global conceptualisations and targets must be integrated with in-depth knowledge of local-level consequences of mining expansion. For the examples of selected hotspots of mining expansion, we demonstrated that many of them are unambiguously related to local socio-environmental risk and disasters.

Further investigating and monitoring the spatial and temporal evolution of metal mining can serve as an early warning mechanism and will help to anticipate potentially hazardous developments and better-inform mining management and policy making. Our results have implications for the way we organise the biophysical basis of our economic systems, because they underline that reoccurring local ecological distribution conflicts all across the globe are not to be solved at the case level. Instead, they are consequences of an expansion systematically affecting species-rich, water-scarce, complex, fragile and hence vulnerable ecosystems.

CRediT authorship contribution statement

Sebastian Luckeneder: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing. **Stefan Giljum:** Conceptualization, Writing - original draft, Writing - review & editing. **Anke Schaffartzik:** Writing - original draft, Writing - review & editing. **Victor Maus:** Methodology, Software, Writing - review & editing. **Michael Tost:** Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank Nikolas Kuschnig for valuable comments and discussions on a previous version of this manuscript, Jakob Gutschlhofer and Mirko Lieber for their support in compiling the data, and two anonymous reviewers, who helped to improve this paper. This work was funded by the European Commission under the ERC Consolidator Grant FINEPRINT (Grant Number 725525). Anke Schaffartzik acknowledges the financial support of the Austrian Science Fund (FWF) through Hertha Firnberg project T949.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at https://doi.org/10.1016/j.gloenvcha.2021.102303.

References

Asner, G.P., Llactayo, W., Tupayachi, R., Ráez Luna, E., 2013. Elevated rates of gold mining in the Amazon revealed through high resolution monitoring. Proc. Natl. Acad. Sci. U.S.A. 110 (46), 18454–18459. https://doi.org/10.1073/pnas.1318271110.

Asner, G.P., Tupayachi, R., 2016. Accelerated losses of protected forests from gold mining in the Peruvian Amazon. Environ. Res. Lett. 12 (9), 094004 https://doi.org/10.1088/1748-9326/aa7dab.

Ali, S.H., Giurco, D., Arndt, N., et al., 2017. Mineral supply for sustainable development requires resource governance. Nature 543 (7645), 367–372. https://doi.org/10.1038/nature21359.

Bebbington, A., Chicchon, A., Cuba, N., et al., 2020. Opinion: Priorities for governing large-scale infrastructure in the tropics. Proc. Nat. Acad. Sci. 117 (36), 21829–21833. https://doi.org/10.1073/pnas.2015636117.

Bebbington, A., Hinojosa, L., Humphreys Bebbington, D., Burneo, M.L., Warnaars, X., 2008. Contention and Ambiguity: Mining and the Possibilities of Development. Dev. Change 39 (6), 887–914. https://doi.org/10.1111/j.1467-7660.2008.00517.x.

Bebbington, A., Williams, M., 2008. Water and Mining Conflicts in Peru. Mt. Res. Dev. 28 (3), 190–195. https://doi.org/10.1659/mrd.1039.

Birkmann, J., Wisner, B., 2006. Measuring the unmeasurable: the challenge of vulnerability. UNU Institute for Environment and Human Security, Bonn.

Bridge, G., 2004. Contested Terrain: Mining and the Environment. Annu. Rev. Environ. Resour. 29 (1), 205–259. https://doi.org/10.1146/annurev.energy.28.011503.163434.

Brunsdon, C., Fotheringham, A.S., Charlton, M.E., 1996. Geographically Weighted Regression: A Method for Exploring Spatial Nonstationarity. Geog. Anal. 28 (4), 281–298. https://doi.org/10.1111/j.1538-4632.1996.tb00936.x.

Caballero Espejo, J., Messinger, M., Román-Dañobeytia, F. et al., 2018. Deforestation and Forest Degradation Due to Gold Mining in the Peruvian Amazon: A 34-Year Perspective. In: Remote Sensing 10.12, p. 1903. https://doi.org/10.3390/rs10121903.

Conde, M., 2017. Resistance to Mining. A Review. Ecol. Econ. 132, 80–90. https://doi.org/10.1016/j.ecolecon.2016.08.025.

Dinerstein, E., Olson, D., Joshi, A., et al., 2017. An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm. Bioscience 67 (6), 534–545. https://doi.org/10.1093/biosci/bix014.

Dorninger, C., Hornborg, A., Abson, D.J., et al., 2021. Global patterns of ecologically unequal exchange: Implications for sustainability in the 21st century. Ecol. Econ. 179, 106824 https://doi.org/10.1016/j.ecolecon.2020.106824.

Durán, A.P., Rauch, J., Gaston, K.J., 2013. Global spatial coincidence between protected areas and metal mining activities. Biol. Conserv. 160, 272–278. https://doi.org/10.1016/j.biocon.2013.02.003.

EJatlas, 2020. Rio Tinto/BHP's iron mining destroys sacred Aboriginal sites, Western Australia. In: Atlas of Environmental Justice. Accessed: 3 Dec 2020. https://ejatlas.org/conflict/rio-tintos-iron-mine-and-destruction-of-sacred-aboriginal-sites-australia.

Elshkaki, A., Shen, L., 2019. Energy-material nexus: The impacts of national and international energy scenarios on critical metals use in China up to 2050 and their global implications. Energy 180, 903–917. https://doi.org/10.1016/j.energy.2019.05.156.

Elshkaki, A., Graedel, T.E., Ciacci, L., Reck, B.K., 2018. Resource Demand Scenarios for the Major Metals. Environ. Sci. Technol. 52 (5), 2491–2497. https://doi.org/10.1021/acs.est.7b05154.

Freitas, R. and Almeida, F., 2020. Um ano após tragédia da Vale, dor e luta por justiçaunem famílias de 259 mortos e 11 desaparecidos. In: Globo. Accessed: 3 Dec 2020. https://g1.globo.com/mg/minas-gerais/noticia/2020/01/25/um-ano-apos-tragedia-da-vale-dor-e-luta-por-justica-unem-familias-de-259-mortos-e-11-desaparecidos.ghtml.

Fonseca do Carmo, F., Kamino, L.H.Y., Tobias Junior, R., et al., 2017. Fundão tailings dam failures: the environment tragedy of the largest technological disaster of Brazilian mining in global context. Perspect. Ecol. Conserv. 15 (3), 145–151. https://doi.org/10.1016/j.pecon.2017.06.002.

Gibson, C.C., Ostrom, E., Ahn, T.K., 2000. The concept of scale and the human dimensions of global change: a survey. Ecol. Econ. 32 (2), 217–239. https://doi.org/10.1016/S0921-8009(99)00092-0.

Görg, C., Plank, C., Wiedenhofer, D., et al., 2020. Scrutinizing the Great Acceleration: the Anthropocene and its analytic challenges for social-ecological transformations. Anthropocene Rev. 7 (1), 42–61. https://doi.org/10.1177/2053019619895034.

Gudynas, E., 2010. The new extractivism of the 21st century: Ten urgent theses about extractivism in relation to current South American progressivism. Americas Program Report 21, 1–14.

ICMM, 2020. International Council on Mining and Metals: Mining Principles. Accessed: 3 Dec 2020. http://www.icmm.com/mining-principles.

IRMA, 2020. Initiative for Responsible Mining Assurance. Accessed: 3 Dec 2020. https://responsiblemining.net/.

Krausmann, F., Wiedenhofer, D., Haberl, H., 2020. Growing stocks of buildings, infrastructures and machinery as key challenge for compliance with climate targets. Global Environ. Change 61, 102034. https://doi.org/10.1016/j.gloenvcha.2020.102034.

Krausmann, F., Wiedenhofer, D., Lauk, C., et al., 2017. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. Proc. Natl. Acad. Sci. 114 (8), 1880–1885. https://doi.org/10.1073/pnas.1613773114.

Martinez-Alier, J., 2001. Mining conflicts, environmental justice, and valuation. J. Hazard. Mater. 86 (1), 153–170. https://doi.org/10.1016/S0304-3894(01)00252-7.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Biodiversity Synthesis. World Resources Institute, Washington, DC. https://www.millenniumassessment.org/documents/document.354.aspx.pdf.

Maus, V., Giljum, S., Gutschlhofer, J., et al., 2020. A global-scale data set of mining areas. Sci. Data 7 (289). https://doi.org/10.1038/s41597-020-00624-w.

Mudd, G.M., Jowitt, S.M., 2018. Growing Global Copper Resources, Reserves and Production: Discovery Is Not the Only Control on Supply. Econ. Geol. 113 (6), 1235–1267. https://doi.org/10.5382/econgeo.2018.4590.

Murguía, D.I., Bringezu, S., Schaldach, R., 2016. Global direct pressures on biodiversity by large-scale metal mining: Spatial distribution and implications for conservation. J. Environ. Manage. 180, 409–420. https://doi.org/10.1016/j.jenvman.2016.05.040.

Mwitwa, J., German, L., Muimba-Kankolongo, A., Puntodewo, A., 2012. Governance and sustainability challenges in landscapes shaped by mining: Mining-forestry linkages and impacts in the Copper Belt of Zambia and the DR Congo. For. Policy Econ. 25, 19–30. https://doi.org/10.1016/j.forpol.2012.08.001.

Northey, S.A., Mudd, G.M., Werner, T.T., et al., 2017. The exposure of global base metal resources to water criticality, scarcity and climate change. Global Environ. Change 44, 109–124. https://doi.org/10.1016/j.gloenvcha.2017.04.004.

OECD, 2019. Global Material Resources Outlook to 2060. OECD, Paris. https://doi.org/10.1787/9789264307452-en.

OECD, 2021. Environmental Policy Stringency Index. Accessed: 23 Feb 2021. Paris: OECD. https://stats.oecd.org/Index.aspx?DataSetCode=EPS.

Peša, Iva, 2020. Mining, Waste and Environmental Thought on the Central African Copperbelt, 1950–2000. Environment and History (pre-print). https://doi.org/10.3197/096734019X15755402985703.

Resolve. http://ecoregions2017.appspot.com.

Rockström, Johan, Steffen, Will, Noone, Kevin, et al., 2009. A safe operating space for humanity. Nature 461, 472–475. https://doi.org/10.1038/461472a.

Salem, Jorge, Amonkar, Yash, Maennling, Nicolas et al., 2018. An analysis of Peru: Is water driving mining conflicts? Resources Policy. In press. https://doi.org/10.1016/j.resourpol.2018.09.010.

SNL, 2020. Metals and Mining Database. S&P Global Market Intelligence, New York.

Schaffartzik, A., Mayer, A., Eisenmenger, N., Krausman, F., 2016. Global patterns of metal extractivism, 1950–2010: Providing the bones for the industrial society's skeleton. Ecol. Econ. 122, 101–110. https://doi.org/10.1016/j.ecolecon.2015.12.007.

Schaffartzik, A., Mayer, A., Gingrich, S., et al., 2014. The global metabolic transition: Regional patterns and trends of global material flows, 1950–2010. Global Environ. Change 26, 87–97. https://doi.org/10.1016/j.gloenvcha.2014.03.013.

Schandl, H., Fischer-Kowalski, M., West, J., et al., 2017. Global Material Flows and Resource Productivity: Forty Years of Evidence. J. Ind. Ecol. 22, 827–838. https://doi.org/10.1111/jiec.12626.

Scheidel, A., Del Bene, D., Liu, J., et al., 2020. Environmental conflicts and defenders: A global overview. Global Environ. Change 63, 102104. https://doi.org/10.1016/j.gloenvcha.2020.102104.

Sonter, L., Ali, S.H., Watson, J.E.M., 2018. Mining and biodiversity: key issues and research needs in conservation science. Proc. R. Soc. B 285, 285. https://doi.org/10.1098/rspb.2018.1926.

Sonter, L.J., Dade, M.C., Watson, J.E.M., et al., 2020. Renewable energy production will exacerbate mining threats to biodiversity. Nat. Commun. 11 (1), 1–6. https://doi.org/10.1038/s41467-020-17928-5.

Sonter, L.J., Herrera, D., Barrett, D.J., et al., 2017. Mining drives extensive deforestation in the Brazilian Amazon. Nat. Commun. 8 (1), 1013. https://doi.org/10.1038/s41467-017-00557-w.

Steffen, W., Broadgate, W., Deutsch, L., et al., 2015. The trajectory of the Anthropocene: The Great Acceleration. The Anthropocene Review 2 (1), 81–98. https://doi.org/10.1177/2053019614564785.

Supriatna, J., Shekelle, M., Fuad, H.A.H., et al., 2020. Deforestation on the Indonesian island of Sulawesi and the loss of primate habitat. Global Ecol. Conserv. 24, e01205 https://doi.org/10.1016/j.gecco.2020.e01205.

Temper, L., Del Bene, D., Martinez-Alier, J., 2015. Mapping the frontiers and front lines of global environmental justice: the EJAtlas. J. Political Ecol. 22 (1), 255–278. https://doi.org/10.2458/v22i1.21108.

Tost, M., Murguia, D., Hitch, M., et al., 2020. Ecosystem services costs of metal mining and pressures on biomes. The Extractive Industries and Society 7 (1), 79–86. https://doi.org/10.1016/j.exis.2019.11.013.

Turner, B.L., Kasperson, R.E., Matson, P.A., et al., 2003. A framework for vulnerability analysis in sustainability science. Proc. Nat. Acad. Sci. 100 (14), 8074–8079. https://doi.org/10.1073/pnas.1231335100.

UN IRP, 2017. Global Material Flows Database: Version 2017. United Nations Environment Programme, Paris. http://www.resourcepanel.org/global-material-flows-database.

UN IRP, 2019. Global resources outlook 2019: Natural resources for the future we want. United Nations Environment Programme, Nairobi. https://www.resourcepanel.org/reports/global-resources833outlook.

UN IRP, 2020. Mineral Resource Governance in the 21st Century: Gearing extractive industries towards sustainable development. United Nations Environment Programme, Nairobi. https://www.resourcepanel.org/reports/mineral-resource-governance-21st-century.

UNCTAD, 2019. State of Commodity Dependence 2019. New York: United Nations Conference on Trade and Development. https://unctad.org/en/pages/PublicationWebflyer.aspx?publicationid=2439.

UNEP-WCMC, 2020. Protected Planet: The World Database on Protected Areas 03/2020. UNEP-WCMC and IUCN, Cambridge. https://www.protectedplanet.net.

UNESCO, 2020. Lorentz National Park. Accessed: 4 Dec 2020. United Nations Educational, Scientific and Cultural Organization, Paris. https://whc.unesco.org/en/list/955/.

Vale (2016). Vale inaugurates the largest project in the history of the mining industry. Accessed: 4 Dec 2020. http://saladeimprensa.vale.com/en/Paginas/Articles.aspx?r=Vale_inaugurates_the_largest_project_in_the_history_of_the_mining_industry_&s=Mining&rID=979&sID=6.

Government, WA, 2009. Pilbara water in mining guideline. Accessed: 4 Dec 2020. Government of Western Australia, Department of Water, Perth. https://www.water.wa.gov.au/_data/assets/pdf_file/0013/1570/88526.pdf.

WULCA. http://www.wulca-waterlca.org.

Watari, T., Nansai, K., Nakajima, K., 2020. Review of critical metal dynamics to 2050 for 48 elements. Resour. Conserv. Recycl. 155, 104669 https://doi.org/10.1016/j.resconrec.2019.104669.

Weißhuhn, P., Müller, F., Wiggering, H., 2018. Ecosystem Vulnerability Review: Proposal of an Interdisciplinary Ecosystem Assessment Approach. Environ. Manage. 61 (6), 904–915. https://doi.org/10.1007/s00267-018-1023-8.

Werner, T.T., Mudd, G.M., Schipper, A.M., et al., 2020. Global-scale remote sensing of mine areas and analysis of factors explaining their extent. Global Environ. Change 60, 102007. https://doi.org/10.1016/j.gloenvcha.2019.102007.

Wikramanayake, E., Dinerstein, E., Loucks, C.J., et al., 2002. Terrestrial Ecoregions of the Indo-Pacific: a Conservation Assessment. Island Press, Washington, DC.

Xu, Z., Li, Y., Chau, S.N., et al., 2020. Impacts of international trade on global sustainable development. Nature Sustain. https://doi.org/10.1038/s41893-020-0572-z.