Global patterns of metal extractivism, 1950–2010: Providing the bones for the industrial society's skeleton

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Abstract

During the second half of the 20th century, mining expanded globally and must be considered one of the dominant forms of human intervention into the environment. Metals are strategically important resources for industrialized and industrializing societies. In 2010, the five BRICS countries (Brazil, the Russian Federation, India, China, and South Africa) consumed 54% of the metals mined globally. The analysis of material flow data offers a biophysical perspective on mining as a resource frontier and allows for the identification of patterns in global metals extraction and trade. Since 1950, metal extraction has shifted from the early industrializing countries into the emerging economies. In 2010, only 6% of metals mined stemmed from Europe or North America while 76% were extracted in four countries (Australia, China, India, and Brazil). In the countries hosting large-scale mining operations, socio-ecological pressure ensues the so-called extractivist development path is common. High rates of metal deposit depletion mean that today's metal extractors and exporters may depend on imports of metal from anthropogenic deposits (stocks in buildings, infrastructure, and durable products) in the future. The extractivist path and the shifting of metals from natural to anthropogenic deposits are both associated with potential for conflict.

Keywords

Material flow accounting; mining; metals; trade; extractivism

1. A material take on metals extractivism

The “great acceleration” of global resource use since the 1950s (Steffen et al., 2015) and the unprecedented growth rates during the first decade of the 21st century (Krausmann et al., 2009; Schaffartzik et al., 2014) are related to increased pressure on and damages to the environment, to manifest or looming resource scarcities, and to distributional conflicts. As high levels of consumption in industrialized countries prevail and material requirements in emerging economies grow, the geographical patterns of material extraction, trade, and consumption provide evidence on the role which countries and regions play in the global economy. Understanding these patterns and their dynamics is decisive in identifying the possibilities of and the limits to a future sustainability transition.

Compared to the acceleration that was to follow, the first half of the 20th century showed moderate growth of global material use. Biomass accounted for the largest share of extracted materials while the significance of metal ores increased slowly, their share in extraction rising from 3% in 1900 to 5% in 1950. In terms of the mass of metal mined, iron ores were dominant, accounting for approximately 90% of all extracted metals (Krausmann et al., 2009). After World War II, global material use changed rapidly and, by the 1970s, was composed mainly of abiotic materials, i.e., non-metallic minerals for construction and industrial use, metals, and fossil energy carriers, while renewable, biotic materials contributed a decreasing share (Giljum et al., 2014; Krausmann et al., 2008; Schaffartzik et al., 2014).

Metals, in particular, have been identified as strategically important resources within industrialized and industrializing societies (Graedel et al., 2013; Graedel and Cao, 2010). Iron and aluminum and an increasing range of other metals used in smaller amounts form the ‘skeleton’ of the industrialized economy. In contrast to, for example, biomass or many non-metallic minerals (sand, gravel), metals are point resources, with a very heterogeneous distribution across the globe. Some metals are mined in only a handful of countries (e.g., in 2010, 77% of chromium was extracted in South Africa, India, and Kazakhstan). Where metals are mined depends first and foremost on where deposits of sufficient quality occur and is also strongly subject to political processes (Auty, 2004; European Commission, 2010; Haglund, 1986): If the possibilities to establish and maintain a mining operation, including access to energy, water, and transport infrastructure, are not given where deposits occur (e.g., in areas experiencing violent conflict or where investments are not made),

metals cannot be mined. Trade plays a critical role in securing the metal supply of those countries in which metals are not extracted, providing them with materials crucial for the functioning of industrial society (Graedel et al. 2010). Unlike fossil energy carriers and many industrial minerals (e.g., phosphate), metals are not through-flow materials that are transformed into waste and emissions within a year or less. Instead, the major share of extracted metals is accumulated in stocks of buildings, infrastructure, and durable products, providing opportunities for future “urban mining” (extraction of metals from anthropogenic sources) and recycling (Reck and Graedel, 2012; Bigum et al., 2012). While natural deposits are depleted, anthropogenic stocks of metals have reached a considerable size and continue to grow (Gordon et al. 2006). In Australia, one of the largest global providers of metals, deposits are exploited at high rates. As a consequence, the metal content of mined ores has declined considerably during the 20th century and for some important metals, extraction is assumed to have “peaked” or to peak in the foreseeable future (Mudd, 2010a; Prior et al., 2012): the rate of extraction of these metals has reached its maximum level and is expected to decline in the future. Mining of lower grade ores, e.g., copper from low-grade sulfides instead of high-grade oxides, may delay but not indefinitely avoid these peaks, at the expense of increasing energy inputs and emissions associated with extraction (ICMM, 2012; Mudd, 2010a, 2007a, 2007b; Norgate et al., 2007, Norgate and Haque, 2010). ‘Mining’ of metal from anthropogenic deposits (buildings, infrastructure, and durable products) at the end of their life time is already gaining strategic importance (Gordon et al., 2006).

Global growth in metal demand and long-term increase of world market prices for many metals provide incentives for countries to seek revenue through the exploitation of their natural resource base and the export of primary commodities. The expansion of extraction frontiers drives the potential for conflict between nature conservation, the provision of important ecosystem functions such as carbon sequestration, and different forms of societal resource use. Competition also arises between the proponents of different forms of resource use (e.g., of mining or agriculture, surface mining or rural settlement, corporate or artisanal mining) (Muradian et al., 2012). The expansion of the resource frontier associated with mining operations is often very pronounced and far-reaching environmental and social changes are made in relatively short periods of time. The implications of the extraction of resources for export have been analyzed within political ecology as *extractivism* (and more recently also as *neo-extractivism*, see Burchardt and Dietz, 2014; Gudynas, 2010; Lambert, 2012; Ruiz Marrero, 2011). While the exact definitions of extractivism

vary between researchers (Acosta, 2013), most agree on the basic characteristics: The extractive sectors contribute a large share of total value added, the export of primary commodities is among the most important sources of revenue, and labor and natural resources are exploited beyond their ability to reproduce themselves (Bunker, 1985). Mining operations expand into new territories (Haglund, 2011). The high demand for land, energy, and water associated with metal mining may additionally cause competition for these resources among different local and regional stakeholders (Bebbington et al., 2008). Resource-rich countries that pursue an extractivist development model are particularly prone to conflict in which the role of mining operations has been emphasized by researchers (Bridge, 2004; Hilson, 2002; Jenkins, 2004; Martinez-Alier, 2001; Özkaynak et al., 2012). The “discovery, extraction and processing of mineral resources is widely regarded as one of the most environmentally and socially disruptive activities undertaken by business” (Jenkins and Yakovleva, 2006, p. 272). Evidence has been gathered for Latin America in general (Urkidi and Walter, 2011), for Peru (Bebbington and Williams, 2008; Urkidi, 2010), the Philippines (Holden, 2005), India (Temper and Martinez-Alier, 2013; Martinez-Alier et al., 2014), Ghana (Hilson and Yakovleva, 2007), Namibia (Conde and Kallis, 2012), South Africa (Adler et al., 2007), and New Caledonia (Horowitz, 2009). In several countries, revenues from mining have not significantly improved with increasing rates of extraction, even when primary commodity prices were high. For Sub-Saharan Africa, corruption and nepotism in the administration of mining operations and lack of adequate taxation have been identified as the main obstacles to overcoming the ‘resource curse’ (Bebbington et al., 2008; Campbell, 2006; Rosser 2006; Stürmer, 2010). Conflict with regard to mining also occurs in the industrialized economies in which metal extraction plays an important role such as Australia (Trigger, 2005), with recent conflicts erupting over water extraction in the Murray-Darling basin between farmers and miners (Berry, 2010). Environmental contradictions have also been identified in the mining of copper in the US American Southwest (Bridge, 2000). Political and social factors are crucial in determining whether resource rich countries benefit from the extraction and export of metals or the negative impacts for people and the environment prevail (Rosser, 2006). The strong specialization on individual natural resources, such as metals, for export leaves economies vulnerable to the potentially high price volatility (Dwyer et al., 2011) of these resources (Acosta, 2013; Gudynas, 2010; Svampa, 2013). The focus on mining in extractivist economies can – as long as the exploitation of reserves remains viable – lead into such a ‘specialization trap’, possibly accompanied by deteriorating terms of trade (Harvey et al., 2010), depending on the development of international prices and of the role of other sectors within the

economy (Muradian and Martinez-Alier, 2001). While during the early 21st century, a growing global demand for metals curbed the problems associated with this specialization, stagnating or even declining demand will reinforce these problems for extractivist economies. Simultaneously, the loss of metal reserves through extractive activities must be taken into account when evaluating the economic benefits associated with extractivism (World Bank, 2006).

This article provides a material perspective on metals extractivism in order to complement the existing, qualitative analyses from within political ecology with a quantitative perspective. Drawing on material flow accounting data to trace the global patterns of metal extraction and trade between 1950 and 2010, a spatial disconnect is observed between 1) the exporters of primary metal commodities, 2) countries which transform primary materials into commodities, and 3) the consumers of the latter. By considering not only the pure metal but by also taking the large amounts of waste rock into account which are extracted during mining operations, a proxy for the socio-ecological pressures associated with metal mining is provided (Mudd, 2010a).

2. Material flow accounting for metals: methods and data

Global patterns and dynamics of metal extraction and trade are shaped by biophysical as well as socio-economic factors. In this article, material flow data on metal extraction and trade is analyzed. The data were compiled according to a material flow accounting (MFA) approach (Fischer-Kowalski et al., 2011) in a global database covering extraction and trade by a total of 65 material groups (including 17 different metals or metal groups) in 177 individual countries between 1950 and 2010 (Schaffartzik et al., 2014). An overview of the relevant MFA methods and data sources is provided in the following, a detailed description can be found in the online supplementary material. Two additional levels of detail are introduced for the purposes of this analysis which allow for a better understanding of the patterns and dynamics of global metals extraction and trade: 1) The separate reporting of metal content and waste rock extraction and 2) the distinction of trade in primary and secondary commodities.

Data on metal extraction at the country level was obtained from the United States Geological Survey (USGS, 2013); this data was digitalized by Rogich and colleagues (2009) for the decades from 1970 to 2000. Data from the British Geological Survey (BGS, 2013) was consulted for cross-

checks. Data on imports and exports of ores, metal concentrates, and metal products were extracted from the UN Comtrade database (UNSD, 2013) which provides trade data for individual countries in physical and monetary units from 1962 onwards. Prior to 1980, coverage of trade flows in the UN Comtrade database is sparse for a number of countries. It is possible that these countries were not deeply integrated into global markets in the earlier decades so that the global trade aggregates present only a slight underrepresentation (Loy, 2013).

The development of metal extraction is specifically examined for 14 individual countries, four country groupings, and six different metals (iron, aluminum (bauxite), chromium, lead, manganese, and copper) which provide the ‘skeleton’ of industrial development (Graedel et al. 2010): Iron and aluminum are the quantitatively most important metals and accounted for roughly 95% of all metal mined in the period 1950 and 2010. Copper, chromium, manganese, and lead are four widely used industrial metals for which no or only limited substitutes presently exist (Graedel et al., 2013). Other metals, extracted and used in much smaller quantities, are also important for industrial development and very significant in economic terms but have been excluded from this study.

The MFA conventions require that metal extraction is reported as run-of-mine, i.e., as that amount of material which is extracted and processed (Eurostat, 2012; Weisz et al., 2007). Not included is the overburden which is moved during the mining process but not subject to further processing. For metals, domestic extraction corresponds to the gross ore which consists of the metal content as well as the surrounding (waste) rock. In contrast to standard material flow accounts, waste rock and metal content are reported separately for domestic extraction (Schaffartzik et al., 2014) in order to make it possible to identify patterns in the amount of primary commodity (metal content) and of total material extracted.

To distinguish between gross ore and metal content, information on the corresponding ore grades (i.e., on the metal content of the gross ore) is required. Out of the metals covered in this study, the USGS reports iron, manganese (until 1990), and bauxite in terms of gross ore. Chromium, lead, and copper are reported in metal content only. For these metals, gross ore was calculated using average ore grades for individual countries (either based on major mines or country averages). These ore grades were collected from literature (USGS, BGS, United States Bureau of Mines, and industry reports) and expert assessments. Coupled production from ores containing more than one metal (Graedel, 2011; Hagelüken and Meskers, 2010) was taken into account (Krausmann et al.,

2008). For the six metals examined in this study, average ore grades range from 56% for iron to 0.2-3.9% for copper (Table 1): Approximately 1 ton of waste rock is associated with each ton of pure iron while up to 200 tons of waste rock might be associated with each ton of pure copper. Country-specific ore grades may vary by a factor of over two for iron and chromium and by an order of magnitude for copper and lead. It is therefore essential to use country-specific factors wherever possible. Country-specific information was available for 71% to 99% of globally extracted gross ore in 2010. In case no country-specific information was available, calculated global average ore grades were applied. Constant ore grades based on the year 2000 were used throughout, affording the advantage of eliminating assumptions about their development from impacting the results. However, where ores of successively lower grade were mined, the constant ore grades may lead to an overestimation of the gross ore amounts in the years prior to 2000 (Krausmann et al., 2009). To make the potential impact of this assumption visible and the results accordingly interpretable, gross copper and iron ore were calculated based on changing ore grades. The latter were obtained by interpolating between reported or calculable ore grades. The values obtained for global gross ore extraction of iron and copper in 1950 based on these ore grades differ significantly from the results based on constant ore grades: For copper, declining ore grades reduce the gross ore amount by 33%. For iron, the picture is different: Increasing ore grades in the United States (Mudd, 2010b), the most important extracting country between 1950 and 1970, lead to global metal extraction in 1950 increasing by 11% compared to the value obtained using constant ore grade (Table 1).

	Global average ore grade (calculated)	Lowest ore grade (USGS reported)	Highest ore grade (USGS reported)	Share of gross ore estimated via country-specific ore grades
Iron	56.1%	30.0%	67.9%	91%
Copper	0.8%	0.2%	3.9%	99%
Lead*	5.9%	1.3%	12.6%	33%
Chromium	38.0%	18.0%	50.0%	71%

Table 1: Ore grades and coverage by country-specific data for the year 2000 for the six metals included in this analysis. *Lead is often a by-product of zinc and its gross ore calculated via estimation procedures for coupled production. Bauxite and manganese are reported as gross ore. Sources: USGS, 2013; BGS, 2007 (also see Schaffartzik et al., 2014, Krausmann et al., 2008).

Global metal trade between 1962 and 2010 is covered and trade is analyzed in detail at the country-level for 16 countries and the rest of the world (ROW) for the period 1980-2010. The approach used in this study covers trade flows with the mass they have upon crossing the border. The results therefore differ from consumption-based approaches which cover the material extraction, no matter where in the world it occurs, associated with the monetary domestic final demand of a country (Wiedmann et al., 2014).

In the quantitative analysis of extractivism, data are required not only on aggregate trade flows but also on the degree of processing that the traded goods have undergone. This study therefore distinguishes metals trade flows according to whether they are ores and concentrates (primary commodities) or more highly processed metal goods (secondary commodities). It is thereby possible to add some degree of complexity compared to standard material flow accounts (Eurostat, 2012). Nonetheless, each of these types of trade flows remains very heterogeneous: Ores and concentrates, aggregated here as primary commodities, may contain as little as 20% and as much as 50% metal. While extraction can be reported in gross ore, apparent consumption as it is defined by MFA conventions as domestic extraction plus imports minus exports (Eurostat, 2012) always represents a mix of gross ore (from domestic extraction) and more highly concentrated metal (from trade flows).

3. Patterns in global metals mining and trade

Mining is an important form of human intervention into natural systems and a major socio-economic activity. In 2013, the mining sector was responsible for more than 700 billion US\$ in market capitalization, a more than sevenfold increase since 2002 (Price Waterhouse Coopers, 2014). As the transition from agriculture and forestry to mining as the activity dominating global material provision advances (Krausmann et al., 2009; Schaffartzik et al., 2014), the social consequences of mining are increasingly recognized. Numerous conflicts over access to land and resources involving the mining industry have been documented (Hilson, 2002; Özkaynak et al. 2012; also see Introduction).

A large share of capitalization in the mining sector benefits internationally operating mining companies while most of the socio-ecological pressure associated with mining occurs in the

country of extraction. The deposits of metals which can currently be exploited in an economically feasible manner are unequally distributed. Some indication of this is provided by data on the distribution of reserves (identified resources that could be economically extracted, see Ayres 2007; Craig et al., 2011; Kleijn, 2012; Working Group on Geological Stocks of Metals, 2011). In 2013, 53% of copper and 58% of iron reserves were located in just three countries each (Chile, Peru, and Australia for copper and Australia, Brazil, and the Russian Federation for iron) (USGS, 2014, 2015). These types of mining ‘hot-spots’ are not only due to geological differences. Countries with an established mining sector and the according technology and financial capital are more likely to turn natural deposits into known and exploitable reserves. The more geographically concentrated the extraction of a material is, the greater is the role which trade plays in mediating between extraction and consumption. In this way, the distribution of metal reserves strongly affects material flow patterns.

Following an approach applied by Steinberger and colleagues (2010) to material use in the year 2000, Lorenz curves depict the inequality of extraction and consumption of metals in 1960 and 2010 (Figure 1). The flatter curves in 2010 show that in the 50 years since 1960, countries representing somewhat larger segments of the global population became involved in metal extraction and consumption – distribution is less unequal in 2010 than it was in 1960. Distribution of metal extraction is slightly more unequal than distribution of metal consumption, measured here as domestic material consumption (domestic extraction + imports – exports). In 2010, those countries with the highest rates of per capita gross ore extraction accounting for almost 50% of global extraction were home to 10% of the population while those countries with the highest rates of consumption per capita which were home to 10% of the global population accounted for 41% of consumption in concentrated metal and gross ore. On the one hand, the difference between the distribution of metal extraction and consumption indicates the significance of redistribution through trade. On the other hand, this redistribution as reflected in Figure 1 is lower than might be expected because a high amount of the waste rock extracted in the gross ore remains in the countries of extraction and is not transferred to those countries in which the final demand for metal products arises.

In 2010, world average total metal consumption was approximately 1 ton per capita. 141 countries (out of the 174 covered in this study) consumed less than that global average. Out of the 33 countries which consumed more, 14 also consumed more than they extracted domestically. In most

industrialized countries, high rates of metal consumption are possible only because metal is extracted (and initially processed) elsewhere. International trade allows for consumption of metal in places without extraction activities and is a prerequisite to the industrialization of those countries (Graedel and Cao 2010). As industrialization continues to spread, demand for metals among the 40% of the global population currently consuming under 4% of global metals will increase. This rising demand will fortify the extractivist lock-in which countries with globally relevant mining sectors experience (Acosta, 2013).

Figure 1: International Lorenz curves of gross ore domestic extraction and apparent consumption (domestic material consumption = domestic extraction + imports – exports) of gross ore and concentrated metal in 1960 and 2010

Between 1950 and 2010, global ore extraction shifted from the early industrializers to the emerging economies. By 2013, half of the mining industry’s 40 largest companies by market capitalization ran the bulk of their operations in emerging countries (Price Waterhouse Coopers, 2012). These economies have become important global players not only in terms of their economic growth but also in terms of the available and extracted resources (Price Waterhouse Coopers, 2014).

The role which countries play in global metal and waste rock extraction is determined by whether or not they host mining operations and by the type(s) of metal mainly mined there. In terms of total global metal extraction (in metal content), those countries which mine the ‘bulk metals’ iron and aluminum are likely to figure prominently. In 1950, 86% of all global metal extraction occurred in the United States of America (USA), Europe, and the Soviet Union (USSR) (Figure 2). 90% of global iron was mined in these countries where it accounted for over 92% of all ore extraction. Due

to iron's comparatively high ore grade, the share of waste rock generated in the early industrializers through metal mining (Figure 2) was relatively small (39%). In terms of waste rock, the rest of the world (ROW) grouping contributed more than half to global extraction in 1950 (52%), related to high amounts of mining of ores with metal content significantly lower than iron, especially copper, in South America and Sub-Saharan Africa. Growth in European metal extraction was only significant until 1970. In 1990, the 15 states of the Former Soviet Union (FSU) and 3 individual countries (Australia, China, and Brazil) accounted for over 50% of global metal extraction.

Figure 2: Extraction of metal content of all ores mined (left) and total waste rock (right) in Megatons per year (Mt/a) by regions, countries, and country grouping rest of the world (ROW), 1950-2010; please note the difference in scale of the y-axes.

By 2010, 76% of all metals and 80% of iron mined globally were extracted in just four countries (Australia, China, India, and Brazil) and only 6% of metals stemmed from Europe or North America. Due to the high share of iron, the major mining countries extracted only 56% of global waste rock (Figure 2). A relatively large share of waste rock extraction occurs in the ROW countries where high amounts of metals with lower ore grades (chromium, lead, manganese, and copper) are mined. Australia, China, India, and Brazil also extracted 76% of global aluminum, 63% of lead, and 55% of manganese (Table 2). For the latter two types of metals, extraction occurred mainly in China and Australia. It is only for chromium, manganese, and especially copper that other countries play a bigger role: South Africa mined over 44% of the world's chromium and 21% of manganese in 2010. Kazakhstan mined 20% of chromium, and Chile mined 32% of copper. At the country

level, the distribution of metals extraction clearly exhibits a shift away from the early industrializers in Europe and North America to the emerging economies of especially Latin America and Asia. Australia, as a high-income, high-wage industrialized country with a dominant extractive sector, forms an exception in this regard (for an in-depth discussion, see Schandl et al., 2008). The shift in extraction of ores from the early industrializing to the emerging and developing countries had to occur due to the long history of mineral exploitation in Europe and the USA which resulted in the early depletion of easily accessible deposits in these countries. Investments in technology and infrastructure in emerging economies were used to open previously inaccessible deposits to mining companies. This shift was additionally aided by lenient (environmental) legislation, favorable taxation schemes, and relatively low labor costs in emerging economies which provided an important incentive for investors. The simultaneous rise of large cargo ships capable of transporting bulk materials was a prerequisite to the rapid development of the export-oriented mining industry (ICMM, 2012).

share in global metal extraction (rank)						
	Chromium	Aluminum	Manganese	Lead	Iron	Copper
China	1.0% (11 th)	21.0% (2nd)	19.3% (3rd)	44.7% (1st)	28.5% (1st)	7.1% (3rd)
India	12.7% (3rd)	8.6% (4 th)	7.4% (5 th)	2.3% (7 th)	11.2% (4 th)	0.2% (29 th)
Australia	-	32.7% (1st)	23.0% (1st)	15.1% (2nd)	20.4% (2nd)	5.1% (7 th)
Kazakhstan	20.0% (2nd)	2.5% (8 th)	4.7% (7 th)	0.9% (15 th)	1.0% (12)	2.2% (12 th)
South Africa	44.3% (1st)	-	21.5% (2nd)	1.2% (12 th)	2.9% (7 th)	0.6% (22 nd)
USA	-	-	-	8.9% (3rd)	2.5% (8 th)	6.5% (4 th)
Brazil	0.8% (12 th)	13.4% (3rd)	5.8% (6 th)	0.6% (19 th)	18.4% (3rd)	1.3% (16 th)
Chile	-	-	-	0.0% (30 th)	0.4% (17 th)	31.9% (1st)
Peru	-	-	-	6.3% (4 th)	0.5% (16 th)	7.3% (2nd)
ROW	21.2%	21.8%	18.3%	20.0%	14.2%	37.8%
Total metal (Mt)	9.5	209.4	13.5	4.1	1 274.5	17
Total gross ore (Mt)	23.7	209.4	13.5	42.1	2 593.8	2 164

Table 2: Share and rank of nine individual countries and rest of the world (ROW) grouping in total global metal extraction (metal content) in 2010 by six major industrial metals (iron, aluminum, chromium, manganese, lead, copper). Global totals in Megatons (Mt).

A proxy for the socio-ecological pressures exerted by the mining industry in a country is provided by the waste rock extracted during mining in relation to the area of a country (socio-ecological capacity). In countries like Chile and Peru, which are specialized in the extraction of copper, higher pressure may be caused by mining operations than in countries mining metals with higher average ore grades, where less material has to be moved to obtain the desired metal (Dudka and Adriano, 1997). The socio-ecological pressures potentially associated with mining activities vary not only among countries and metals but even among mines in countries. Depending on its composition, waste rock may be more strongly prone to acid drainage, i.e., to the environmentally highly adverse oxidation and discharge of the sulfide compounds contained in the waste rock, which in turn could be curbed by management practices (Mudd, 2010a). The exact location of the mine determines

which socio-ecological systems are most strongly affected by the extractive process. No single indicator exists which adequately represents the manifold pressures associated with mining activities. A study seeking to make global patterns visible must necessarily reduce the complexity involved in representing these pressures. More so than extraction in terms of metal content, waste rock extraction provides a proxy for the dimensions of the mining operation in question and is thus more strongly linked to pressures caused thereby. In this study, the overburden (unused extraction) is not taken into account in order to maintain the focus on used extraction. Countries which supply the global economy with metals from low-grade ores, thus generating a relatively large amount of waste rock, are especially prone to severe ecological pressure related to mining. In contrast to the metal content, the extracted waste rock has no (or very little) direct economic value. This flow is therefore also a proxy for a pressure which is possibly not ‘balanced’ by an according proportional income. As a proxy, waste rock extraction per area provides an indication of the mining intensity in a country and the potential aggregate pressures arising from mining. This national-level indicator cannot reflect patterns at the subnational level: A large country with intensive mining activity in one area would feature a waste rock to area ratio similar to that of a country with low intensity-mining spread throughout. Country-level in-depth studies are therefore necessary in investigating the global patterns in detail.

In Figure 3, data on countries’ waste rock and metal extraction is plotted in progressive order according to waste rock per area. The x-axis depicts the share of the global area which the plotted countries account for, the primary y-axis represents the share of global waste rock and metal extraction. Where the slope between two points on each of the curves is comparable, the amount of waste rock and metal extracted progress proportionally and the difference between the two slopes is (approximately) 0. The difference between the slopes is plotted on the secondary y-axis. All countries which have a higher share in total global waste rock extraction than in total global metal extraction are indicated by a slope difference smaller than zero. Those countries for which the data are plotted in the top right-hand corner of Figure 3 are those with the highest amount of waste rock extracted per unit area. At approximately 1 kiloton of waste rock per square kilometer and year (kt/km²/a) in 2010, Chile has the highest rate of waste rock extraction by far, most of it related to open pit mining of copper (Giljum, 2004). The second is the island state of New Caledonia with waste rock extraction amounting to 0.4 kt/km²/a in 2010, mostly related to the highly contested open pit mining of nickel (Horowitz, 2009). At 0.2 kt/km²/a, Indonesia is third in

terms of relative waste rock extraction with open pit mining of gold, copper, and nickel as the main drivers. In contrast to Chile's copper extraction, these high-impact mining activities put neither New Caledonia nor Indonesia among the world's largest producers of the metals they extract. The countries for which data are plotted in the bottom left-hand corner of Figure 3 have low extraction of waste rock per area. Despite being very important global extractors of metals (see Table 2), Brazil, the USA, and Australia, for example, have waste rock per area extraction ranging between 0.02 kt/km²/a and 0.04 kt/km²/a – an order of magnitude lower than in countries with high waste rock intensity. The commodified resources (in this case: metals) and the socio-ecological pressures associated with their extraction are not proportionally distributed.

Figure 3: Lorenz curve of waste rock and metal extraction (primary y-axis) by area (x-axis) in 2010: Where the segment of the orange “curve” is steeper than the grey curve, a disproportionate ‘gain’ in metal occurs, where the grey curve is steeper, there is a disproportionate addition of waste rock without a corresponding ‘gain’ in metal content; the difference between the two slopes is plotted on the secondary y-axis.

Trade in metals and metal products links extraction and consumption across spatial distances. Between 1960 and 2010, trade volume in metals at lower stages of processing (i.e., ores and concentrates) increased by a factor of 5, at approximately the same rate at which extraction increased. Trade in more highly processed metal products surpassed trade in ores and concentrates in 2000 and grew by a factor of almost 10 across the whole time period (Figure 4). Countries with

metal extraction increasingly export not only primary but also secondary commodities made from metal and countries without or with little metal extraction import ores and concentrates to produce highly processed metal products for export. China's imports of ores and metal concentrates, for example, increased by a factor of almost 10 between 2000 and 2010. During the same decade, China also almost quadrupled its exports of metal products. In 2010, net imports of metals were dominated by emerging economies. These patterns are highly relevant in identifying extractors of metals and exporters of primary metal commodities who may be dependent on imports in meeting their demand for more highly processed metal commodities.

Figure 4: Global trade volumes of ores and concentrates and metal products in million tons per year (Mt/a) between 1960 and 2010

In examining countries' roles as global suppliers or consumers of primary and/or secondary metal commodities, four general patterns can be identified: I. Countries are net exporters of primary as well as secondary metal commodities, II. countries are net exporters of primary and net importers of secondary metal commodities, III. countries are net importers of primary and net exporters of secondary metal commodities, and IV. countries are net importers of primary as well as secondary metal commodities. Countries following pattern I tend to have a strongly developed mining sector as well as metals processing industry. Examples are Australia, Brazil, and South Africa as well as two countries emerging from the collapse of the USSR with major metal processing capacities: the Russian Federation and Ukraine (see Table 3). In these countries, the focus on the extractive sector is coupled with an additional focus on secondary production with its value added. The same cannot

be said of countries following pattern II which are net suppliers of metals to the global market and simultaneously dependent on imports in meeting their needs for more highly processed metal products. Examples include India and Indonesia, two of the five most important net exporters of ores and concentrates in 2010, as well as Mexico and Thailand. Among the net importers of primary metal commodities, two distinct patterns can be identified. Pattern III describes those countries which have strongly developed industrial production sectors focused on export in which imports of primary metal commodities are transformed into exports of secondary commodities. By 2010, China, accounting for 64% of global net imports, had emerged as the most important net importer of metal for further processing followed by Japan, the Republic of Korea, and Germany. China, Japan, and the Republic of Korea were also the three most important net-exporters of metal products (see ranks in Table 3). The USA were a net importer of metal products until 2010 when they became a significant exporter of metal-based machinery and iron and steel scrap, following pattern III. Pattern IV describes those countries in which no metals mining occurs or the amounts mined do not suffice to meet domestic demand. These countries, such as Egypt and Turkey, must rely on imports from other countries for both primary and secondary metal commodities.

In interpreting the role of the highly ranked countries in global metals trade, it is important to note that flows of iron and aluminum essentially determine this rank: In 2010, 82% of the extracted metal content was iron and another 13% was aluminum. Beyond the countries that traded the major shares in these metals, many others exhibited the same types of trade patterns but are not listed in Table 3 because the amounts were much lower.

c

		PTB primary 2010 [Mt/a]	rank 2010	rank 1980	PTB secondary [Mt/a]	rank 2010	rank 1980		
I	Australia	-	416	1	2	-	3	14	7
	Brazil	-	320	2	3	-	4	10	5
	South Africa	-	62	4	4	-	8	8	3
	Ukraine	-	23	7	*	-	27	4	/
	Russian Federation	-	16	12	*	-	30	3	/
II	India	-	130	3	6		14	5	9
	Indonesia	-	55	5	15		12	7	4
	Mexico	-	3	17	33		31	1	2
	Thailand	-	1	24	24		15	3	8
III	China		709	1	/	-	51	2	/
	Japan		148	2	1	-	66	1	1
	Republic of Korea		62	3	8	-	12	6	9
	Germany		48	4	2	-	10	7	2
	USA		4	18	3	-	20	5	~
IV	Egypt		2	23	21		18	2	11
	Turkey		4	20	14		15	4	13
	ROW		48				128		

* The largest net exporter of primary metal commodities was the USSR.

~ The USA were a net-importer of secondary metal products in 1980.

Table 3: Physical trade balance (PTB = imports minus exports) of primary metal commodities (ores and concentrates) and secondary metal commodities (metal products) in Megatons per year (Mt/a) by 16 countries and rest-of-the-world (ROW) grouping in 2010. The rank of the individual countries amongst the net exporters/importers in 2010 and 1980 is additionally provided. Net exporters are highlighted in *italics*, the top 3 net importers and net exporters in each category are in **bold**. / indicates lack of sufficient data. Roman numerals I-IV refer to distinct trade patterns further discussed in the text.

Countries following patterns I and II exhibit characteristics of extractive economies in terms of their material extraction and use. Among them, countries with the highest levels of gross ore extraction per area are those with large-scale mining operations in relation to the size of their territory and/or those which focus on the mining of metals with comparatively low ore grades: Chile, Jamaica, New Caledonia, Indonesia, and Uzbekistan followed by Poland, China, Peru, South Africa, and Ghana (indicated by the shading of countries in the map in Figure 5). With the exception of China and Poland – net importers of primary and net exporters of secondary metal commodities – these countries all follow one of the two ‘extractive’ trade patterns I and II (also indicated by the bar charts integrated into Figure 5). Ghana, Peru, Indonesia, and Jamaica, for example, entertain

large-scale, intensive mining facilities in their countries for the sake of extraction for export and are simultaneously dependent on imports in meeting their needs for secondary metal products. The extraction and export of metals may be relevant from the perspective of individual countries even if they are not among the largest global suppliers. For example, exports of ores and concentrate made up well over 50% of total physical exports in 2010 in Jamaica (bauxite), Madagascar (chromite), and the Philippines (nickel). New Caledonia almost exclusively exports nickel ores and concentrates. In these countries, metal extraction – often occurring in open pit mining – is associated with high socio-ecological pressure. Much lower pressure due to their comparatively low waste rock extraction per area are enjoyed by many of the countries which export secondary metal products made from imported primary commodities (pattern III), such as Germany, Republic of Korea, and Japan (Figure 5).

Figure 5: World map of gross ore extraction per country area and net trade in ores and concentrates and metal products in 2010. The countries which extract metals are shaded according to their gross ore extraction per area measured in tons per km²; the more extraction per area, the darker the shading. The integrated bar charts show net trade (imports minus exports) in kilotons per year (kt/a) of ores and concentrates (left bars) and metal products (right bars). Please note that the net trade values have been plotted on a logarithmic scale. Map prepared by Susan Härtig (susanhaertig.com).

4. Implications of global patterns in metals extraction and trade

While approximately 0.9 Gt/a of gross ore was globally extracted in 1950, this figure rose to 6 Gt/a by 2010. Metals mining which was, in 1950 and 1960, still concentrated in the early industrializing countries of North America and Europe, increasingly shifted into the emerging, newly industrializing economies, especially into China, Brazil, and India. Australia is the only early industrializer which continues to be a major global supplier of metals. This shift in extraction has meant that industrialized countries increasingly meet their needs for metals via imports (following either pattern III or IV, see Table 3) so that in many cases consumption of metals and the socio-ecological pressures associated with their extraction and primary production occur at a spatial distance. Taking waste rock per area as a proxy, a shift of the socio-ecological pressures into developing and emerging economies can be observed. Those countries where extraction now occurs often tend to export primary metal commodities (ores and concentrates) and import secondary metal products made from these primary commodities (pattern II, see Table 3). The extracting countries also face the possibility of metals ‘peaking’ (Prior et al., 2012), i.e., of the rate of extraction declining due to mining of lower-grade ores at higher costs (e.g., for the case of bauxite: Mudd, 2010a). This leads to growing strategic importance of anthropogenic sources of metals. The global patterns of metal extraction and trade during the 60-year period between 1950 and 2010 determined that the metal deposits of the future would be concentrated in the early industrialized countries.

The analysis of material flow data points to two ways in which the distribution of socio-ecological burdens and benefits of metals extraction and trade is linked to potential causes of conflict:

1. Socio-ecological pressures associated with the pathway of extractivism in mining activities,
2. Concentration of metals in anthropogenic sources as mediated by current trade patterns.

4.1. The role of material flow data in evaluating extractivism

Many of the countries in which conflicts related to mining operations have been identified (see Introduction) are emerging economies that became global suppliers of metal during the late 20th and early 21st century. In spite of the high potential for conflict, mining operations are pursued within an extractivist portfolio and supported by the involved governments with the proclaimed

hope that the economic benefits will outweigh the socio-ecological burdens. The biophysical evidence compiled in material flow accounts and the detailed case studies on occurrences of extractivism and their conflict potential are highly synergistic. The extraction of waste rock per area as a proxy for socio-ecological pressure from mining points to where mining-related conflicts may occur. Whether and how such conflicts specifically unfold is, however, strongly shaped by the geological, political, economic, and social framework conditions accompanying the mining operation. With regard to extractivism, the biophysical data suggest that next to the mining ‘hotspots’ on which some research has already been done, there may be other, less well-known occurrences of extractivism worth investigating. With regard to the ecological pressures associated with mining, the biophysical data do not indicate significant differences between the material flows associated with the extractivism of the 1970s and 1980s and in more recent decades. This may be important in light of the shift towards *neo*-extractivism which political ecology has observed. In this socio-political development model, mainly pursued in a few Latin American countries, the role of the state vis-à-vis private business in the extractive sector (mining operations in this case) is strengthened in order to increase the benefits for the national economy and to ensure a more equal distribution of these benefits across the population (Burchardt and Dietz, 2014). Governments that pursue *neo*-extractivist development models use the revenues from the often state-led extraction of resources to improve the standard of living within the country. The biophysical data suggest that even if a certain distribution of income from the extractive industries is possible, the sheer dimensions of the intervention into the given social and ecological functions of the targeted areas remain. This may be important in explaining why the neo-extractivist pathway remains inherently linked to (potential for) conflict (Bebbington, 2011; Kohl and Farthing, 2012).

Where gross ore extraction per area is high and areas of intensive extractive activities are closely tied to global markets but not fully integrated into the national economy, territorial fragmentation may accentuate local inequalities. The expansion of the mining frontier is linked to contamination and biodiversity loss, additionally fueling socio-ecological conflict (Gudynas, 2010). The biophysical data points to a systematic trade-off between financial incomes with ecological burdens, which means neo-extractivism may be, just like extractivism, associated with high environmental costs and may thus ultimately fail its social goals. The latter is especially true where economies fail to establish strong and transparent institutional frameworks regulating the activities of the primary sector. Such failure may lead to the concentration of resource-related wealth, not

improving the standard of living overall. Where societal groups exposed to the burdens are not the same as those experiencing the benefits, potential for conflict may result from the neo-extractivist development path (the link between material flows and conflict has been explored for case studies in India by Martinez-Alier et al. (2014)).

4.2. Current material flows indicate future material sources

Next to the potential for conflict associated with the extractive industries to which the global patterns in material flow data point, a possible shift in future metal sources has also been indicated. During the 60 years covered by the data in this study, growing amounts of metals have been accumulated in buildings, infrastructure, machinery, and durable products. These anthropogenic stocks are increasingly viewed as being exploitable for reuse and recycling, especially for metals used in bulk by industrialized and industrializing societies – iron and aluminum – and for metals for which no appropriate substitute currently exists, such as copper, chromium, manganese, and lead (Graedel et al., 2013). It has been estimated that for some metals the amount in use and deposited in landfills exceeds natural reserves (Gordon et al., 2006). Due to the continuously high level of metal consumption in the early industrializers made visible through the material flow data, the anthropogenic sources of metal are concentrated there. In countries undergoing a demographic transition, for example, important shares of the currently in-use stocks will eventually be dismantled, making those countries which have consumed metals at high rates in the past important sources of (recycled) metal in the future. In the 1990s, the USA became a major exporter of iron and steel scrap which may be evidence of such a development. Recycling of metal eventually also reduces the energy and material requirements compared to the extraction and processing of primary materials, further increasing the incentive to exploit anthropogenic stocks of metals.

Those countries engaged in metal exports, whether of primary or secondary commodities, may be, in a sense, exporting the ‘mines’ of the future and may be dependent on imports of recycled or recyclable metals from other countries in the future. This potential shift from the further exploitation of natural stocks to the recycling of anthropogenic stocks will lead to a spatial shift in the global distribution of available resources, a relationship potentially prone to conflict at an international level in the future.

5. The need to link local and global studies on extractivism

Material flow accounting data provide a first indication of two types of conflict potential which may result from the identified patterns in global metals extraction and trade. This conflict potential is inherently related to 1) the high resource demand and far-reaching socio-ecological pressures associated with mining operations and 2) the spatial disconnect between exporters and importers of primary (and secondary) metal commodities. As more countries industrialize and the industrialized countries maintain their high levels of material use, global material demand will continue to grow. The question of which countries dig up the ‘bones’ for the metal ‘skeleton’ of old and new industrialized societies is of increasing strategic relevance. Currently, some countries are specialized in metal extraction to the extent that they follow a (neo-)extractivist pathway in their mining endeavors. The material flow data on metals and waste rock extraction and trade in primary and secondary metal commodities illustrate that those countries mainly engaged in metal extraction and net-exports of ores may experience both immediate and long-term detriment to their environment. Simultaneously, an import-dependency for secondary metal products may emerge. The high rate of exploitation of non-renewable natural resources which the (neo-)extractivist pathway entails enhances the future strategic relevance of anthropogenic sources of metals for all countries. Based on the material aspects of (neo-)extractivism within the global system, potential long-term socio-ecological drawbacks of this development can be identified.

The global, quantitative analysis of metal flows provides insights on the patterns and potential consequences of (neo-)extractivism with regard to metals. From qualitative country (or sub-national) case studies stem the analyses of political, economic, social, and cultural drivers as well as of the manifold local impacts of and resistance to expanding metals extraction. The underlying research frameworks of both approaches are mutually complimentary. If they are more strongly combined, greater analytical depth can be added to quantitative, global studies. Country-level studies could increasingly take into account the repetition of similar patterns of drivers and pressures in other cases. The stronger integration of local and global studies would allow for a bridging across levels of scale. The combination of insights from local and global studies will improve understanding of the resulting potential for conflict and of the precursors to necessary change.

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