Import-based Indicator for the Geopolitical Supply Risk of Raw Materials in Life Cycle Sustainability Assessments

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Summary

There is a growing concern over the security and sustainable supply of raw material among businesses and governments of developed, material-intensive countries. This has led to the development of a systematic analysis of risk incorporated with raw materials usage, often referred as criticality assessment. In principle, this concept is based on the material flow approach. The potential role of life cycle assessment (LCA) to integrate resource criticality through broadening its scope into the life cycle sustainability assessment (LCSA) framework has been discussed within the LCA communities for some time. In this article, we aim at answering the question of how to proceed toward integration of the geopolitical aspect of resource criticality into the LCSA framework. The article focuses on the assessment of the geopolitical supply risk of 14 resources imported to the seven major advanced economies and the five most relevant emerging countries. Unlike a few previous studies, we propose a new method of calculation for the geopolitical supply risk, which is differentiated by countries based on the import patterns instead of a global production distribution. Our results suggest that rare earth elements, tungsten, antimony, and beryllium generally pose high geopolitical supply risk. Results from the Monte Carlo simulation allow consideration of data uncertainties for result interpretation. Issues concerning the consideration of the full supply chain are exemplarily discussed for cobalt. Our research broadens the scope of LCA from only environmental performance to a resource supply-risk assessment tool that includes accessibility owing to political instability and market concentration under the LCSA framework.

Introduction

The scarcity of resources is becoming one of the priorities in the political agenda of developed, material-intensive countries in the world, as concerns over the security of sustainable supply of resources continue to grow. The advancement of modern technology increased the variety of metals used from a few metals in the past to almost the full range of the periodic table. Some technologies are highly dependent on specific functional materials (Moss et al. 2013), many of which are not substitutable in their main applications (Graedel et al. 2013). The price increase of raw materials in recent years, together with strategic technology promotion, lead to the necessity of a systematic analysis of risks incorporated with raw material usage, be it at micro-, meso- or macroeconomic levels. This is exactly what criticality assessments can provide, if they are combined with life cycle assessments (LCAs).

[This article was corrected in June 2015 because the abstract contained a copyediting error that listed tungsten, antimony, and beryllium as rare earth elements.]

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LCA is a systematic tool that quantifies environmental burdens associated with the entire life cycle of a product by linking emissions and resource uses to a number of midpoint impact categories and then to classes of endpoint categories, the so-called areas of protection (AoPs) (Guinée et al. 2002; ISO 2006a, b; Sonnemann et al. 2003; Jolliet et al. 2004; Udo de Haes and Lindeijer 2002; Udo de Haes et al. 1999). LCA is an advanced tool in addressing damages to the AoPs "human health" and "ecosystem quality" given that there are well-established life cycle impact assessment (LCIA) methods, for example, IMPACT 2002+ (Jolliet et al. 2003) or ReCiPe (Goedkoop et al. 2009). However, addressing the direct impacts from the use of natural resources and linking them to the AoP "natural resources" has been widely debatable and needs further elaboration (Emanuelsson et al. 2013; Stewart and Weidema 2005; Wäger and Classen 2006; Yellishetty et al. 2009; Eldh and Johansson 2006). Resource depletion has been used as a measure of impacts from the use of resources and is based on the principle of estimating future resource scarcity as a result of current consumption with reference to geological availability. Limitations of resource access owing to socioeconomic, geopolitical, and other aspects are usually missed and a new perspective giving emphasis to a broader dimension of availability is indispensable. At this point, the LCA can progress by adapting the methodological findings of criticality assessments that would allow it to evolve from a sole environmental performance evaluation tool to a more comprehensive life cycle sustainability assessment (LCSA) method (UNEP/SETAC Life Cycle Initiative 2011).

The criticality assessment of raw materials is the attempt to display an aggregation of different risks connected with their use, be it in a product, company, national, or global scope (Graedel et al. 2012). It encompasses a number of supply risks, which are hazards associated with the economic, environmental, or social aspects and the potential consequences of those risks, the latter often referred as vulnerability to supply restrictions (Achzet and Helbig 2013). Several working groups have progressed on the methodology of raw material criticality assessments. The U.S. National Research Council (NRC) (NRC 2008) has provided a framework for criticality assessments from which subsequent assessments have taken on both the dualism of supply risk and vulnerability to supply restriction as well as the concept of a criticality matrix. The Ad-hoc Working Group of the European Commission (EC) (EC 2010, 2014), under the framework of the European Union (EU) Raw Materials Initiatives (Moss et al. 2013), has published two successive editions of a well-acclaimed study that, in its second (2014) edition, identifies 20 raw materials critical to the European economy. The working group of Graedel and colleagues (2012) has extended the NRC framework by considering different scopes of risk assessments. Most criticality assessments carried out thus far are based on the material flow analysis principle and are designed as stand-alone evaluations of raw materials. However, interest has been shown recently from the LCA community for the combined use of criticality concept in LCSA (EC 2012).

The main focus of this article is to elaborate a method to integrate the assessment of the geopolitical supply risk (GeoPolRisk) into the LCSA framework, which also accounts for the need for regionalization of LCA. Regionalization allows LCA practitioners to map the supply chain along a product life cycle, which is considered important for the improvement of LCA methods. Geopolitical aspects are of significant importance for companies, regions, or countries in order to understand short- and mid-term constraints of their supply chain and also to help them in their long-term decision-making strategy. However, these aspects have been given almost no attention in previous LCA studies. Thus far, few attempts have been made to the introduction of the geopolitical element under the LCSA framework (Emanuelsson et al. 2013; Schneider et al. 2013). Schneider and colleagues (2013) have proposed a rescaling methodology for frequently used criticality indicators to enable them being used within the LCSA framework. The indicators developed for existing criticality assessment methodologies are not fully regionalized thus far, given that they settle themselves with global indicators for a specific resource. Our method is meant to give an import-based indicator for the GeoPolRisk of resources under the LCSA framework. Figure 1 displays how the criticality assessment, such as the one proposed by Graedel and colleagues (2012), can be integrated within the LCSA framework. Life cycle inventory (LCI) results from unit process modeling that are linked with damage to human health and ecosystem quality are addressed by using a well-established method, such as ReCiPe (Goedkoop et al. 2009), whereas impacts from the use of resources can be captured in the socioeconomic dimension as resource scarcity and accessibility.

The article is structured as follows. The second section of this article describes the proposed method for the assessment of a national characterization factor for the GeoPolRisk and also describes the system on which we applied the method. Data-quality issues and their recognition through Monte Carlo simulation are described. The third section is dedicated to the presentation of the main results and discussion. The final section deals with the main conclusions and future perspectives.

Method

The Geopolitical Supply Risk

There are different methods available for assessing the supply risk of resources (NRC 2008; Graedel et al. 2012; EC 2010, 2014; Erdmann and Graedel 2011; Achzet and Helbig 2013). A wide range of aggregated indicators have been used in different criticality assessment literature in order to compare the potential supply risk of resources at different levels, be it global, regional or company level. In most cases the supply concentration, evaluated with the Herfindahl-Hirschman Index (HHI), alongside with the World Bank's Worldwide Governance Indicators (WGI), which measure the relative governance quality of a country, are both used for supply-risk assessment (EC 2010;

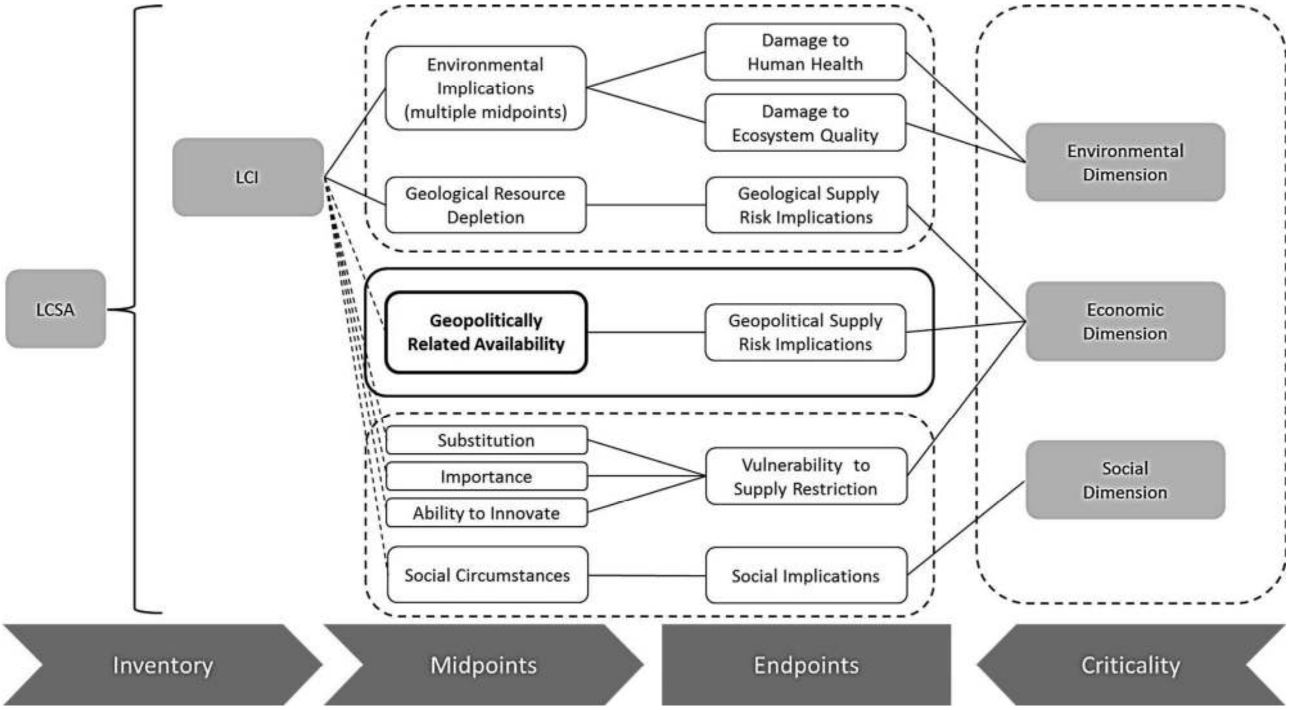

Figure 1 Integration of geopolitical-related supply risk and other criticality components within the life cycle sustainability assessment framework. The criticality assessment indicators are adapted from Graedel and colleagues (2012). LCI = life cycle inventory; LCSA = life cycle sustainability assessment.

Graedel et al. 2012; Nassar et al. 2012; NRC 2008; Schneider et al. 2013).

The WGI scores are usually weighted by average production share (EC 2010; Graedel et al. 2012; Nassar et al. 2012; NRC 2008; Schneider et al. 2013). By doing so, the geopolitical supply risk is expressed as an inherent attribute of the world-wide commodity market, which overlooks regional particularities or typical supply-chain patterns. Our method defers in this regard because it weights the WGI scores by import share. It is considered that a direct supply risk could be observed depending on the instability of the most important trade partners, rather than the global suppliers. In those cases, where a sourcing country is a commodity trade center and does not possess domestic production, it is considered that supply-chain risks are pooled and represented by the instability of this single trading partner. Contract reliability of the direct trading partner and the existing physical stocks of trading hubs are further reasons for this risk representation assumption. Whereas governance stability of the sourcing countries indicates the average risk for the supply disruption event overall, the market concentration indicates the overall market ability to restructure trade flows in order to compensate decreased or disrupted sourcing from the instable countries. The global production concentration is calculated with the HHI and enters the calculation of the characterization factor as a multiplicative risk mitigating factor. The model is described in equation (1).

$$SR_{c,i} = \left[\left(\sum_{k=1}^{n} s_k^2 \right) * \left(\sum_{k=1}^{n} g_k * f_{i,k} \right) \right] \tag{1}$$

$SR_{c,i}$ expresses the supply risk of the evaluated country i concerning the commodity of interest c. s_k is the share of country k in the global production (mining or refining) of the commodity c. g_k is the political instability indicator of country k, which is derived from the WGI, and $f_{i,k}$ is the import share of country k in the supply chain of country i.

Similar to an environmental midpoint impact in LCIA, the GeoPolRisk in this proposed method is expressed as a midpoint characterization factor in LCSA with values between 0 and 1, indicating a share of the commodity import being at risk, assuming a linear relationship between WGI score and supply disruption propability. Connections between GeoPolRisk and implications for additional costs for policy options such as hedging, as an effect factor, would require an additional linking endpoint characterization factor, which is not an easy task owing to other price effect factors, such as unregulated finance. This still needs further research. The data required for the calculation of the GeoPolRisk as proposed here consists of three parts: first is the global production distribution on a country level, which is usually available from national geological institutes or raw material experts. Second comes the distribution of imports, which can be provided by national or regional institutes, or if the data are required for multiple importing countries, from international trade statistic databases. The third part is the essential estimation of the sourcing countries' instability. Additionally, giving information about the uncertainty associated with quality of the selected data is essential for avoiding wrong decision making resulting from misleading false-positive findings.

System Description

In order to display the proposed methodology for the GeoPolRisk assessment, we exemplify the calculation for 13 different regions: the seven major advanced economies; the Group of Seven (G7) countries, namely, Canada, France, Germany, Italy, Japan, UK, and the United States; the so-called BRICS countries, which are Brazil, Russia, India, China, and South Africa, and the EU-27. The G7 countries are among the most developed regions, which are well known for their high demand on resources (Wiedmann et al. 2013). BRICS countries are the fastest growing emerging countries that are speculated to become the dominant countries in the global market owing to their large, fast-growing economies. Although all BRICS countries show strong economic growth, they differ concerning their economic structures. For example, Brazil and Russia are mainly mineral exporting countries with relatively little added value on their territories, whereas China is also a massive importer of minerals and is actively engaging in developing added values.

The proposed method is applied for 14 resources that are strategic to both G7 and BRICS economies. A summary table with their United Nations Commodity Trade Statistics Database (UN Comtrade) IDs and potential application is presented in table 1. Thirteen of the resources have been rated as critical by the initial version of the EU study for critical raw materials (EC 2010). Uranium has not been evaluated at the EU level, owing to the fact that the Ad-hoc Working Group focused on nonenergetic minerals and metals, but is included here to display the method's extended applicability. The selection of a variety of countries and commodities allows for a better understanding of patterns in commodity trade and significant changes in GeoPolRisk.

Data Acquisition

Regarding the world-wide production in mining or refining activities, data from the U.S. Geological Survey (USGS) has been used. The USGS provides freely available, country-specific data, such as the annual production and the estimated reserves, on a yearly basis in its mineral commodity summaries (USGS 2013).

The commodity import amounts have been extracted from UN Comtrade, which is freely provided by the UN Statistics Division (UN 2013). The Harmonized Commodity Description and Coding Systems (HS), of which there is the HS classification for the lowest available disaggregation, is considered in our calculation. Owing to different accounting practices, differences of the reported import amounts to the reported export amounts of the partner country can occur. Confidentiality issues are a frequent reason for these inconsistencies. In the presented application of the method, only the reported import volumes are taken into account.

There are some limitations of the data used from UN Comtrade and some basic assumption have been made. One of the challenges in addressing the geopolitical supply risk of resources is the intensive data requirement to model the full supply chain: the flow of resources from mining, smelting, and refining, until they get to the production site. Because different countries are involved, it requires specific data in the resource's supply chain. The geopolitical supply risk owing to resource import comes not only from the first-level suppliers, but rather it is the cumulative risk from all the countries involved in the life cycle of the supply chain. However, in our case, because the data from UN Comtrade do not provide detailed information on where exactly the mining, smelting, and refinery processes occurred, we assume that all processes occurred in the same country. Typical problems raised by this assumption are described in the *Discussion* with the example of cobalt.

Considering the geopolitically related risk emerging from specific countries, the WGI aggregated and published by the World Bank have been used (World Bank 2013). The WGI methodology compresses several individually published rankings and assessments about the governance quality of countries and aggregates these into six meta-indicators. Regarding the supply risk of a country, the World Bank's indicator, called Political Stability and Absence of Violence/Terrorism (WGI-PV), has been considered from the six meta-indicators as the best indicator for supply disruption propability. This selective use of WGI scores has already been used in other criticality assessments before (Graedel et al. 2012; Schneider et al. 2013). Figure 2 shows the WGI-PV scores for all countries for the year 2012.

Uncertainty Analysis Using Monte Carlo Simulation

In order to provide uncertainty analysis for the GeoPolRisk, a Monte Carlo simulation has been performed considering all data-source qualities. Monte Carlo simulation is a standard method for uncertainty that can also be run in established LCA software tools such as SimaPro (Goedkoop et al. 2010), in extensions of spreadsheet programs such as @RISK (Palisade 2014), or in numerical programs such as MathLab. The uncertainty related to the data is calculated using Graedel and colleagues' (2012) Pedigree matrix, which is adapted from Goedkoop and colleagues (2010). It was proposed and applied by Weidema and Wesnæs (1996) to evaluate uncertainty related to data input in LCA. The geometric square of the standard deviation ($^{2}_{g}$) is then calculated using the set of data-quality indicators (Reliability (U_1), Completeness (U_2), Relevance (U_3), Precision (U_4), and Corroboration (U_5)) and their corresponding uncertainty factors (1.00 to 1.20), as displayed in equation (2).

$$\sigma_g^2 = e^{\sqrt{[ln(U_1)]^2+[ln(U_2)]^2+[ln(U_3)]^2+[ln(U_4)]^2+[ln(U_5)]^2}} \qquad (2)$$

This approach is oriented along the methodology of Graedel and colleagues (2012), which is developed for metal criticality determination.

The USGS aggregates and reviews data from various souces, but uncertainty information is not explicitly provided. The UN Comtrade database consists of values reported by the UN member countries. Uncertainties are also not given. The squared

Table 1 List of elements considered in the study with their symbols, UN Comtrade IDs, and main applications

Element	*Symbol*	*UN Comtrade IDs*	*Application*
Antimony	Sb	81 10	Flame retardants, lead-acid batteries, glass, lead alloys (Schwarz-Schampera 2014a)
Beryllium	Be	81 12 12, 81 12 19	Alloys (aerospace, electrical, and electronic) (Trueman and Sabey 2014)
Cobalt	Co	81 05	Batteries, superalloys and magnet alloys, catalysts (Roberts and Gunn 2014)
Fluorspar	CaF_2	25 29 21, 25 29 22	Hydrofluoric acid production, steelmaking, aluminium production (Bride et al. 2011)
Germanium	Ge	28 25 60	Fiber optics, infrared optics, polymerization catalysts, electronics and solar electrical applications, radiation detectors (Melcher and Buchholz 2014)
Graphite	C	25 04	High-temperature lubricants, brushes for electrical motors, friction materials, battery and fuel cells (USGS 2013a)
Magnesium	Mg	81 04	Aluminum alloys, Structural applications, Desulfurization of iron and steel (Neelameggham and Brown 2014)
Platinum group metals[a]	PGM	71 10 11, 71 10 19, 71 10 21, 71 10 29, 71 10 31, 71 10 39, 71 10 41, 71 10 49	Autocatalysts, jewelery, electrical, cytostatic drugs (Gun 2014; Thorenz and Reller 2011)
Rare earth elements[b]	REE	28 05 30	Magnets, metal alloys, catalysts, polishing, glass phosphors and pigments, ceramics (Wall 2014)
Indium	In	81 12 92	Flat panel displays, solders, photovoltaics, thermal interface materials, batteries (Schwarz-Schampera 2014b)
Selenium	Se	28 04 90	Rubber compounding, steel alloying, rectifiers (USGS 2013a)
Tantalum	Ta	81 03	Capacitor, hard-disk drives, ink-jet printer heads, sputtering targets (Linnen et al. 2014)
Tungsten	W	81 01	Hard metals, steel and other alloys, mill products (Brown and Pitfield 2014)
Uranium	U	28 44 10	Nuclear power plants, military uses

[a] Platinum group metals are meant to be ruthenium, rhodium, palladium, osmium, iridium, and platinum.

[b] Rare earth elements are meant to be scandium, yttrium, lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium.

geometric standard deviation of the lognormal distribution for both USGS and UN Comtrade data was estimated with 1.228, resulting from reliability of national reports and the corroboration quality of a single source. Distributions are applied to reported country-specific volumes, whereas for Monte Carlo simulation measures, the global production and total import volumes are calculated from the simulated country-specific data. This estimation of uncertainty is not necessary in the case of a given and justified distribution function, as it is the case for the WGIs (Kaufmann et al. 2011).

Results

Table 2 displays the results of the quantitative assessment of the GeoPolRisk. It also shows the underlying value for the production concentration (HHI). For comparison reasons, results from the production-based method (a method that weights the governmental stability risks with the production shares) and the method used by the EU paper (EC 2010) are also presented.

Data were available in the UN Comtrade database for all country-commodity combinations except beryllium for South Africa and uranium for India. A lack of data can mean either no relevance of the commodity for that economy, purely domestic trade, or confidentiality reasons. Overall, this gives a collection of 180 values for the GeoPolRisk, among which the uranium supply risk for Italy, Japan, and the UK is the lowest with just 0.05, whereas Brazil and Canada have the highest geopolitical risk for their rare earth imports counting up to 0.55. Because mostly already critical elements were evaluated, the market concentration in production and refining shows concentrations between 0.19 for uranium and 0.91 for rare earths. The WGI factors, weighted by import shares, have taken values between 0.38 and 0.61, accounting for the WGI method, which provides only relative governance scores, manually setting the average country score to 0.5 and the standard deviation to 0.2 (0 and 1 in the World Bank's original data scale) (Kaufmann et al. 2011).

The production-based estimation and the EU method of the global GeoPolRisk show only slight differences between themselves and vary between estimations of 0.08 and 0.55,

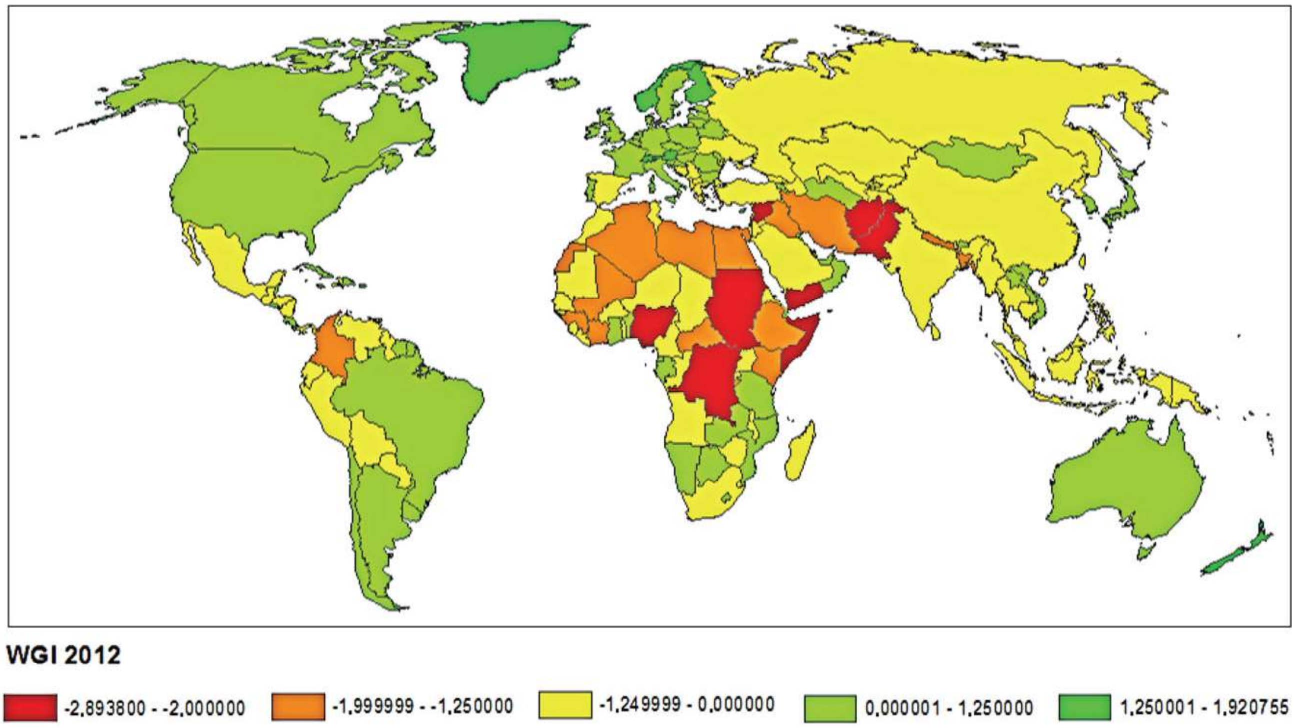

Figure 2 Worldwide Governance Indicators—original World Bank scores for the indicator political stability and absence of violence/terrorism for the year 2012. For the supply-risk evaluation method presented here, these values get rescaled linear to a 0 to 1 scale.

overall a bit narrower than the individual country scores, which was expected (EC 2014). Because global production gives a baseline for average import share distribution without indirect trading hubs, country scores should be nearby the global score. The differences in import- versus production-based scores and the uncertainty within this assessment are to be discussed.

The calculation of GeoPolRisk in the assessment of critical raw materials for the EU, presented in 2011 by the Ad-hoc working Group of the EC (EC 2010) and the governance stability part of the the ensemble streamflow prediction (ESP) presented by Schneider and colleagues (2013) both did not include commodity trade values into their calculation, but rather focused on a global expression of GeoPolRisk using world supply shares for their calculations. Whereas the EU study had a criticality assessment basis, evaluating the most critical raw materials for the EU (EC 2010), the approach by Schneider and colleagues (2013) was implemented into a proposed assessment of the economic resource scarcity potential in LCSAs. In contrast to the ESP method of Schneider and colleagues (2013), the hereby proposed method just uses the WGI scores in the dimension political stability and absence of violence/terrorism instead of the average of three different governance dimensions. Here, the WGI scores are weighted by the countries' import shares instead of using production shares. After this weighting process, the method of Schneider and colleagues (2013) additionally rescales the result by comparing it with a 0.25 threshold value (Schneider et al. 2013). Such a comparison with a threshold value for impact evaluation could be part of a future endpoint assessment, but the specific threshold value of 0.25 needs further justification beforehand.

Unlike many other approaches, in which GeoPolRisk is calculated based on global production, here in our method we considered the import share as a key component. The production-based estimation gives only the global effect, the same geopolitical supply-risk values for all regions. It does not explicitly address the risk on different regions based on their import patterns. Figure 3 compares the risk when it is based on production versus import shares for the case of beryllium. The GeoPolRisk factor based on production is 0.33; it is the risk associated with the consumption of beryllium from the global market of any country. The import-based estimation provides country-specific values based on their import structure. For all observed countries, just as for the reported high-risk country United States (0.45), a major producer and end user of beryllium, the GeoPolRisk factor applies to imported volumes only, owing to the fact that domestically produced and consumed commodities are not considered to be affected by geopolitical instabilities. The conversion factor between the calculated GeoPolRisk factor for import volumes and the factor applying to total domestic consumption is the net import reliance. India, on the other side, is at a relatively lower risk concerning its imported supply (0.21) compared with other countries in the list.

Table 2 Summary of the quantitative assessment of the GeoPolRisk for all resources and countries and comparison with other methods

	Countries' GeoPolRisk														*Comparison with other method*	
	HHI	*BRA*	*CAN*	*CHN*	*EU-27*	*FRA*	*GER*	*IND*	*ITA*	*JAP*	*RUS*	*UK*	*USA*	*ZAF*	*Production*	*EU method*
Sb	0.7	0.39	0.41	0.38	0.42	0.42	0.37	0.41	0.25	0.41	0.47	0.27	0.43	0.41	0.41	0.42
Be	0.83	0.26	0.31	0.26	0.43	0.32	0.32	0.21	0.33	0.32	0.32	0.41	0.45	—	0.33	0.31
Co	0.32	0.19	0.12	0.28	0.27	0.12	0.12	0.12	0.12	0.09	0.14	0.12	0.14	0.11	0.18	0.19
CaF_2	0.44	0.28	0.25	0.19	0.26	0.22	0.21	0.28	0.27	0.26	0.18	0.14	0.27	0.19	0.26	0.27
Ge	0.46	0.17	0.18	0.18	0.23	0.25	0.19	0.19	0.22	0.23	0.23	0.20	0.24	0.17	0.25	0.27
C	0.51	0.24	0.20	0.26	0.27	0.24	0.22	0.30	0.21	0.30	0.29	0.22	0.27	0.29	0.31	0.31
In	0.37	0.21	0.17	0.16	0.17	0.16	0.17	0.21	0.12	0.16	0.14	0.14	0.17	0.14	0.18	0.21
Mg	0.49	0.24	0.28	0.29	0.30	0.26	0.23	0.30	0.24	0.30	0.30	0.26	0.25	0.30	0.29	0.30
PGM	0.41	0.19	0.19	0.17	0.17	0.13	0.17	0.16	0.17	0.21	0.18	0.13	0.19	0.17	0.22	0.21
REE	0.91	0.55	0.55	0.26	0.50	0.53	0.52	0.54	0.41	0.50	0.53	0.45	0.48	0.45	0.55	0.55
Se	0.23	0.09	0.08	0.10	0.11	0.08	0.07	0.09	0.08	0.12	0.08	0.08	0.10	0.10	0.09	0.08
Ta	0.21	0.14	0.10	0.13	0.10	0.08	0.09	0.07	0.09	0.11	0.12	0.10	0.11	0.09	0.12	0.11
U	0.19	0.07	0.08	0.10	0.09	0.10	0.07	—	0.05	0.05	0.08	0.05	0.07	0.18	0.09	0.10
W	0.72	0.28	0.28	0.33	0.36	0.25	0.26	0.33	0.26	0.38	0.43	0.32	0.34	0.35	0.43	0.44

Notes: GeoPolRisk = Geopolitical Supply Risk; HHI = Herfindahl–Hirschman Index; BRA = Brazil; CAN = Canada; CHN = China; EU-27 = 27 member states of the European Union (EU), which include Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom; FRA = France; GER = Germany; IND = India; ITA = Italy; JAP = Japan; RUS = Russia; UK = United Kingdom; ZAF = South Africa. Sb = antimony; Be = beryllium; Co = cobalt; CaF_2 = fluorspar; Ge = germanium; C = graphite; In = indium; Mg = magnesium; PGM = platinum group metals; REE = rare earth elements; Se = selenium; Ta = tantalum; U = uranium; W = tungsten.

The uncertainty analysis through Monte Carlo simulation is also displayed in figure 3, exemplified for the GeoPolRisks of beryllium. Consideration of uncertainty is important to prevent false-positive findings, particularly for assessments for which the decision maker might have a lack of experience. This uncertainty analysis example shows that in the case of beryllium, for 6 of 13 countries and regions, the import-based assessment has provided a more thorough result, which is stable toward data uncertainty and reflects the country's supply-chain structure in a more elaborate way. It shows higher geopolitical risks in case of EU-27, the UK, and United States and lower risks for Brazil, China, and India. For all other six countries, the uncertainty levels are bigger than the differences between the calculated GeoPolRisk of the different countries and also bigger than the difference to the global geopolitical supply risk, calculated by production-based weightings for governance stability. Concerning South Africa, no import-based value could be calculated for beryllium because of a lack of import data from the UN Comtrade database. It is likely that beryllium is of low general relevance to the South African economy. The striking difference between EU-27 evaluation and the evaluation of France, Germany, and Italy emerges from the different accounting of intra-European trade. Whereas the two main suppliers of beryllium commodities according to the UN Comtrade database for EU-27 are, by far, China and the United States, the UK is the only of the four hereby selected European countries that receives commodities directly from China in large volumes. For France, Germany, and Italy, only EU-27 member states and the United States are important sourcing countries. The contribution of major trading partners for China, the EU-27 and United States toward the calculation of the GeoPolRisk are displayed in figure 4.

Discussion

The consideration of import shares is in line with the LCA principle, in which the resource flows to a product system are taken into consideration to determine the proportional environmental burden linked with the inputs and outputs. The same principle works here. The overall GeoPolRisk at the national, regional, or company level is estimated to be the sum of risks from different regions proportional to their import contributions and political stabilities. The countries evaluated in this article thereby represent an average of their corresponding importing companies, in which decision makers are confronted with supply risk as one part of the AoP resource use.

It is still important to keep in mind that the first-level trading partner countries, which are reported in the UN Comtrade statistics, might not be producing countries for the questioned commodity and might be affected by third-party instability supply risk. A clear example for this problem among the 14 considered elements and element groups is the cobalt metal case. Whereas the Democratic Republic of Congo is the most important country for cobalt mining with a share of 55% in 2011, the main producer in cobalt refining is China with a market share of 43% in 2011 according to the USGS. Calculating the global supply concentration for the mining or the refining sector of cobalt thus makes a difference. Whereas the HHI of cobalt mining is a value of 0.32 for 2011 and therefore generally

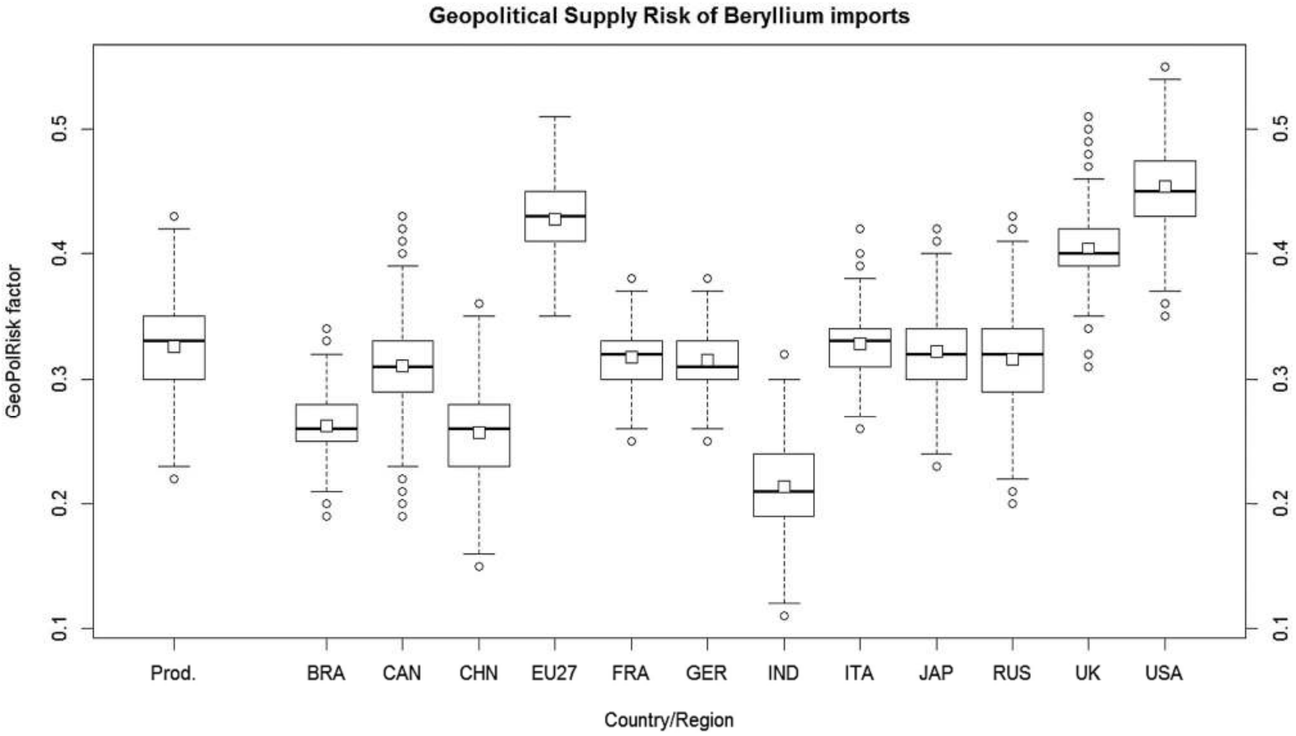

Figure 3 Comparison of geopolitical supply risk of beryllium when it is calculated based on global production vs. import share. Box plots display the median (thick line), mean (squares), the 25% and 75% quantiles (box), 1.5 interquartile ranges (whiskers), and outliers. On the x-axis: Prod. = Production; BRA = Brazil; CAN = Canada; CHN = China; EU27 = 27 member states of the European Union, which include Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom; FRA = France; GER = Germany; IND = India; ITA = Italy; JAP = Japan; RUS = Russia; UK = United Kingdom; USA = United States of America.

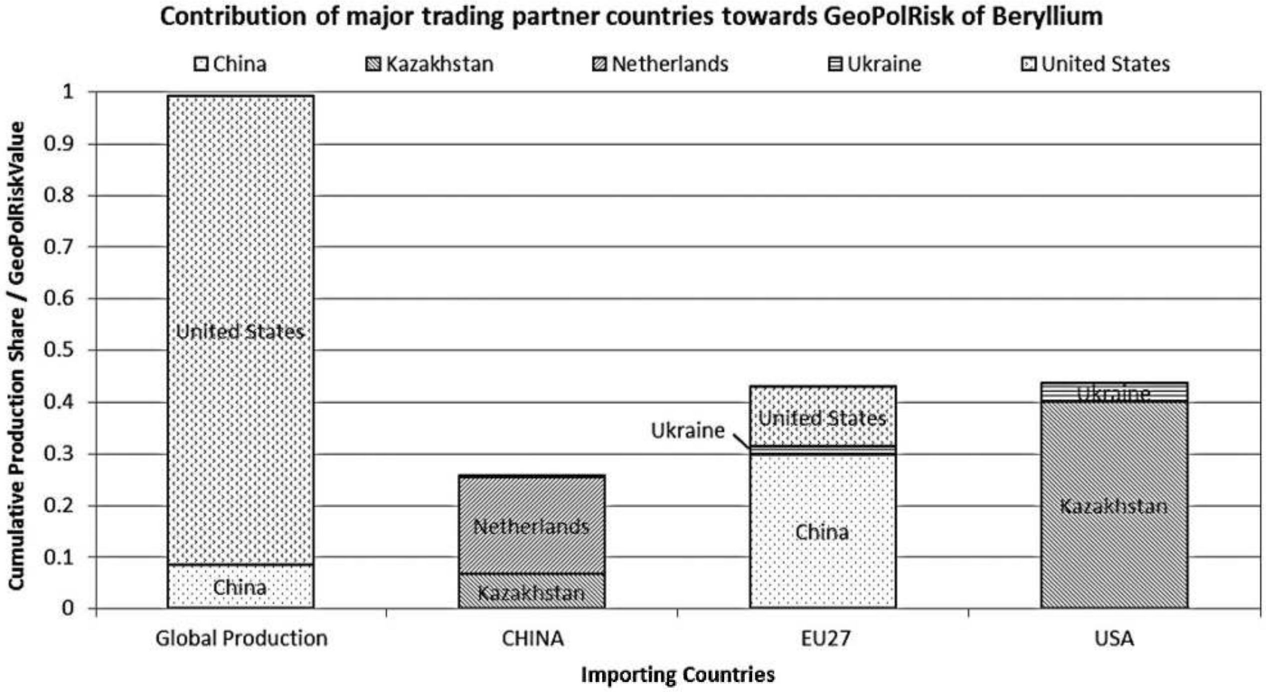

Figure 4 Contribution of major trading partner countries toward the geopolitical supply risk. Displayed are the global production distribution for beryllium and the contribution of the major import sourcing countries for China, the EU-27, and the United States. Minor countries' contribution to the final value is not displayed.

considered as highly concentrated, the refining sector only has a country concentration of 0.22, which is considered as moderately concentrated (Commission 2010).

In this article, the calculations for cobalt have been made with the country concentration of the mining industry. This allows for consistency along with most of the other 13 evaluated materials for which no explicit distinction between mining and refining has been made by the USGS or the Western North America region. Values of germanium, indium, and selenium are for refining production because these resources are extracted from carrier metals at the metallurgical stage; all others refer to mining production. Looking on the import volumes of cobalt, it is striking that among the considered regions, China and the EU are, by far, the biggest importers of cobalt metal commodities with reported volumes of 83 and 64 kilotonnes (kt). However, the four considered countries within in the EU-27 together have imported less than 14 kt. The gap is mainly filled by Finland, which has reportedly imported 54 kt of cobalt metal commodities in 2012 (UN 2013). Note that EU-27 total imports are lower than the sum of individual country's imports, given that intra-EU trade is not accounted for that region. Also, the world-wide annual accounted cobalt mining production is lower (109 kt) than the sum of the reported imports of China and the EU-27 alone, and concerning the most important cobalt mining country, the Democratic Republic of Congo, the EU-27 and China report that they are importing approximately 130 kt from this country, whereas the USGS data only credit the country a mining production of 60 kt (USGS 2013; UN 2013). This hints that there are major inconsistencies concerning world-wide production and trade accountings, at least in the case of cobalt. These issues particularly affect resources that can be processed and traded at different quality levels. From the selected materials, cobalt is the only resource for which accounting is made on multiple processing levels (mining and refining), whereas trading volumes can be cobalt ores, concentrates, and cobalt-containing chemical products. The complexity and variability of each commodity has to be considered for the application of the presented method to further resources.

The results show, however, that the proposed method is suitable to give a region-specific midpoint character for the geopolitical supply risk, which is one of the criticality aspects that need to be considered in LCSA modeling. The resource issue as it has been addressed in the conventional LCA focused on long-term potential geological availability. Though it is important to have a more long-term vision on resource availability, the short-term effects of supply risk owing to geopolitical and related effects become crucial, especially for metals such as rare earth elements, which are widely used in low-carbon and high-tech applications (UNEP 2009).

To date, only Schneider and colleagues (2013) tried to address the issue of shortcomings of existing resource-use evaluations in the LCSA framework through applying it for selected resources and comparing the results with the ones obtained from the CML method (Guinée et al. 2002), a method recommended as a best available midpoint LCIA method to assess resource availability (EC 2011). The ESP method proposed by Schneider and colleagues (2013) provided significantly different high-risk results (i.e., for rare earths and gold) than the abiotic depletion potential (ADP) of the CML method. The same working group also proposed an extension of the ADP method, the anthropogenic stock extended abiotic depletion potential (Schneider et al. 2011), which is a step into the right direction, given that it extends the naturally available stocks by anthropogenic stocks, giving a more justified view on the available resource volumes. However, even for that method, the problem of distribution and accessibility of stocks, as well as potential trade disruptions, persists. This shows the inconsistency between the old and new methods and highlights the need for current LCA to go beyond geological availability toward more-comprehensive criticality assessments of resources through incorporating the geopolitical and global supply concentration indicators along with others, so that it can be a more useful tool for decision making in resource strategy. Although the method from Schneider and colleagues (2013) is a step forward for the possible integration of geopolitical and other scarcity indicators into the LCSA framework, it does not differentiate between the supply risks of different resource users owing to imports because it is based on global production. Our proposed method for the geopolitical part rather provides different geopolitically supply risk values for all countries given that it takes into account the resource supply mix. Uncertainty analysis is also performed to see the variations of the results associated with the quality of the data used. Here, it is also important to note that the geopolitical issue, as it is addressed in our article, should not be linked only to minerals, but also with water and land-use issues.

One of the main challenges in the attempt of integrating the geopolitical and other aspects within the LCSA framework is data availability. The already available LCI database, such as ecoinvent (Frischknecht and Jungbluth 2007) and Gabi (PE Internatinal 2013), are not explicitly addressing the resource issue in their LCI. Data for only very few resources already exist and moreover they are not geographically regionalized. Besides this, most critical metals are not well reported in the LCI. Owing to the fact that they are present in a very small amount, compared with other commodity flows, their contribution to the global environmental burden is relatively small. Their role for a supply risk can be huge, however— for example, in the case of rare earth elements. They are usually avoided from the inventory owing to cut-off rules. Therefore, the goal and scope of LCA, which is intended for resource criticality assessment, has to be defined properly, so that important attention should be paid to include all relevant resources and supply risks in the inventory analysis. As a next step, we would like to test the operationality of the proposed method through applying it to a case study.

Although the research provides interesting results, it still lacks for accounting of different supply-chain levels. Because different companies are involved in the life cycle of a resource—from its mining, refinery, smelting, and other processes—the supply chain is very long and complex. Considering only the global primary producer or only the first-level supplier may result in a misleading conclusion. Future work could further enhance the method by consideration of complex multilevel trading patterns, including each country's domestic production and consumption. For some resources, the production is widely distributed among different countries, but large parts of the supply chain may be dominated by a few multinational corporations, leading to a high company concentration. This suggests the importance of looking down to the companies' profile, rather than only focusing on the country, to get a better insight on the potential supply risk. The challenge here is to manage modeling risk from the supply chain so that the overall supply risk can be better reflected. Tracking and tracing of metals is a very difficult task owing to the complexity of the supply chain or the lack of information resulting from confidentiality (Young and Dias 2011; RESOLVE 2010). Other difficulties arise from the physical aspects of the metal in the supply chain, in which they undergo a number of processes (RESOLVE 2010). During all these processes, multiple sources from the global maket are used, which makes the traceability of metals very difficult. A life cycle management is required to better understand the physical life cycle of the metal supply chain for an effective supply-chain management, as suggested by Young and Dias (2011). This will be an issue that we would like to address in the future.

Conclusion

Our article highlights the importance of including geopolitical and related indicators to fill the gap within the LCSA framework, which the current LCA practice of impact assessment with regard to the AoP of natural resources cannot achieve. By including factors other than geological availability that affect accessibility, such as the geopolitical supply situation, the criticality assessments best practice could play an important role for the LCSA framework. The socioeconomic and geopolitical issues related to natural resources are relevant for sustainability and hence need to be an integral part of a modern LCSA framework to keep the overall LCA methodology relevant for current and future sustainability challenges. The main challenge here is the availability of data; in almost all existing LCI databases, little attention is paid to critical resources that exist in a very small amount in a product's life cycle. A proper definition of the scope and goal would allow to include information in LCA databases, methods, and studies so that it can contribute to the criticality assessment of resources.

Among the 14 resources covered in this study, rare earth elements, tungsten, antimony, and beryllium seem to be the most geopolitically critical resources for many countries. One of the main reasons behind this is their high market concentration. For example, in the case of rare earth elements, approximately 95% of the global production is concentrated in China. This implies that any policy change, instability, or other geopolitical factors can induce high supply disruption.

From BRICS countries, Russia faces the highest geopolitical supply risk for most imported resources. From G7 countries, Canada is subjected to the highest risk from the import of rare earth elements imports, whereas the United States and the EU-27 have relatively the highest risk factor for beryllium.

Our results generally suggest that the geopolitical supply risk should not be handled with the world average production, rather it has to be differentiated among countries depending on their import structure. Different import structures of resource-demanding countries are displayed in the calculated supply risk emerging from the estimation of the political stability of the sourcing countries. Monte Carlo simulation, exemplified on the case of beryllium, showed that the usage of only one commodity trade database, which provides no explicit uncertainty information, leads to unneglectible uncertainties of the final GeoPolRisk values. However, even with consideration of uncertainties, half of the evalued regions showed a risk that was significantly different than the global average. This underlined the impact that supplier country selection can have on the geopolitical supply risk. The case of cobalt further displayed the pitfalls of the supply chain, with the Democratic Republic of Congo being the main mining country and China being the main refining country for cobalt commodities. Beryllium and cobalt exemplarily showed that trade between stable countries (i.e., intra-European trade) can lead to an apparent reduction of the GeoPolRisk, which then calls for a further evaluation of the second supplier level, which is more difficult to establish.

In principle, the integration of geopolitical information under the LCSA framework allows the conventional LCA to broaden its scope so that it can be used by decision makers in their pursuit to secure the sustainable resource supply. Such an analysis could reveal the potential future constraints on specific resources and help policy makers and business leaders to take the necessary mitigation options. One could reduce the supply risk either through shifting import from countries at high political instability to stable and local conflict-free regions or through diversifying their global supply chain. The other mitigation option could be to promote substitution of resources that are at a very high risk of future supply constraint with resources that are abundantly available. This can be achived by encouraging the development of scientific research in the relevant field of knowledge studies. Stimulating the more efficient way of recycling and reuse of resources through introducing a very strict waste management policy also needs to be considered as a mitigation option.

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