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Ecosystem services costs of metal mining and pressures on biomes

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Abstract

Metal mining has significant impacts on the land it uses. With increasing demand for metals, these impacts will continue to intensify. One way to look at land use and related environmental impacts is the concept of ecosystem services (ES), defined as the benefits people derive from services provided by ecosystems. This paper estimates the costs of the reduction of ES due to metal mining`s global land use by analysing four key metal ores – bauxite (aluminium), copper, gold and iron, and by doing so, provides also novel information from which biomes those metals are extracted.

The overall ES cost caused by metal mining is estimated at about USD 5.4 billion/year (2016), with about two thirds in forested areas. If added to prices, it would lead to increases of between 0.8% and 7.9% for the four commodities studied.

The authors do not understand ES valuation as a market-based, stand-alone tool to lower the land impact of metal mining. Other policy tools would have to play a leading role, such as zoning regulations, environmental minimum standards or closure legislation. However, it would be a useful support for such policy tools in all stages of mining where land use aspects play a role.

Keywords

Ecosystem Services, Costs, Metal Mining, Land use, Biomes

1. Introduction

With the economic and population growth of recent decades, land use - and its implications on a wide range of issues such as biodiversity, climate change and agricultural productivity - has been recognized as a major, global area of concern (e.g. (Foley, et al., 2005), (UNEP, 2019)). In the Sustainable Development Goals (SDGs) of the United Nations (UN), goal number 15 (Life on Land) talks about the need to "*protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss*" (United Nations, 2018). However, in its progress report for 2018, the UN notes that the protection of forest and terrestrial ecosystems is on the rise and forest loss has slowed, while other aspects like biodiversity protection, land productivity and genetic resources and the loss of species need accelerated action (United Nations, 2018).

The global land occupied by mining is estimated to be between 0.3% (Hooke & Martín-Duque, 2012) and 1% (Bridge, 2004) of the overall land area available on the Earth. To put this in relation, the FAO lists 0.6% covered by artificial surfaces and 12.6% covered by cropland (Food and Agriculture Organisation of the United Nations, 2019), with Foley and colleagues stating that cropland and pastures for agriculture cover about 40% (Foley, et al., 2005). However, as Tost and colleagues (2018a) point out, the estimates for mining are vague. Only recently, more detailed research has emerged on the issue of land use change brought about by mining, both quantitative and qualitative. Murguia (2015) looks at the global land directly disturbed by mining for iron ore, bauxite, copper, gold and silver and calculates the cumulative land use in 2011 to be 1.2 million ha (about half the size of Belgium). Murguia and Bringezu (2016) calculate what they call "weighted disturbance rates" (WDR), estimating the annual quantity of hectares newly disturbed per million metric tons of ore extracted. They also create scenarios based on estimates of future demand and look at the pressure on biodiversity caused by mining these five metal ores (Murguía, et al., 2016). Other studies mainly focus on qualitative aspects of land use change through mining as well. Kobayashi and colleagues (2014) and Duran and colleagues (2013) also analyze biodiversity pressures at a global level. Others are local/regional in scope, like the work by Sonter and colleagues (2017), who look at direct and indirect mining-induced deforestation in the Brazilian Amazon, or Mishra and Mishra (2017), who look at the connection of mining land use and environmental impacts in Odisha, India. In conclusion, there is a need to look further into global metal mining's land use and related environmental pressures.

As stated above, in order to get mineral raw materials out of the ground, land is disturbed – as are ecosystems. One way of assessing ecosystems and of quantifying the impact of human activities on them is through the concept of ecosystem services (ES), which the Millennium Ecosystem Assessment defines as "*the benefits people obtain from ecosystems*" (Millennium Ecosystem Assessment, 2005). The Economics of Ecosystems and Biodiversity (TEEB) report (TEEB, 2010) lists 22 ES ranging from provisioning (e.g. food, water, raw materials), regulating (e.g. air purification, climate regulation), habitat or supporting (e.g. maintenance of genetic diversity) to cultural services (e.g. tourism, spiritual experience). TEEB was also key in making the concept known to a broader audience and monetizing ES, with De Groot and colleagues

(2012) analyzing existing studies in a meta-analysis and bringing them together at a biome[1] level in what they call the Ecosystem Service Value Database (ESVD). Building on this work, Costanza and colleagues (2014) estimate the monetary value of total global ES for 2011 to be USD 125 trillion/year, almost twice the value of global gross domestic product (GDP).

So far, a limited number of studies have looked into ES and mining. They focus on local and regional applications (Van Buggenhoudt, 2017), employing ES as a tool for mine closure and assessing post-closure land use options (Larondelle & Haase, 2012), (Rosa, et al., 2018), for the assessment of policy decisions in mining regions (Mercado-Garcia, et al., 2018) or permits for a new mine (Rosa & Sanchez, 2016). Neves and colleagues (2016) analyse the fines paid after the Samarco tailings dam failure in Brazil and argue that these fines do not cover the reduction of ES; however they do not provide any estimations of these ES damage costs. What this study has in common with the other studies is, that they all agree that mining has a negative impact on the services provided by an ecosystem, or – to put this in economic terms - mining has an ES cost. Due to growing demand for metals (e.g. (OECD, 2019), (Schipper, et al., 2018), (IRP, 2017)) and decreasing ore grades (e.g. (Mudd, 2007), (Crowson, 2012)), land use and related impacts on ES from mining will continue to increase and thus will intensify metal mining´s ES costs.

The objective of this paper is to develop and apply a methodology to estimate the ES costs of global metal mining`s land use. This is done for four key metal ores - bauxite (from which aluminium is processed), copper, gold and iron. Together they represent over 96 percent of all metals mined globally in terms of bulk tonnage and over 68 percent of financial value (Tost, et al., 2018a), (Ericsson & Hodge, 2012). To do so, the different biome types are overlaid with a sample of mines from around the world. Hence, in addition to providing novel information about ES costs of mining, also the biome distribution of the extraction of the four metals is established. The global nature of this information enables mining stakeholders, i.e. companies and policy makers, to understand the global distribution of mining pressures on ES that can orientate policy discussions on how to best avoid or minimize ecosystem degradation. This allows making better informed decisions; from where to direct exploration investments, establish new mines, including no-go-zones, compensate for or off-set land impacts, all the way to how to finance and do early, ongoing and post-closure rehabilitation.

In Section 2, the authors explain the method for estimating the land use requirements for mining the selected four metals, how to link them to the biomes and how to calculate the ES costs. In Section 3, the biome distribution, the ES costs and their potential impact on prices are presented. The results are discussed in Section 4 and conclusions are presented in Section 5.

2. Materials and Method

To approach the question of the ES costs of global metal mining, the authors follow De Groot et al. (2012) and use a biome-based approach. Based on the assumption that the original ecosystem and its related ES are fully destroyed once mining takes place, for each biome, the

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[1] A biome is a community of plants and animals living together in a certain kind of climate. Each biome can be split into ecoregions (ecosystems of regional extent) / ecosystems (Resolve, 2017).

authors compute the (cumulative) area disturbed by mining and multiply it with the ES value (on an area basis) computed by De Groot et al. The result indicates the 'cost' or 'damage' caused by the loss of ES through the mining of each metal in each biome and globally.

Computations are based on a sample of mines selected from the SNL metals & mining database provided by S&P Global Market Intelligence (SP Global Market Intelligence, 2019), which is the most comprehensive mine database currently available. The sample is selected focusing on large-scale, industrial mines, i.e. artisanal, small-scale mines are out of scope. Calculations follow these 5 steps:

1. Calculate cumulative mine production of each metal (1990-2016)
2. Allocate cumulative production (1990-2016) to biomes
3. Estimate land use by metal per biome (2016)
4. Calculate ES costs of land use by metal per biome (2016)
5. Extrapolate from SNL sample to global production (2016)

Assumptions underlying the method include i) no rehabilitation is done for active mines and ii) the distribution of mine production per biome in 1990-2011 equals historic distribution.

2.1 Calculate cumulative mine production of each metal (1990-2016)

First, the authors calculate the annual and cumulative ore and metal extracted in each mine during the period 1990-2016. The period is selected to start in 1990 because SNL data is very limited with regard to temporal coverage before and end in 2016 because it is the last year with data fully available. By that means the longest possible period is covered allowing to track changes in patterns. The authors use the historical global metal production numbers as informed by the USGS (United States Geological Survey) (2019) as a reference for total global production and make the assumption that large-scale industrial mining started in 1900, the first year for which USGS provides historical data.

For each mine, the authors download from the SNL database the name, geographic location[2], country, mine type, the main commodity, annual amount of ore processed and metal production in the period 1990-2016. In case of polymetallic mines where more than a single metal is mined (mainly copper and gold), all metals produced are considered.

Sample sizes and their representation of overall global production vary, ranging from a low 20% for iron ore in 1994 to a high 99% for copper in 2002 (Table1). The authors deal with this incomplete representation in step 5.

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[2] Murguia et al (2016) validated the accuracy of the geographic data from SNL and concluded them to be sufficiently accurate for overlapping with regional data.

	Number of mines in sample used		**Sample percentage of global production (%)**	
	min (year)	**max (year)**	**1990-2016**	**historic**
Bauxite	17 (1991)	53 (2013)	71.6	48.5
Copper	113 (1990)	408 (2016)	90.9	51.1
Gold	424 (1994)	714 (2013)	71.1	30.2
Iron Ore	40 (1994)	301 (2013)	68.7	36.8

Table 1: Range of numbers of mines and percentage of global production considered in this study.

2.2 Allocate cumulative production (1990-2016) to biomes

The mine-specific data are linked by overlaying two layers to a geographical layer retrieved from Ecoregions 2017 (Resolve, 2017) which is the biome classification used by the United Nations for the UN Biodiversity Lab (2019), showing the world's biomes and ecoregions (Figure 1 shows a screenshot). As a result, each mine gets assigned a specific biome and ecoregion.

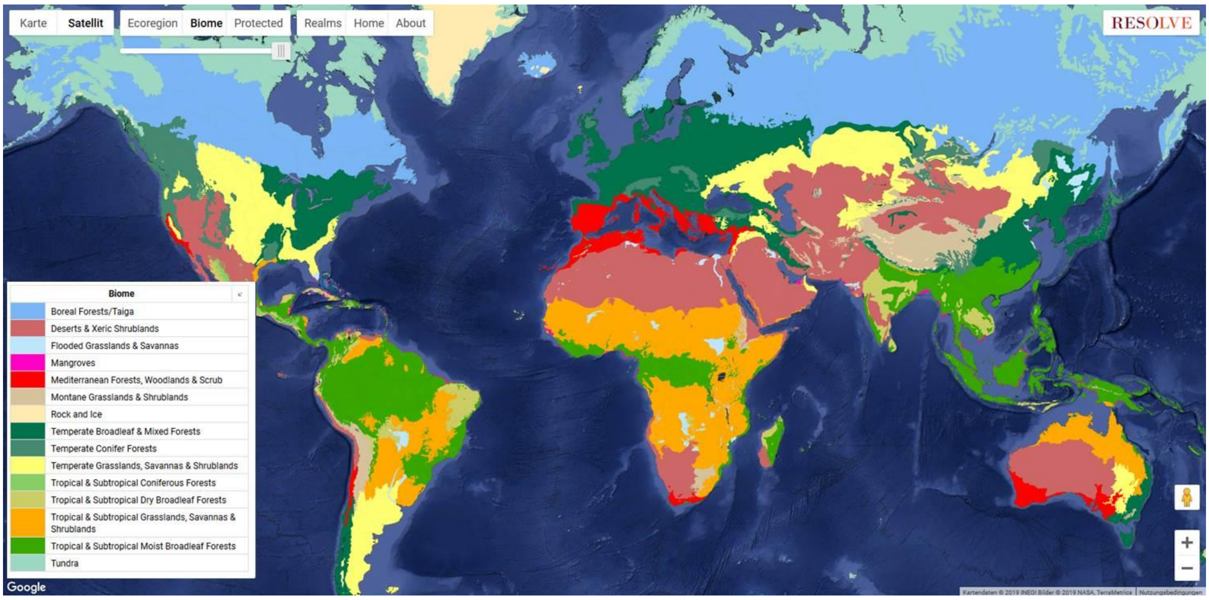


Figure 1: Map of global biome distribution according to Ecoregions 2017 (Resolve, 2017)

In the following step, the production for each metal and year (1990-2016) is allocated to the respective biomes by adding up mine production per biome.

2.3 Estimate land use by metal per biome (2016)

The estimation of cumulative land use is based on work done by Murguia (2015). The authors therefore use the same definitions for land use, i.e. only land directly used for the mines is considered. Indirectly induced impacts on land, e.g. for transport infrastructure or because of immigration, are not considered.

Murguia calculates the land used for 2011 for each metal. The results are used by the authors as a starting point to scale from global production provided by USGS to the SNL production percentage used in this study. The cumulative SNL production from 1990 to 2011 is then allocated to a biome as a percentage and thus gives the land used in each biome. Table 2 shows the status of the global area disturbed directly by mining of each ore in 2011 as well as the "weighted disturbance rates" (WDRs – see introduction), which for copper and gold are different for open pit (OP) and underground (UG) mines.

Ore	Global land use 2011 (ha)	WDR (ha/ Mt ore)
Bauxite	95,780	7.98
Copper	415,245	3.99 (OP) / 7.6 (UG)
Gold	371,815	6.34 (OP) / 17.96 (UG)
Iron Ore	267,344	4.25

Table 2: Cumulative direct land use in 2011 and WDRs for the four metals (Murguia & Bringezu, 2016)

For 2012 to 2016, the annual amount of hectares newly disturbed by mining is calculated using the WDRs (Table 2). The total amount of hectares newly disturbed in those 5 years is added to the status quo shown in Table 2; the result is the global amount of hectares disturbed directly by mining in 2016 (what is referred to as "the land use for each ore in 2016" in Step 4 below).

WDR numbers refer to quantities of produced ore. For copper and gold, the SNL database provides production figures only for the metal content of the extracted ore. Not in all cases the underlying ore production figures are presented as well. In cases where ore data is only missing for certain years, gaps are filled using single imputation, based on metal content and ore production from previous or following years to calculate an ore grade, which is then used to calculate the ore production for the missing year(s). Table 3 shows an example.

Year	Mine	Ore processed (t)	Cu prod. (t)	Grade
2012	Piedras Verdes	12,245,420	⟵ 30,000	0.0024499
2013	Piedras Verdes	14,683,000	35,488	0.00241694
2014	Piedras Verdes	14,516,000	36,041	0.00248285
			average	0.0024499

Table 3: Example single imputation: The average from the 2013 and 2014 grades is used to estimate 2012 ore processed for the Piedras Verdes Mine in Mexico. The red numbers indicate the calculated additions.

In the case where ore data is missing for all years, a search in mining-specialized databases is done to find ore grades for these mines. In some cases ore grades can be found on company websites, however the majority of data are retrieved from miningdataonline.com (MDO, 2019). As a commercial provider, they do not provide actual production ore grades for free, but do so with ore grades for proven reserves, which the authors use as a proxy.

In addition, many of the copper and gold mines are polymetallic mines (see above), in which case the different metals have to be allocated to the ore production. This is done for the cumulative production of the 5 years (2012-2016) using economic value relationships following the Eurostat EWMFA Guide 2013 (Eurostat, 2013) and using the average metal prices of 2012-2016.

Since the WDRs are only relevant for production from open pit and underground mines, production from dredging, from dumps and shown as "NA" is excluded. This represents 1.12% of copper and 0.9% of gold production in the SNL sample. Table 4 shows an example of missing data calculation from literature and monetary value based allocation.

Year	Mine	Main ore	Ore processed (t)	Cu prod. (t)	Au prod. (Oz)	Ag prod. (Oz)	Grade main ore
2012	Escondida	Cu	170,936,508	1,076,900	98,000	3,501,000	0.0063
2013	Escondida	Cu	189,126,984	1,191,500	94,000	4,032,000	0.0063
2014	Escondida	Cu	183,158,730	1,153,900	90,100	4,883,000	0.0063
2015	Escondida	Cu	183,301,587	1,154,800	88,500	4,812,000	0.0063
2016	Escondida	Cu	157,365,079	991,400	132,600	5,971,000	0.0063
		Sum	883,888,888	5,568,500	503,200	23,199,000	

Avg price (USD/ Unit)	6,494	1,354	21
Value (USD)	36,160,892,355	681,534,080	496,922,580
Value allocation (% of total)	96.84	1.83	1.33
Ore allocated (t)	855,992,720	16,133,125	11,763,042

Table 4: Example missing data estimation from a mining database and value allocation for a polymetallic mine: missing ore processed data for Escondida mine is calculated with the grade given for proven reserves (0.63%) on miningdataonline.com (MDO, 2019). The ore is allocated to the three metals produced at Escondida based on each ore's value allocation. The red numbers indicate the calculated additions and calculated ore allocations. Source for average prices: (USGS, 2019)

The direct cumulative land use per biome in 2016 is then calculated for each metal by adding up the 1990-2011 and 2012 to 2016 figures.

2.4 Calculate ES costs of land use by metal per biome (2016)

The estimation of the ES costs is based on figures provided by De Groot et al. in the ESVD database (De Groot, et al., 2012). Therefore, the authors have to first make a conversion from the Ecosystems 2017 classification system for biomes to the system as used by De Groot et al. (and for which no digital data file exists) (TEEB, 2010) (p.39). To convert from one classification to the other, the authors use ecoregions. For example, for the biome "Mediterranean Forests, Woodlands & Scrub" in Ecoregions 2017, ecoregion "Coolgardie woodlands (AUS)" is allocated to the De Groot biome "Woodlands", and ecoregion "Pindus Mountains mixed forests (GRE)" is allocated to the "Temperate forest" biome. The full list of the biome classification system transfer can be found in the supplementary data.

To calculate the ES costs for each metal, the costs from the ESVD, provided in 2007 international dollars (which equal purchasing power adjusted USD) per hectare per year, are adjusted for inflation, using an average 3.63% global inflation rate as reported by the World Bank for 2007-2016 (The World Bank, 2018). The adjusted figures range from about 2,200 USD per hectare per year for “Woodlands” to over 267,000 USD per hectare per year for “Coastal wetlands”, with the values for all biomes shown in the supplementary data. In a final step the ES costs for each biome are multiplied by the land use for each ore in 2016 (as calculated in Step 3, see above).

2.5 Extrapolate from SNL sample to global production (2016)

In a last step, the authors calculate the biome distribution and ES costs for the global production of each metal by doing an extrapolation of the above results based upon SNL data to global figures as presented by USGS. This is done at a country level, since this is the lowest level USGS provides data for. The authors compare SNL and USGS production figures for the periods 1990 to 2011 and 2012 to 2016 and calculate the differences between the two. A weighted, country-based extrapolation is then done, using the three to five countries with the largest differences, accounting for at least 50% of the overall difference, and a “rest of the world” and their biome distribution calculated as explained above. This way, more weight is given to the biome distribution of the countries with the largest production differences as compared to a linear extrapolation. Two assumptions that have to be made are that the biome distribution and the ore grades for copper and gold within a country stay the same. The final result is again the land use for each ore per biome and the respective ES costs.

The resulting ES costs per ton are compared with the average 2016 prices for each ore/metal.

3. Results

Figure 2 shows the cumulative production distribution of the four selected metals per biome for the years 1990-2016. The total land use in 2016 and the 2016 ES costs for each metal are shown for the estimated extrapolation to global USGS figures in Figure 3. The detailed annual distribution data is shown in the supplementary data.

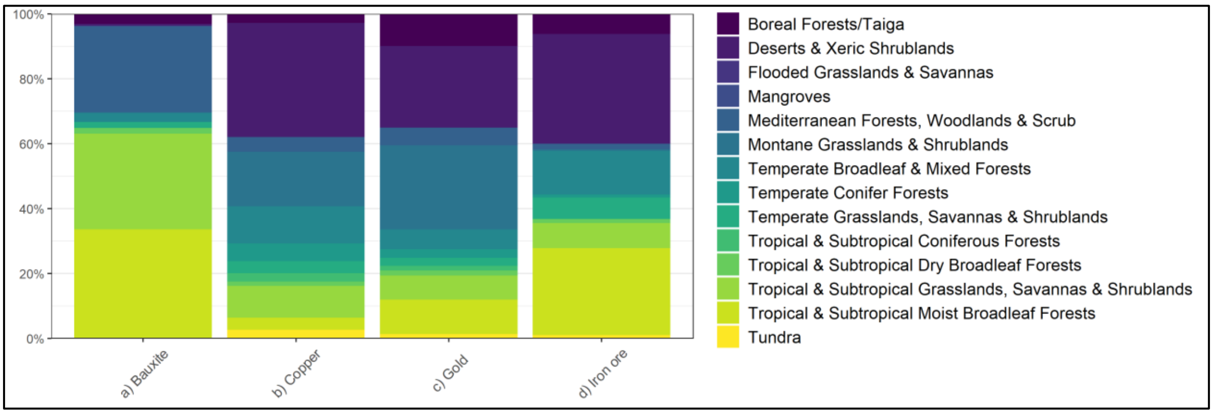
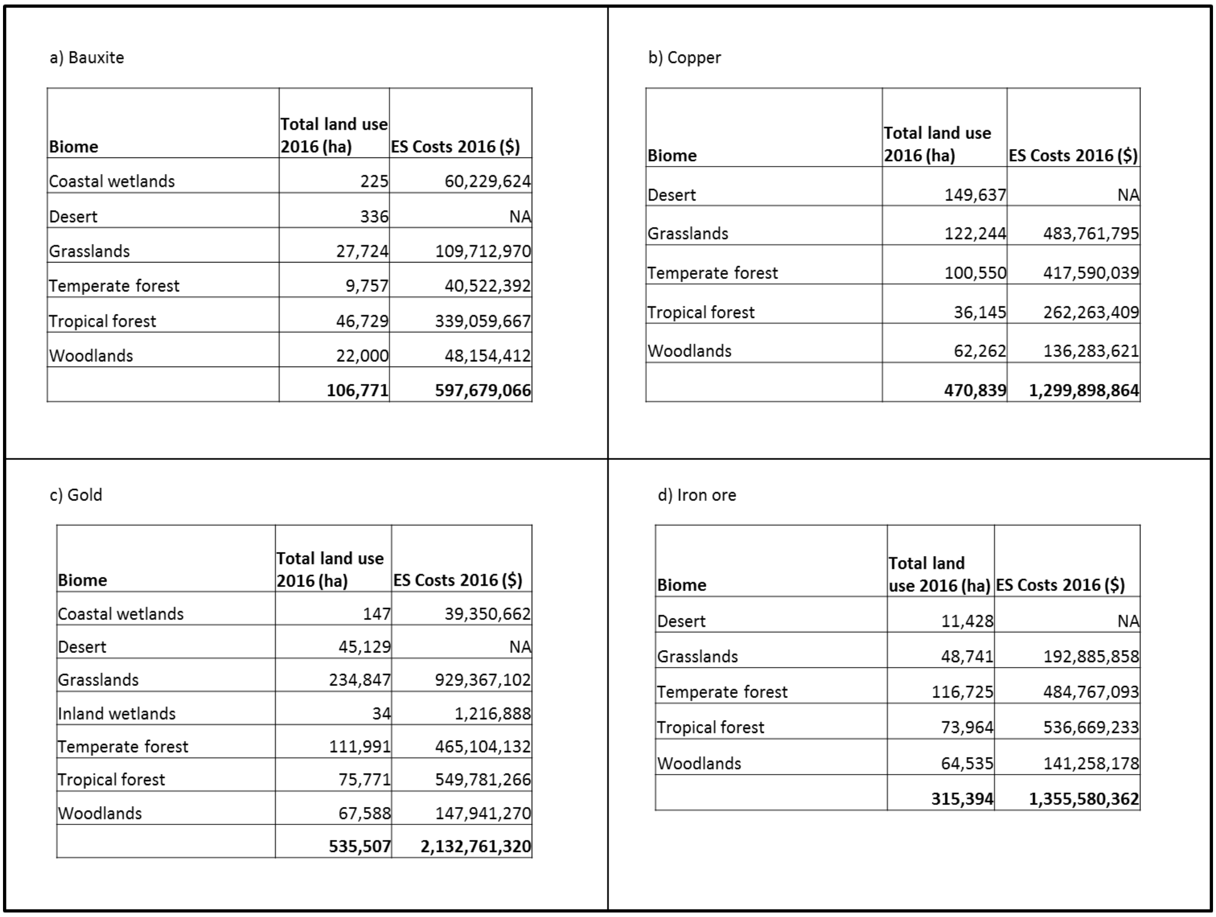


Figure 2: Production distribution per biome according to Ecoregions 2017 (Resolve, 2017) 1990-2016 in the SNL sample for a) bauxite, b) copper, c) gold and d) iron ore.



a) Bauxite

Biome	Total land use 2016 (ha)	ES Costs 2016 ($)
Coastal wetlands	225	60,229,624
Desert	336	NA
Grasslands	27,724	109,712,970
Temperate forest	9,757	40,522,392
Tropical forest	46,729	339,059,667
Woodlands	22,000	48,154,412
	106,771	**597,679,066**

b) Copper

Biome	Total land use 2016 (ha)	ES Costs 2016 ($)
Desert	149,637	NA
Grasslands	122,244	483,761,795
Temperate forest	100,550	417,590,039
Tropical forest	36,145	262,263,409
Woodlands	62,262	136,283,621
	470,839	**1,299,898,864**

c) Gold

Biome	Total land use 2016 (ha)	ES Costs 2016 ($)
Coastal wetlands	147	39,350,662
Desert	45,129	NA
Grasslands	234,847	929,367,102
Inland wetlands	34	1,216,888
Temperate forest	111,991	465,104,132
Tropical forest	75,771	549,781,266
Woodlands	67,588	147,941,270
	535,507	**2,132,761,320**

d) Iron ore

Biome	Total land use 2016 (ha)	ES Costs 2016 ($)
Desert	11,428	NA
Grasslands	48,741	192,885,858
Temperate forest	116,725	484,767,093
Tropical forest	73,964	536,669,233
Woodlands	64,535	141,258,178
	315,394	**1,355,580,362**

Figure 3: Total estimated land use and EC costs (USD) per biome for the global 2016 production of a) bauxite, b) copper, c) gold and d) iron ore. NA = not available.

3.1 Bauxite

Figure 2a shows that bauxite mining is mainly concentrated in three biomes, "Tropical & Subtropical Moist Broadleaf Forests" (e.g. countries such as Brazil, India and Jamaica), "Tropical & Subtropical Grasslands, Savannas & Shrublands" (Australia and Guinea) and "Mediterranean Forests, Woodlands & Scrub" (Australia and Greece), which account for over 90% of production. Most bauxite mining is currently taking place in "Tropical & Subtropical Moist Broadleaf Forests". This has geological reasons, as bauxite occurs where intense weathering and drainage of the source rock is happening – which is in the tropics.

The authors calculate the global cumulative land use in 2016 with 106,771 ha. The ES costs for the land used by bauxite mines amounts to almost USD 600 million, with over half of the costs resulting from mines in tropical forests. The ES costs estimated are USD 0.08/t of ore mined since 1900 and USD 2.21/t of global production in 2016. If ES costs were added to the average bauxite price of USD 28/t in 2016 (USGS, 2019), the price would increase by about 7.9 %. The impact would be even more significant on the bauxite mining cash cost curve, which shows the distribution of production costs across the different mining companies. The additional cost would mean an increase of about 25% for the producers at the low end of the curve and would make 3-5% of producers unprofitable at the high end (Alumina Limited, 2018, p. 24; data for 2017).

3.2 Copper

Over one third of the cumulative copper production comes from mines in the “Deserts & Xeric Shrublands” biome (i.e. mainly from Chile, but also from Peru and USA) (Figure 2b). Biome distribution is stable over time, with the dominating “Deserts & Xeric Shrublands” biome showing a slight downward trend and the second placed “Montane Grasslands & Shrublands” biome (i.e. China) showing a slight upward trend in recent years, as shown in the supplementary data.

The cumulative land use for the copper mines is calculated at 470,839 ha in 2016 (Figure 3b). The mines in the “Desert” biome cover the largest proportion of land with over 149,000 ha. The ES costs for the land used by the copper mines covered in this analysis amount to almost USD 1.3 billion[3], with about two thirds of the costs resulting from mines in the “Grasslands” and “Temperate forest” biomes. However, the authors would like to highlight that no ES costs are yet available for the “Desert” biome. The ES costs are USD 1.95/t of historic global production and about USD 64.67/t if attributed to global 2016 production figures in the extrapolation. This would mean a price increase of about 1.3% to the average price of copper in 2016 of USD 4,860/t (USGS, 2019) and no significant impact on the copper cost curve, same as for the other two metals below.

3.3 Gold

Over half of the cumulative gold production comes about equally from mines in two biome types “Montane Grasslands & Shrublands” (e.g. South Africa, Peru) and “Deserts & Xeric Shrublands” (e.g. Australia, China, Chile) (Figure 2c). Biome distribution shows a decline for “Montane Grasslands & Shrublands”, which in 2010 was overtaken by the “Deserts & Xeric Shrublands” biome. Two tropical biomes show significant increases: “Tropical & Subtropical Moist Broadleaf Forests” tripled and “Tropical & Subtropical Grasslands, Savannas & Shrublands” more than doubled in the period covered (see supplementary data).

The cumulative land use for global gold mining is calculated with 535,507 ha in 2016 as shown in Figure 3c. The ES costs for the land used by gold mines amount to more than USD 2.1 billion, with the largest contribution resulting from mines in the “Grasslands” biome. Worth noting is also that, whilst mines in the “Temperate forest” biome cover a larger area than mines in the “Tropical forest” biome, the ES costs are higher for gold mining in the “Tropical forest”. The ES costs are USD 0.39/Oz of historic production or about USD 19 for each ounce produced in 2016, given that land use costs are cumulative. This would mean a price increase of about 1.7 % regarding the average price of gold in 2016 of USD 1,152/Oz (USGS, 2019).

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[3] The authors use 10^9 for billion.

3.4 Iron ore

Almost two thirds of iron ore comes from two biomes, “Deserts & Xeric Shrublands” and “Tropical & Subtropical Moist Broadleaf Forests” (Figure 2d), representing mainly Australian and Brazilian mines. The contribution from the “Deserts & Xeric Shrublands” biome more than doubled in the period covered, overtaking “Tropical & Subtropical Moist Broadleaf Forests”, which has declined overall in the period, in 2000.

The authors estimate the cumulative land use of the iron ore mines with 315,394 ha in 2016. Figure 3d shows the land use in the biome types according to the classification system used by De Groot et al, as well as the resulting ES costs. The ES costs for the land used by the iron ore mines amount to more than USD 1.3 billion, with almost half of the costs resulting from mines in “Tropical forests”. As a result and from an ES perspective, iron ore mined from “Tropical forests”, e.g. in Brazil, Indonesia or Vietnam is more costly, i.e. creates a higher damage to ES, than iron ore extracted from ecosystems with a lower valuation such as “Temperate forests” or “Grasslands” (e.g. Australia). This can also be seen in the extrapolation to the global figures, where missing production from China, which is responsible for almost 67% of the difference between SNL and USGS data, leads to a significant shift towards the “Temperate forests” biome and its contribution to ES costs being almost equal to that of “Tropical forests”. The ES costs are low at USD 0.02/t for historic global production. They are USD 0.58 for each tonne of ore mined in 2016. If these ES costs were added to the average iron ore price of USD 73/t in 2016, the price would increase by about 0.8% (USGS, 2019).

3.5 Four metals

Overall, the ES costs for the four metals add up to about USD 5.4 billion/year in 2016, with gold being the largest contributor (40%), followed by iron ore (25%), copper (24%) and bauxite (11%). In terms of biomes, regarding the four metals, the largest land areas are used in “Grasslands” (30%), followed by “Temperate forest” (24%) and “Tropical forest” (16%). The largest costs to ES come from “Grasslands” (32%) and “Tropical forest” (31%), followed by “Temperate forest” (26%), re-iterating the point made above that mining in the “Tropical forest” biome comes at a high cost to ES. Overall, about two thirds of the ES costs come from mines in forested areas. For “Coastal wetlands” the 2016 ES costs exceed about 1.5 times the revenues achieved by mining gold and bauxite in these biomes. Again, the authors would like to point out that no ES costs are yet available for the “Desert” biome, which is especially relevant for copper.

4. Discussion

This study presents a novel way to look at the impact on land by large-scale industrial metal mining by placing the mines into biomes and estimating the impact on ecosystem services in monetary terms thus producing novel results and insights. It does so by building on work done by Murguia (2015) on metal mining`s land use and by De Groot el al. (2012) on the value of ecosystem services in monetary units. They both discuss limitations to their approaches, which are relevant for this study. One is the underrepresentation of Russian and Chinese mines in SNL data, which the authors accounted for by using a weighted, country-based extrapolation from SNL to USGS, as described in Section 2.5. Another limitation are measurement errors derived from the visual interpretation of the satellite images used to calculate the WDRs. A paper to be published by Murguia and colleagues includes an accuracy assessment of the method employed to compute the WDRs and concludes that measurement errors are small, i.e. over 94% of pixels were correctly classified. This accuracy level is more than enough for any global assessment of land disturbances (Murguia & Bringezu, 2016). A third limitation is restricted data availability and reliability, distribution of data on ES and their values over biomes, value heterogeneity and range or choice of valuation method (De Groot, et al., 2012).

The concept of De Groot et al. (2012) is not without criticism, i.e. concerning the treatment of ES at the scale of biomes and the extrapolation of site-specific values to the global scale (Liekens & De Nocker, 2013); as is the concept of monetization of ecosystem services itself, i.e. that human preferences are irrelevant for what is essential for the maintenance of life support systems and that monetization further increases the commodification of nature (Splash, 2008). Despite these constraints, the results of the approach taken in this study show the relevance of taking land use in mining into consideration in the economics and policy making of global metal mining.

Data reliability and availability is a cause of concern for the mining data used, as described also in other publications (e.g. (Luckeneder, et al., 2019), (Tost, et al., 2018a), (Northey, et al., 2013)). The production data retrieved from the SNL database for the years 1990-2016 fluctuates between a low 20% for iron ore in 1994 and a high 99% for copper in 2002 when compared to data from the USGS. It covers between 31% (gold) and 51% (copper) of historical production. Given these differences, a weighted extrapolation at the country level was done, which should be seen as an estimate, given the assumptions that biome distribution and ore grades stay the same in the two data sets. Looking at these differences at a country level, the authors find in general across the four metals that SNL seems to be underreporting production from China and Russia. This matters, as both biome distribution and ES costs change towards biome types for mines in these countries, as the extrapolation shows especially for iron ore. New research is ongoing, aiming at filling these gaps and compiling a comprehensive mine-specific global database (Wirtschaftsuniversität Wien, 2019). Once this is ready, even better results can be produced.

An assumption made for this study is that all ecosystem services on the land used directly by mining are completely reduced to zero. No literature could be found that quantifies this impact, but there is mentioning of *“a significant disturbance and clearing of land due to the intensive nature of extraction and persistence of associated wastes”* (Franks, 2015), a lack of consideration in mining for landform design, maintenance of soil quality or other conditions needed for local flora and fauna to re-establish (Erskine, 2014) or that *“restoring ecosystem functions is not an easy task, especially in case of mined sites, because the more degraded is an ecosystem, the less effective is restoration”* (Rosa, et al., 2016), thus explicitly supporting the assumption in this study.

Also, this study gives no consideration to ongoing rehabilitation and considers land use to be cumulative for active mines until their time of closure. Mining companies have for some years recognized a need for progressive, on-going rehabilitation to restore the land and ecosystems and thus also ES. Whilst this might not always be the case for certain types of mines (e.g. large open pit copper or gold mines), it is certainly possible for bauxite mining, where it has been recognized as part of the Sustainable Bauxite Mining Guidelines issued in 2018 by the International Aluminium Institute (World Aluminium, 2018) and figures about average regeneration periods have been published (World Aluminium, 2018 a). This analysis provides strong support towards ongoing rehabilitation in bauxite mining, as shown above.

However, this is still a conservative estimate of the land area disturbed by large-scale metal mining since it only considers land used directly by mining. More work is needed on indirect land use induced by mining operations, which could have a far bigger impact on ES. For example, Sonter et al. find in their Brazilian Amazon focused study *"…that 12 times more deforestation occurred than within mining leases alone. Pathways leading to such impacts include mining infrastructure establishment, urban expansion to support a growing workforce, and development of mineral commodity supply chains."* (Sonter, et al., 2017). Similarly, more research is needed on the impact of artisanal and small scale mining (ASM), especially in gold, but also nickel and cobalt mining (Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF)., 2017), (Elmes, et al., 2014).

The implications of the price increases due to the additional ES costs described for each metal also need further research. Could a market-led price differentiation strategy lead to more funds for the conservation of ES? How could these extra funds be institutionally collected and distributed to fit their purpose and to ensure they are not mismanaged, i.e. how to deal with mismanagement, corruption or weak institutions? Any kind of instrument or mechanism created to strengthen the capacity (monetary, human resources, information, coordination, etc.) of those institutions also requires policy coherence with international commitments by governments framing the SDGs.

The authors have chosen to develop their approach for four key metals due to their significance to the economy. Since the study, despite the limitations discussed, provides a useful way to quantify metal mining's impact on land, it should be expanded to cover other raw materials and their impact on ES, i.e. construction materials such as sand and gravel and mineral fuels such as coal due to their high production numbers.

5. Conclusions

Applying the concept of ES valuation to metal mining as proposed in this paper is a useful way to quantify, in monetary terms, metal mining's impact on the land it uses. The overall ES cost of about USD 5.4 billion/year is little compared to the cost of global land use changes between 1997 and 2011 of between USD $4.3 and USD 20.2 trillion/year (Costanza, et al., 2014). Overall, the price increases of between 0.8% and 7.9% for the four commodities studied are small in comparison to increases caused by Paris Agreement-target consistent carbon prices (Tost, et al., 2019) and would be within market-driven price fluctuations of recent years. From the viewpoint of this analysis, the “Coastal wetlands” biome should be a no-go-zone for gold and bauxite mining, as the ES costs exceed the revenues generated by mining.

As a consequence, except for aluminium and the point raised above regarding “Coastal wetlands”, the authors therefore do not see ES valuation, applied for instance as a tax, as a stand-alone policy tool to lower the land impact of metal mining. Yet it can be seen as an important supplement of other country-specific policy tools such as zoning regulations, environmental minimum standards, or closure and post-closure legislation. It could also be part of globally harmonized best practices for responsible mineral resource development, described by Ali and colleagues (2017).

It would be a useful support for such policy tools in all stages of mining where land use aspects play a role. Ores from “high value biomes” such as tropical rain forests have higher ES costs than ores from “low value biomes” and thus, following this approach of ES valuation, would be less competitive in comparison. In the planning and permitting phase as a requirement of (strategic) environmental impact assessments, it incentivises less land intensive options, both quantitatively (lower footprint areas) and qualitatively (mining methods with lower impact on ES). ES valuation also provides an incentive for companies for early, progressive, on-going rehabilitation since restoring ES services as quickly as possible would reduce land use and restore ES, and therefore reduce ES costs - as well as closure provisions in legislations where these are required. The concept supports Neves et al. (2016), as it allows calculating the impact of mining accidents on ecosystems and their services. Lastly, it also supports research by Murguia et al. (2016) which indicates that there is geological potential for opening new mines in areas of low biodiversity in the future.

As demand for metals will continue to increase (IRP, 2017), internalising ES costs would also be an additional incentive for the mining industry to improve its sustainability performance (Tost, et al., 2018b) and to find new business models (Dunbar, et al., 2019) and innovate in order to decouple such demand growth from increased land use and ecosystem services. Endl and colleagues (2019) list a number of innovation concepts like “*Better resource characterisation*” or “*Disruptive new or alternative mining methods, such as in-situ leaching*” with a positive impact on SDG 15 “Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss” whose uptake and implementation should be positively affected by ES valuation.

Supplementary Materials: Biome conversions, biome distribution 1990-2016, land use and ES costs, ES costs per biome.

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