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Assessing environmental implications associated with global copper demand and supply scenarios from 2010 to 2050

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ABSTRACT

Utilisation of resources is closely linked to population growth and economic and technological development. Hence, it is expected that global resource demand will increase substantially over the next decades. This resource challenge is currently partly addressed by the UNEP-IRP resource scenario activity, where metals, non-metallic minerals, and biomass resource availability and consumption scenarios are being developed. Advancements in the understanding of environmental impacts induced by anthropogenic activities indicate that large-scale exploitation of metal resources adversely affects the natural environment. Global copper demand is expected to grow significantly over the next decades, which is likely to result in increasing environmental stress and can be problematic for efforts to reduce the global environmental footprint. This research aims to estimate environmental implications of copper demand scenarios from present to mid-century by applying a life cycle sustainability analysis (LCSA) methodology. The results indicate that the environmental impacts related to global copper supply are expected to increase substantially between 2010 and 2050 – e.g., the carbon footprint is estimated to increase by 100% to 200%, depending on the scenario. This research discusses the main drivers of growing environmental implications of global copper supply scenarios and shows potential focus areas for mitigation policies.

1. Introduction

Growing world population, increasing global welfare, rising urbanisation rates, and technological development result in significant elevations of resource demand (UNEP, 2007). For some resources, demand rises faster than others. Copper (Cu) is such a resource – the global demand of refined copper has more than doubled between 1990 and 2015 (USGS, 1994, 2016). Copper is considered essential for various economic sectors, including electrical and communication wiring, infrastructure, electrical and electronic equipment, and transportation (Ayres et al., 2002; Mudd et al., 2012; Elshkaki et al., 2016). Since the drivers of copper demand are not expected to decrease over the next decades, it is expected that the demand for copper will increase significantly during this century (Kapur, 2005).

Production of raw materials poses environmental challenges in terms of resource depletion (e.g. copper ores), emissions and pollution (e.g. greenhouse gas emissions), and landscape impacts (e.g. conversion of natural habitat to metal mines). Metals are generally associated with high energy and material intensities, consequently resulting in high environmental impacts. Roughly 7–8% of global primary energy production is consumed by the metal sector (UNEP, 2013a). Rapidly increasing copper demands could be problematic for greenhouse gas (GHG) mitigation and for reducing other anthropogenic pressures on the environment.

Although the life cycle environmental impacts of copper production systems have been quantified in several studies (Krauss et al., 1999; Norgate and Rankin, 2000; Norgate, 2001; Ayres et al., 2002; Norgate and Lovel, 2006; Norgate et al., 2007; Classen et al., 2009; Norgate and Haque, 2010; Norgate and Jahanshahi, 2011; Northey et al., 2013), a quantification of the environmental impacts related to copper demand at global level is missing in current literature. Whereas some studies have addressed specific aspects of future copper supply (e.g., Harmsen et al., 2013), integrated explorations of future developments regarding copper demand and supply and the related environmental impacts are hardly available. Since copper is an important resource for many renewable energy technologies and since the production is expected to increase substantially over the next decades, this is an important gap in current literature, which we intend to address in this paper.

Here, we present a Life Cycle Sustainability Assessment (LCSA) methodology for assessing potential environmental implications related

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to global copper demand scenarios by combining a life cycle approach with metal demand scenarios for the period 2010–2050. We follow the methodology as outlined by van der Voet et al. (2018) and specify methodological choices and data below.

2. Methodology

The impacts related to copper demand depend on how the demand is supplied. Translating demand scenarios into supply scenarios includes, i.a., differentiating between copper production routes and technologies (e.g. primary and secondary production), specifying the amount of energy (influenced by energy efficiency, and ore grades), and type of energy (e.g. fossil or renewable) consumed during the extraction and production stages (Norgate and Rankin, 2000; Norgate and Haque, 2010; Norgate and Jahanshahi, 2010; Memary et al., 2012; Northey et al., 2013, 2014; UNEP, 2013b; Castro-Molinare et al., 2014; Kulczycka et al., 2016). As these variables change over time, the impacts related to copper production per unit will change accordingly (Mudd et al., 2013; Northey et al., 2013, 2014) – even if the total copper output would remain constant. Changing global supply quantity in combination with the changing global supply system (including the aforementioned variables) explain how environmental impacts might evolve on a decade timescale.

Life Cycle Assessment (LCA) is a tool widely used for quantifying and comparing environmental impacts of products and services (Finnveden et al., 2009). LCSA is a comprehensive framework originating from the field of LCA. In LCSA, the level of analysis of a traditional LCA is broadened by expanding spatial and temporal scales. The framework typically integrates models rather than being a model in itself (Guinée, 2016). Although we did not include these in this study, LCSAs may include social and economic impact assessments in concert with the environmental impacts with which the traditional LCA is concerned (Valdivia et al., 2011),

In the LCSA presented here, we use existing LCA methods and databases as a basis for calculating the current global average cradle-to-gate environmental impacts related to the production of refined copper (i.e., copper cathode). Subsequently, a temporal scale is added by including changing variables over time (e.g., production route ratios, amount of energy consumed during extraction and production processes, and types of energy consumed) to specify environmental impact scenarios of the per unit global average production of refined copper between 2010 and 2050. Finally, to upscale the average production model to the global level, the projected impacts per unit are multiplied with copper demand scenarios, whilst specifying various copper production routes, to quantify the environmental implications of the copper demand scenarios.

Environmental implications of copper demand scenarios are quantified by following three primary methodological steps. First, the current global average production system is modelled using LCA methods and databases to identify various distinct copper production routes and the related impacts per kg copper produced. Second, copper supply system scenarios are modelled from 2010 to mid-century based on projected developments in the supply system. Third, the copper supply system scenarios are aligned with the demand scenarios by specifying the supply ratios of distinct copper production technologies as part of the total demand scenarios and by linking specific supply system scenarios to the corresponding demand scenarios – i.e., linking IEA energy scenarios incorporated in the supply scenarios with the United Nations Environmental Programme-International Resource Panel (UNEP-IRP) LCSA copper demand scenarios. Once the supply system and demand scenarios align, the corresponding scenarios are multiplied to quantify environmental implications of the global UNEP-IRP copper demand scenarios.

2.1. Step 1: LCA of current global average copper production system

The scope in this study is the cradle-to-gate global average production system of refined copper, which can be supplied through two principal primary production technologies (i.e. pyrometallurgy or hydrometallurgy) or through secondary copper production (i.e. recycling of copper scrap) (Classen et al., 2009; Norgate and Jahanshahi, 2010; Elshkaki et al., 2016). A schematic representation of the pyrometallurgical, hydrometallurgical, and secondary copper production systems can be found in the Supplementary information (S1). Specific process data has been collected for the foreground system of pyrometallurgical, hydrometallurgical, and secondary copper production (i.e., copper recycling) from Ayres et al. (2002); Classen et al. (2009); Krauss et al. (1999); Norgate (2001); Norgate and Haque (2010); Norgate and Lovel (2006), and Norgate and Rankin, 2000). In short, pyrometallurgy refers to the metal extraction processes through smelting (i.e., high tempereature processes where chemical reactions take place). Hydrometallurgy refers to metal extraction processes involving leaching (i.e., applying aqueous solutions to extract metals from ores) (Ayres et al., 2002). Strictly speaking, secondary copper production falls under the category of pyrometallurgy. However, we adopted the terms pyrometallurgy to refer to primary pyrometallurgical copper production processes; hydrometallurgy to refer to primary hydrometallurgical copper production processes; and secondary copper production to refer to secondary (pyrometallurgical) copper production processes.

The Ecoinvent v2.2 database (Frischknecht et al., 2005) has been used for the life cycle inventory (LCI) background system. A detailed overview of all material and energy in- and outflows per production process of the LCI can be found in the Supplementary information (S2).

In the copper production stages, by-products such as Mo, Ag, Se, and Te, are generated (Ayres et al., 2002; Green, 2006; Classen et al., 2009; Mudd et al., 2013). This implies that not all environmental impacts of the copper production processes should be allocated to the production of 1 kg copper, but that part of the impacts should be allocated to the by-products. We applied economic allocation to these by-products, which is based upon the mass and economic value of copper material and the by-products.

For the LCIA, the CML2002 methodology and impact categories have been adopted (Guinée, 2016). Because of the importance of energy consumption for the magnitude of environmental impacts (Norgate and Haque, 2010; Kulczycka et al., 2016), the cumulative energy demand (CED) has been added as an indicator to quantify the total energy required for producing refined copper in each of the three copper production technologies.

In the LCIA, the environmental implications of each of the three global average copper production routes per kg refined copper produced are estimated. The results are presented in the Supplementary information (S3).

2.2. Step 2: copper production system scenarios

For including a temporal dimension into the model, the following variables that affect the environmental implications of copper production are considered: (1) developments in the background electricity supply mix, (2) ore grade degradation, and (3) energy efficiency improvements in the foreground system. Developments in the ratio of the different copper production routes are an important aspect as well, but this will be elaborated upon later in Section 2.3 when discussing the copper supply scenarios.

2.2.1. Background energy supply mix

To account for developments in the background energy supply mix from 2010 to mid-century, the International Energy Agency (IEA) World Energy Outlook (2012) energy scenarios have been adopted and incorporated into the LCA model (Verboon, 2016). This means that multiple LCA models have been created, based upon the model described in Section 2.1., where the electricity supply is altered according to the energy scenario adopted in the year between 2010 and 2050. The IEA (2012) developed three distinct electricity mix scenarios: (1) current policies (CP) scenario, where no changes in current energy policies are assumed and the future electricity supply chiefly reflects the current system; (2) new policies (NP) scenario, where policy commitments aim to gradual reductions in GHGs and phasing out of fossil-energy subsidies, which leads to moderate increases in the share of renewable energy sources; (3) 450 scenario, which is consistent with the goal of limiting the global temperature increase to two degrees Celsius. Detailed information about the projected energy shares in each scenario can be found in the Supplementary information (S3). The IEA World Energy Outlook estimates future energy shares based on projected energy consumption, fossil fuel and bioenergy supply, and energy transformation, The distinct IEA World Energy Outlook scenarios differ in the assumptions regarding the evolution of energy-related government policies (IEA, 2012).

There are two reasons for only incorporating the developments in the electricity supply, instead of incorporating developments of other energy supply systems as well. First, many machines or smelters that consume fossil fuels are not likely to shift to different energy sources in the short term, since this would essentially mean a complete replacement of the conventional machinery and equipment. Second, the effects on the environmental impacts of incorporating a changing energy mix as a whole compared to incorporating a changing electricity mix only are marginal for copper – which we found out by comparing the LCA results of including and excluding the complete energy mix.

The IEA World Energy Outlook (2012) covers the period from 1990 to 1935. We extended the trends of the scenarios to 2050, using linear regressions. The energy scenarios based upon the IEA Energy Outlook (2012) show three distinct pathways of global energy production between 2010 and 2050 (Fig. 1). The CP scenario (Fig. 1a) denotes a business as usual scenario where fossil fuels will remain the predominant energy sources up until 2050 with more than 70% of the total energy supply generated from coal, oil, or gas. In contrast, the 450 scenario (Fig. 1c) points towards a decrease in fossil fuels and towards a significant increase in carbon neutral energy sources (42% fossil energy in 2050). The NP scenario (Fig. 1b) hovers in between the CP and 450 scenarios regarding the shares of renewable and fossil energy sources.

After defining the electricity supply scenarios, three LCI time series have been created for the years between 2010 and 2050, with intervals of five years – based upon the varying electricity supply mix trajectories specified above. This resulted in distinct environmental impacts related to a global average unit refined copper produced per scenario per year. This means that we created nine LCA models (2010, 2015 … 2050) per scenario (CP, NP, and 450), resulting in 27 distinct LCA models.

2.2.2. Ore grade degradation

Ore grade is the metal content in a rock ore body. Hence, the ore grade is an indicator for the quality of the ore (Northey et al., 2013). Ore grades are inversely related to energy consumption in the mining and beneficiation stages, meaning that as ore grades degrade, the energy consumption increases (Norgate and Haque, 2010; Norgate and Jahanshahi, 2010; Northey et al., 2013, 2014;Ballantyne and Powell, 2014;Castro-Molinare et al., 2014; Koppelaar and Koppelaar, 2016). Since high ore grade ores are mined first, global ore grades deteriorate over the course of time (Northey et al., 2014). Hence, the energy consumption related to copper extraction is expected to increase over time (Mudd, 2009; Mudd et al., 2013).

Estimating increasing energy consumption due to ore grade degradation, comprises three steps: (1) identifying the relation between ore grade and energy requirements, (2) projecting future global average ore grade level, (3) combining the ore grade-energy relation with the projected ore grades to estimate the future energy consumption related to degrading ore grades.

The ore grade-energy requirement relation is estimated using a power regression based on data of the energy consumption of copper mines and beneficiation processes and the copper ore grades in these mines (Fig. 2b). Data of multiple copper extraction sites has been taken from Northey et al. (2013), resulting in the following ore grade-energy relation:

$$E = 15.63G^{-0.53} \tag{1}$$

Where E is the gross energy requirement (GJ/t mined copper containing material), and G the corresponding ore grade (% copper in ore).

Estimations of ore grades between 2010 and 2050 are based upon a power regression of historic global ore grades presented by Crowson (2012) (Fig. 2a):

$$G = 4 * 10^{82}y^{-25.05} \tag{2}$$

Where G is the ore grade in year y.

By combining the two functions (Eqs. 1 and 2) the energy requirements of copper mining and beneficiation processes for a specific year in the future are estimated:

$$E = 15.63(4{\cdot}10^{82}\,y^{-25.05})^{-0.53} \tag{3}$$

This can also be written as:

$$E = 2.60{\cdot}10^{-43}\,y^{13.52} \tag{4}$$

This function indicates that the energy consumption increases on average 3.3% per year between 2010 and 2050.

The material and energy inputs in the copper extraction (i.e. mining and beneficiation) phases in the LCI of each copper production scenario (mentioned in Section 2.2.1.) are increased according to the estimated annual increase of energy requirements as the consequence of gradual ore grade degradation.

2.2.3. Energy efficiency improvements in foreground system

Energy efficiency is defined as the proportion of the total energy input used to contribute to the function of the system (as opposed to the energy that is wasted). Improvements in energy efficiency are often the result of breakthroughs in technological development (Ruth, 1995;U.S. DOE, 2002). Hence, increasing energy efficiencies do not occur gradually, but typically in bursts. Most processes in the metal industry are optimised, with energy requirements relatively close to the theoretical minimum (Norgate and Haque, 2010; Norgate and Jahanshahi, 2010).

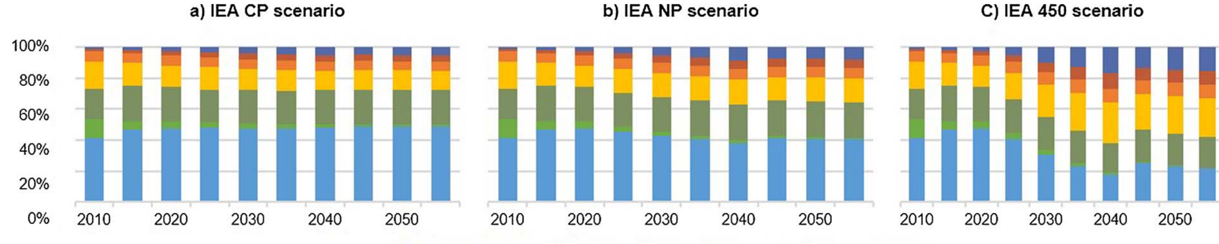

Fig. 1. Background energy mix scenarios.

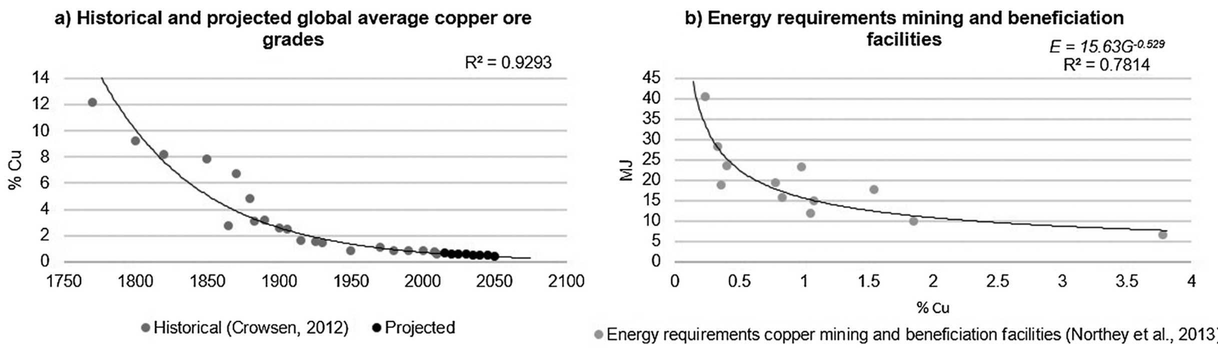

Fig. 2. Historical and projected ore grades and energy requirements mining facilities.

This is especially the case for copper (Alvarado et al., 2002; Ayres et al., 2002). Therefore, we chose not to rely on regression analyses of historical developments in energy efficiencies for projecting energy efficiency improvements in this study.

In this research, the U.S. DOE mining industry energy bandwidth method (U.S. DOE, 2007) has been adopted to calculate potential energy efficiency improvements by using the global average energy requirements, the current best practice energy requirements, and the theoretical minimum energy requirements of copper production processes to estimate the practical minimum energy requirements. The practical minimum is calculated using the following function:

$$P = B - (B - T)^* \frac{2}{3} \tag{5}$$

Where P is the practical minimum, B the best practice, and T the theoretical minimum.

Although there is data available on total energy requirements of the copper industry (Ballantyne and Powell, 2014), data on energy requirements for specific copper production processes isolated from external factors such as ore grade degradation effects, best practices, and theoretical minimum energy requirements is scarce. Nevertheless, the available data suggests that energy requirements per unit of copper produced in Chile remained relatively constant over the last decades, with minor decreases in fuel consumption and increases in electricity consumption (COCHILCO, 2015b). We decided to include energy efficiency improvements for processes where there was sufficient data available to support our calculations. Data was taken from Kulczycka et al. (2016), who reported on pyrometallurgical smelting and reduction processes. For these two processes we assumed that the energy efficiency improvements would match the estimated practical energy requirements in 2050 and incorporated the decreasing energy requirements in the LCIs of the copper production scenarios (mentioned in Sections 2.2.1. and 2.2.2.).

2.3. Step 3: aligning copper production with copper demand scenarios

2.3.1. UNEP-IRP copper demand scenarios

We used the global copper demand scenarios as specified by Elshkaki et al. (2016), which forecast global copper demand between 2010 and 2050 based on GDP (gross domestic product) growth rate estimates taken from the UN GEO-4 scenarios (UNEP, 2007), and time (in years). Note that time itself does not influence copper demand, but that the variable includes hidden variables such as technological development and population growth. By using time as an explanatory variable, it is assumed that future trends of parameters like technological development and population growth will resemble historic trends. The four copper demand scenarios are based on distinct narratives:

(1) Market first (MF), which posits that market forces will enable emerging markets to acquire living standards similar to those of the more developed countries;
(2) Policy first (PF), which is similar to the MF scenario except that government policies are more respectful towards the environment and make efforts to stimulate the development of renewable energy;
(3) Security first (SF), which assumes a reduction in international commerce due to protectionist policies.
(4) Equitability first (EF), which aims for an inclusive world with extensive improvement of those living in developing countries, as well as an advanced transformation of the energy system towards a renewable one.

Elshkaki et al. (2016) have made the first step for linking the demand scenarios with supply scenarios by specifying future primary and secondary copper production rates in each scenario. However, since there are two primary copper production routes (i.e. pyrometallurgy and hydrometallurgy) that are associated with distinct characteristics in terms of environmental implications, the primary copper supply estimates of Elshkaki et al. (2016) have to be specified further.

2.3.2. Pyro- and hydrometallurgical supply specifications

Pyrometallurgy is applied to sulphide ores, which generally have higher ore grades compared to oxide ores. Hydrometallurgy is a newer technique that emerged in the 1960s allowing to economically mine the lower grade oxide ores (Paynter, 1973; Classen et al., 2009; Norgate and Jahanshahi, 2010). As sulphide ores are depleted, hydrometallurgical copper production from oxide ores becomes increasingly more attractive.

To estimate future pyro- and hydrometallurgical copper production rates, regression analysis of historic copper production rates has been used. Data has been taken from the International Copper Study Group (2015). Up until 1985, hydrometallurgical copper production grew slowly. When hydrometallurgical metal extraction expertise evolved and technology developments led to decreasing costs, extraction from lower grade oxide ores became profitable. As a consequence, hydrometallurgical copper production expanded rapidly between 1985 and 2000 (ICSG, 2015). After 2000, the rapid expansion of copper hydrometallurgy halted and it has been gradually increasing ever since. By taking into account the complete developmental trajectory of hydrometallurgical copper production (i.e. from 1960 up until now), the vast expansion between 1985 and 2000 will strongly influence the future hydrometallurgical production estimates. Since the expansion was mainly caused by the fact that hydrometallurgy became merely established, one can assume that this period is not representative for hydrometallurgical production rates in the decades to come. This notion is supported by the forward looking assessments of the Chilean Copper Commission (COCHILCO, 2015a). Therefore, the regression model is based on pyro- and hydrometallurgical production from 2000 until 2014.

2.3.3. Linking supply scenarios with the UNEP-IRP demand scenarios

Having specified the supply volumes of the copper demand scenarios (Sections 2.3.1. and 2.3.2.) enables linking the demand scenarios

Table 1
Linking copper demand scenarios to production scenarios.

Combinations of UNEP-IRP and copper production scenarios with distinct energy background systems (IEA)	
UNEP-IRP Cu demand scenario	Cu production and IEA background energy mix scenario
Market first (MF)	Current Policies (CP)
Policy first (PF)	New Policies (NP)
Security First (SF)	Current Policies (CP)
Equitability first (EF)	450

with the three production scenarios (Sections 2.2.1–2.2.3.). This means that the copper supply volumes per scenario, production route, and year, can be multiplied with the environmental impacts of the corresponding scenario, production route, and year per kg copper produced.

To do this, the three production scenarios based on the distinct background energy mixes (i.e. CP, NP, and 450 scenarios) have to be linked to the four UNEP-IRP (i.e. MF, PF, SF, and EF) scenarios. We linked the scenarios based on the similarity of the scenario narratives (Table 1). Because MF and SF demand scenarios do not assume any future efforts made to reduce GHG remissions or increase the share of renewable energy technologies, these copper demand scenarios are linked to the production scenario with the CP background energy mix. The PF demand scenario is linked to the NP production scenario because both scenarios assume moderate investments in renewable energy technologies and efforts to reduce GHG emissions. The EF demand scenario is linked to the 450 production scenario since both scenarios project significant efforts to mitigate climate change. All scenarios take into account a decline in ore grade and marginal increase in energy efficiency of some processes.

This has resulted in four alternative time series of copper supply between 2010 and 2050. For each production route (i.e. pyrometallurgy, hydrometallurgy, and secondary production) in each scenario (i.e. MF, PF, SF, EF), there are nine environmental profiles (one for each year between 2010 and 2050, with intervals of five years) of copper supply. In each scenario, the sum of the impacts of the three production routes in a specific year indicates the total environmental impact of copper production in that year. This allows for comparison of the environmental impacts related to the four copper supply scenarios.

3. Results

3.1. Impacts current technologies per kg copper produced

The LCA of current global copper production has resulted in estimates of various environmental impacts related to the production of 1 kg copper for each distinct copper production route (i.e. pyrometallurgy, hydrometallurgy and secondary copper production). A selection of the impact categories is shown in Table 2 to illustrate variations in the environmental implications of each production route. A full list of all impact categories can be found in the supplementary information (S4).

The results show that hydrometallurgical copper production has consistently the highest environmental footprint per kg copper produced. In part, this can be explained by the relatively high energy requirements compared to the other two technologies (Norgate and Rankin, 2000; Norgate and Haque, 2010; Norgate and Jahanshahi, 2010; Elshkaki et al., 2016). As one would expect, the impacts related to secondary production are substantially lower compared to the other two technologies, since energy and material intensive processes (e.g. mining and beneficiation) are skipped in the secondary production route.

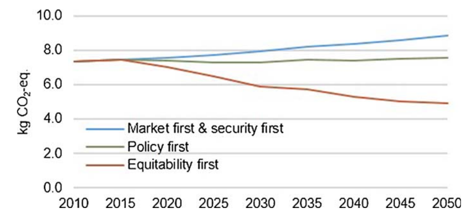

Fig. 3. Global warming impact scores of 1 kg hydrometallurgically produced refined copper for four copper supply scenarios.

3.2. Impacts copper production scenarios per kg copper produced

Incorporating the energy outlooks in combination with ore grade degradation and energy efficiency estimates into the LCA model results in estimations of future environmental implications of the identified copper production processes.

Fig. 3 is an example of the global warming impact score of hydrometallurgical production of 1 kg copper between 2010 and mid-century with the three distinct energy background systems. Estimated decreasing ore grades are expected to drive up the environmental impacts, whereas energy efficiency improvements and advancements towards cleaner energy technologies are expected to reduce the footprint of copper production. The global warming impact score per unit copper produced can increase or decrease notably between 2010 and 2050 – considering the changing background energy system, degrading ore grades, and energy efficiency improvements – from a 20% increase to a 30% decrease. Note that the global warming impact category is highly related to energy consumption. This illustration is therefore not representative for the other impact categories, which can be found in the Supplementary information S3.

As expected the EF scenario as the background energy system is associated with the lowest CO_2-equivalent emissions since the share of renewables is highest in this scenario. Interestingly, the decrease in fossil energy consumption seems to offset the ore grade degradation in terms of CO_2-equivalent emissions – as will be indicated later in Fig. 6a and b. In contrast, the MF and SF scenario leads to an increase in global warming impact score, as the status-quo energy scenario will not compensate for increasing energy requirements due to ore grade degradation.

Fig. 4 presents how the different copper production technologies respond to a changing energy background system, ore grade degradation, and slightly increasing energy efficiencies. It should be noted that ore grade degradation primarily influences the initial copper production processes (i.e., mining and beneficiation). Subsequent processes (e.g., smelting, solvent extraction, and refining) remain largely unaffected by the initial ore grade. The figure shows that hydrometallurgical copper production is more dependent on electricity than

Table 2
Selected LCIA impact categories and impact scores of pyrometallirgical, hydrometallurgical, and secondary production of 1 kg refined copper.

Impact category	Characterisation factor	Pyro-metallurgy	Hydro-metallurgy	secondary copper production	unit
Global warming	Global Warming Potential (GWP)	5.34E + 00	7.33E + 00	1.58E + 00	kg CO_2-eq.
Acidification	Acidification Potential (AP)	7.72E-02	1.29E-01	1.63E-02	kg SO_2-eq.
Energy requirements	Cumulative Energy Demand (CED)	8.99E + 01	1.20E + 02	1.78E-02	MJ
Terrestrial ecotoxicity	Terrestrial Ecotoxicity (TAETP)	7.27E-02	1.01E-01	3.26E + 00	kg 1,4-DCB-eq.
Freshwater ecotoxicity	Freshwater Ecotoxicity (FAETP)	1.23E + 02	3.28E + 02	2.25E + 01	kg 1,4-DCB-eq.

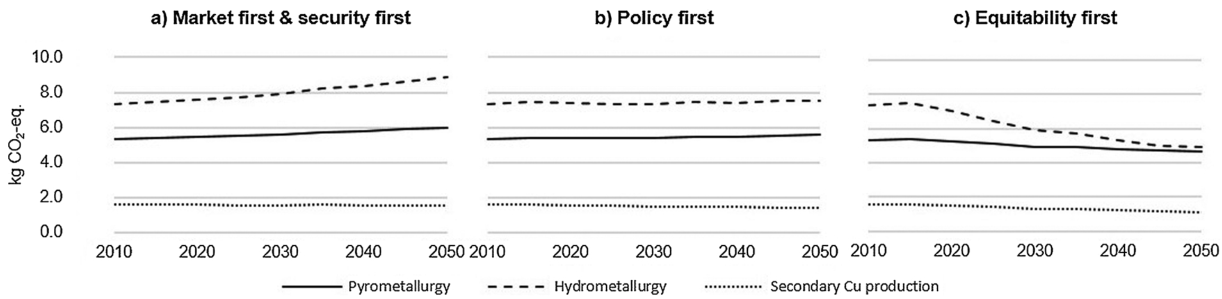

Fig. 4. Global warming impact score of 1 kg pyrometallurgically, hydrometallurgically, and secondary produced refined copper for four copper supply scenarios.

pyrometallurgical and secondary copper production, which is indicated by the steep decline of CO_2-equivalent emissions related to hydrometallurgy in the EF scenario (Fig. 4c). This decline is not witnessed in the other scenarios (Fig. 4a and b). The increasing energy demand in the MF scenario (i.e. business as usual) as a result changes in geological conditions and (back- and foreground) production processes (Supplementary information S3) is in line with the forecasts of the Chilean Copper Commission (COCHILCO, 2015a).

The global warming impact score of secondary copper production does not increase in any of the scenarios, since secondary copper production is not affected by the degradation of ore grades. The opposite is true for primary copper production. The global warming impact score of secondary copper production remains between a factor 4 and 5 lower than the primary production technologies.

3.3. Environmental impacts of copper demand and supply scenarios

All four UNEP-IRP scenarios point towards significant increases in copper demand over the next decades, from more than doubling between 2010 and 2050 in the SF scenario to an increase of almost 250% (increase of a factor 3.5) in the EF scenario (Fig. 5a). This equals an average yearly increase in copper demand between roughly 2% and 3%.

The increasing demand is most substantial in the EF scenario, most moderate in the SF scenario, and the MF scenario denotes a business-as-usual pathway – the copper demand in the PF scenario is identical to the MF scenario.

Fig. 5b–d provide a detailed overview of how the demand is supplied in each UNEP-IRP scenario. Pyrometallurgical copper production is the dominant technology in all scenarios, except for the years 2045–2050 in the EF scenario, where pyrometallurgy is projected to be exceeded by secondary copper production. In the EF scenario, the vastly increasing demand is expected to be increasingly met by recycling of copper (Fig. 5d), in contrast to the SF scenario where secondary copper production increases modestly between 2010 and mid-century (Fig. 5c). The tables with the demand and supply quantities of each scenario can be found in the Supplementary information S5.

Combining the progressing environmental impacts of future copper production systems with the supply scenarios gives us insight into the potential environmental implications of copper supply between 2010 and 2050. In Fig. 6, the four copper scenarios are compared in four different impact categories (global warming, total energy requirements, abiotic elements resource depletion, and freshwater ecotoxicity). The increase in impacts seem to mimic the increase in total copper supply, indicating the total amount of copper produced is the most important indicator for the footprint of copper production. The impacts are expected to increase substantially in every scenario, from more than doubling to more than tripling between 2010 and mid-century – with an average annual increase of impacts between 2% and 3%.

In Fig. 6c and d, the MF scenario is hardly visible, as it is closely overlapped by the PF scenario. The high degree of overlap can be explained by the identical supply rates and fairly similar background energy systems. The overlap of the MF and PF scenarios confirms that the copper supply quantity is the dominant indicator.

The EF scenario is associated with the highest impacts for most

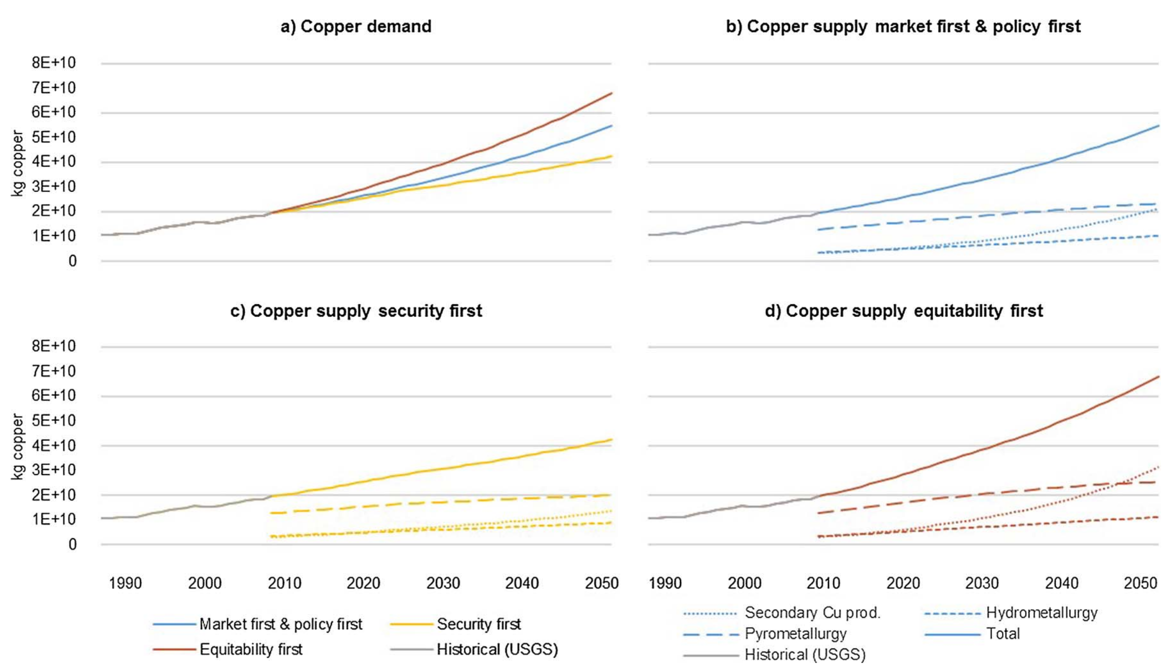

Fig. 5. Demand and supply scenarios.

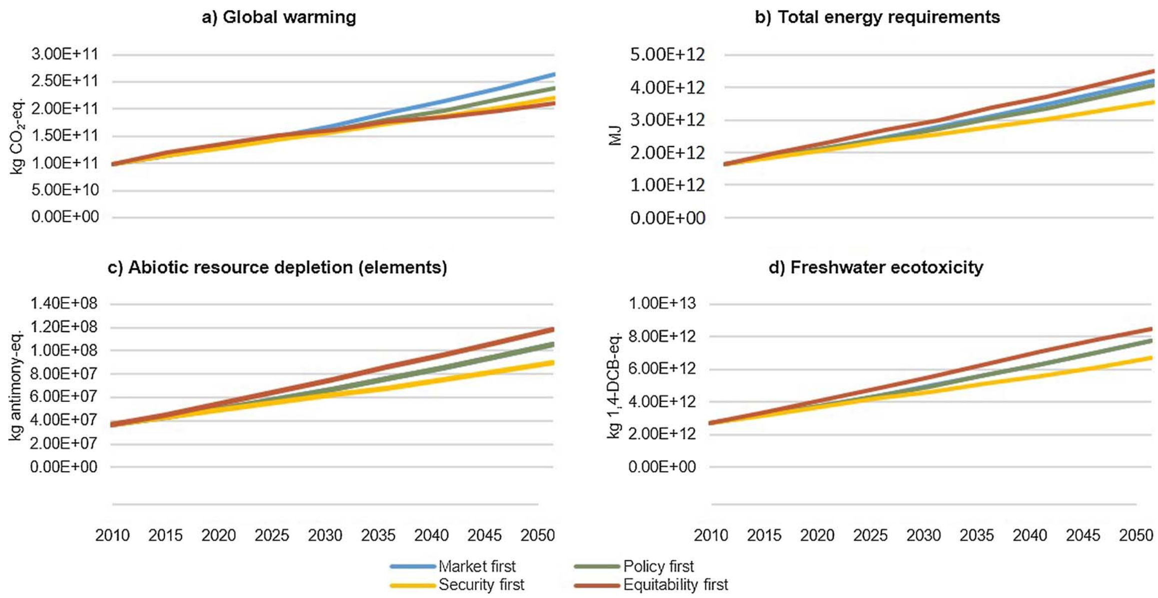

Fig. 6. Environmental implications of copper supply scenarios for impact categories of Global warming, total energy requirements, abiotic elements resource depletion, and freshwater ecotoxicity.

impact categories (see Supplementary information S6 for complete list of impact categories). Nevertheless, the relatively clean energy background system and high secondary production ratio in the EF scenario seems to partly offset the vast total supply in the global warming category (Fig. 6a), where the EF scenario actually scores most environmentally friendly compared to the other scenarios. This tells us that clean energy and recycling of copper can significantly contribute to lowering the environmental footprint of global copper supply even though the total copper supply increases substantially.

Fig. 7 shows a detailed illustration of the (stacked) contributions of each production technology in each scenario for the global warming impact category. The figures illustrate that even though secondary copper production increases substantially in all scenarios, the impacts of secondary copper production increase only modestly – which is due to the low impacts of secondary copper production per unit.

What is more, displaying both the copper supply quantities and environmental impacts shows the environmental efficiency of copper production in each scenario. Since the total copper supply is lowest in the SF scenario, the related environmental impacts are generally low as well. However, the impacts are disproportionally high for the amount of copper supplied when compared to the PF and EF scenarios. The vast increase in total copper production (indicated by the black lines in Fig. 7) combined with a more moderate increase of environmental impacts (indicated by the coloured areas in Fig. 7) indicate decoupling of resource use (or economic activity) and environmental impacts. That is, even though the SF scenario might seem to be the most environmentally friendly in Fig. 6, the production system is actually not, as indicated by Fig. 7.

The complete list of all impact categories and scenarios can be found in the Supplementary information S6.

4. Discussion

The doubling and tripling of environmental impacts related to

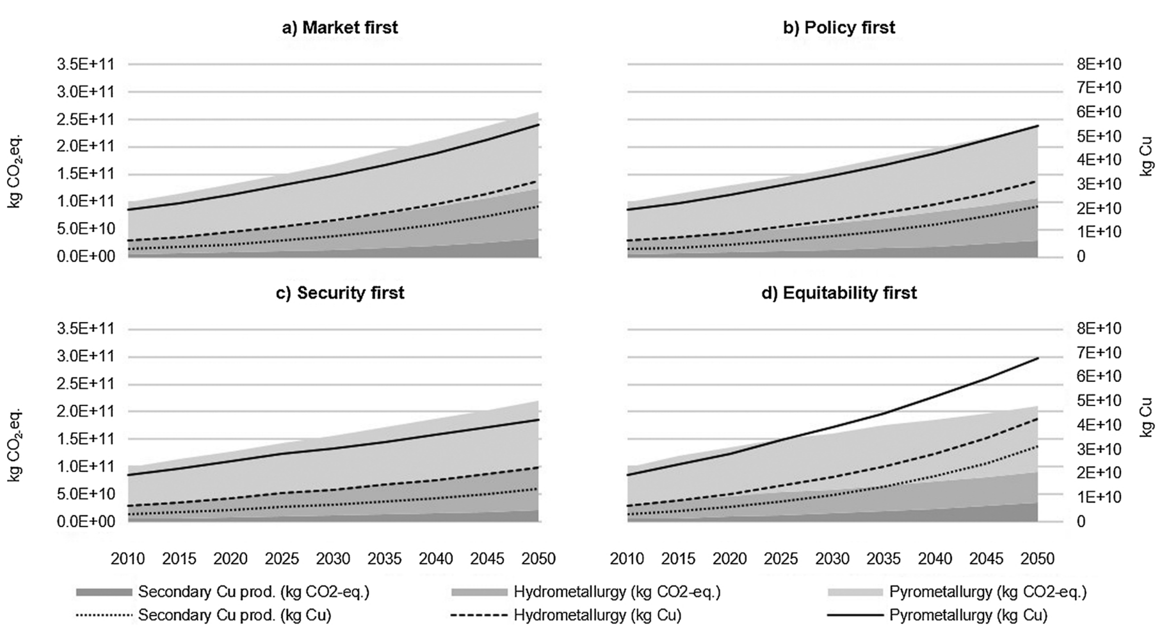

Fig. 7. Global warming impact scores of the supply scenarios.

copper supply between 2010 and 2050 can be attributed to growing demand and gradually declining ore grades. Factors that reduce the impacts of time are shifts from primary to secondary production, progressive development of carbon neutral background energy systems, and increasing energy efficiencies. The three explanatory variables with the highest influence are copper demand, shift from primary to secondary copper production, and the shift from fossil energy to renewable energy. Copper demand is the dominating factor, which is why the impacts are generally lowest in the SF scenario, despite the conservative energy background system. If these three factors can be influenced through (inter)national policies, investments, private strategies, or research and development, this would signify that there is potential to slow down increasing impacts related to global copper supply. It has to be noted that increase in the supply of secondary copper is only possible if the copper scrap is available. As long as the global copper consumption grows – e.g. due to population growth (total increase) or urbanisation (increase per capita) – the copper in-use stock is building up, meaning that primary copper is required even if 100% of the copper waste would be recycled (van der Voet et al., 2018).

Probably the most difficult to slow down is the growing copper demand, which is the strongest contributor to the increasing environmental pressures. Copper demand is strongly related with GDP, although copper use may become saturated once a certain GDP threshold is reached (Ayres et al., 2002; Kapur, 2005; Northey et al., 2014). Economic development in developing countries and a shift from a fossil based to a more electricity based energy systems is expected to result in a significantly growing copper demand that cannot be halted easily (Kwakkel et al., 2013; Elshkaki et al., 2016). Even if 50% of the energy supply would stem from carbon-neutral energy sources and the primary-secondary production ratio would be 1:1 (EF scenario), the CO_2-equivalent emissions are still expected to double between 2010 and 2050. Therefore, although investments in green energy technologies and recycling can reduce the environmental pressures of the production system significantly, it cannot completely offset the impacts of growing supply rates.

Although advancements in renewable energy technologies and energy efficiencies can lead to decoupling of environmental effects related to resource extraction and production, this study shows that moving towards renewable energy systems will not cause a decrease in total environmental impacts, although it can to some extent mitigate the increasing impacts due to growing demand. This indicates that we have to rethink our current resource use to effectively combat environmental degradation. One option is to substitute copper by other materials that are associated with lower environmental impacts per functional unit. Although polyvinyl chloride (PVC) materials have been replacing copper in some less rigorous plumbing applications (e.g. sewers or irrigation systems) and optical fibre technologies have been replacing copper in communications wiring, copper is not easily substituted by alternative materials in electrical applications due to its unique conductive qualities (U.S. Congress Office of Technology Assessment, 1988). In some cases, aluminium is used for electrical transmission due to its low weight, but copper is generally considered the preferred material due to its higher conductive efficiency (Yoshida and Doi, 2014). We did not assess the environmental impacts of PVC plumbing applications and aluminium electrical transmission systems, so we cannot say whether a shift towards these technologies will actually lead to a reduction in environmental pressures.

Another option is to further increase secondary copper production rates where possible approximately 50% of copper scrap is currently recycled (UNEP, 2011). This does not only involve improvements in copper scrap collection, but also in, e.g., product designs that allow for easier copper re-use and recycling at the product's end-of-life. Modelling copper in-use and scrap stocks and flows (e.g., Graedel et al., 2004) can help identify copper recycling potentials. Moreover, estimations of past and future flows can foster the anticipation on future copper supply and demand issues on the societal level. These past and future stocks and flows are typically modelled in so-called dynamic material flow analyses (MFAs) (Müller et al., 2014). There are various examples of such dynamic MFAs for the case of global or regional copper stocks (Spatari et al., 2005; Wittmer and Lichtensteiger, 2007; Daigo et al., 2009; Glöser et al., 2013).

Assessing the effectiveness technological and regulatory initiatives to reduce the environmental footprints related to global copper supply can be subject for future research.

There are a few reasons to be careful when interpreting the results presented here. First, copper production is a heterogeneous composite of processes depending on geological, geographical, and technological conditions. Hence, introducing global average copper production routes (i.e., pyrometallurgy, hydrometallurgy, and secondary copper production) is to a certain degree ambiguous and introduces uncertainty. The LCI model is based on various data sources (Section 2.1) and site-specific characteristics of certain production processes have been mainly excluded – e.g., gold has not been modelled as a by-product of copper mining and beneficiation, whereas there are examples of copper concentrators that produce gold as a by-product (Kesler et al., 2002).

Second, in this study we assumed that the copper production technologies and the associated process will remain largely unchanged over the next decades. Although the copper production system is fairly robust and has not been subject to much change over the last decades, it is possible that technological development will lead to different environmental patterns of global copper supply. This assumption implies that we do not take changes in technologies into account that result from changing environmental regulation and management strategies. However, it should be noted that changing environmental regulation, environmental management, and resource governance initiatives have led to reductions in the environmental footprints over the last decades (due to, e.g., treatment of sulphur dioxide, mine tailings and other waste flows).

Third, the ore grade degradation rate is assumed to be identical in every scenario. This is probably not entirely accurate. Declining ore grades are a product of cumulatively mined ore, improvements in metallurgical technologies, movements towards high-volume and lower cost extraction technologies, and the economic advantages of extending the life of older mines compared to establishing new ones (West, 2011). From that point of view, ore grade degradation is partly influenced by resource extraction rates and because the extraction rates differ per scenario, the ore grade degradation rates could be expected to differ per scenario as well. However, because ore grade degradation is such a complex issue involving many interconnected factors, it is impossible to accurately predict the degradation rates for every scenario – differences between the scenarios would be inappropriate due to the uncertainty range of the predictions.

Fourth, we did not study how copper availability influences the copper price, which in turn might affect copper demand. We simplified our copper supply projections by assuming that supply will follow the demand trend between 2010 and 2050. This assumption is based on the belief that copper resource availability is expected to be sufficient to meet the demand up until mid-century (Northey et al., 2014).

Finally, uncertainties embedded in the LCIA methods should be acknowledged. Although LCIA methods can be regionally specific (e.g., Murguía et al., 2016; Northey et al., 2017), LCA impacts are not location-specific and should not be interpreted as such. This means that some impact categories, that are context-specific in nature (e.g., ecotoxicity and biodiversity loss), are associated with higher uncertainties than others (Santero and Hendry, 2016). Furthermore, there is a variety of LCIA models to estimate environmental impacts (Dreyer et al., 2003) – of which we adopted the CML2002 method – indicating that there is not one correct way of estimating environmental impacts. Considering the LCI and LCIA modelling choices made in the study, the results presented here should be interpreted as global average indications of impacts and their trends, and not as site-specific environmental impacts.

Although these limitations will affect the exact values of the results, they are not likely to alter the overall trends of increasing environmental impacts and indications of differences in environmental implications between the scenarios and distinct production technologies.

Scenarios can be useful tools to anticipate on potential future events and conditions (e.g. IPCC's emissions scenarios and IEA's world energy outlook). Scenarios are representations of storylines – e.g. based on demographic, economic, technological, and environmental information – that provide plausible future trajectories in a complex system in which the outcome is uncertain (Schweizer and Kurniawan, 2015). That is, scenarios do not predict the future, but rather show what might happen next under a set of assumptions (Marcus, 2009).

5. Conclusion

Growing world population, increasing global welfare, and technological development are likely to drive up copper demand substantially over the next decades, resulting in similar increases of environmental pressures. This research shows that (growing) resource supply is an important aspect of the growing global environmental footprint. Shifting from fossil energy sources to renewables might slightly release environmental pressure, but will not be enough to balance for the impacts related to growing resource use. Materials like copper are of special concern, as they are energy intensive to produce and closely related to the development of ('sustainable') electrical energy technologies. To reduce environmental impacts, it should be explored whether copper could be substituted by other materials that are less energy and material intensive to produce. Either reducing (primary) resource consumption or shifting to products with low production-related impacts should therefore receive attention from policy makers and strategy developers.

The trends estimated in this study can serve as a proxy for similar metals, indicating that the resource challenge is not only a challenge of meeting future demand, but also about trying to mitigate environmental pressures under conditions of vast expansions of resource extraction and processing. Significantly increasing (e.g., doubling or tripling) impacts, like the global warming impact score, may occur in various production systems as demand for other materials than copper and metals is likely to increase as well. This may significantly affect climate change mitigation efforts and should therefore be considered by policy makers pursuing to reduce the (global) environmental footprint of anthropogenic activities. Shifting away from primary resource extraction towards recycling might be an important step in the right way – a way towards a global economy more in harmony with the natural environment.

Furthermore, this study shows that the LCSA methodology can be a powerful tool for assessing global environmental impacts related to scenarios. The methodology used in this research is not exhaustive for copper only, but can be used for various other metals as well. van der Voet et al. (2018) have done this in a study on environmental impacts of seven major metals.

It needs to be stressed that the results shown here indicate how possible trends might unfold given a set of assumptions encapsulated by different scenarios. This implies that the results are not projections, and these scenarios neither claim nor aim to predict the future. Rather, the results show some environmental consequences if the future unfolds in a certain way, as specified by these scenarios.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gloenvcha.2018.02.008.

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