13. Mineral resource scarcity

Marisa Vieira[1,2], Mark A.J. Huijbregts[1]*

[1] Department of Environmental Science, Radboud University Nijmegen, The Netherlands

[2] PRé Consultants b.v., The Netherlands

* vieira@pre-sustainability.com

Based on: Vieira *et al.* (2012) and Vieira *et al.* (2016).

13.1. Areas of protection and environmental mechanisms covered

Description of impact pathway

Mineral resources are key raw materials in many industrial sectors and hence their demand is increasing. Although it has been argued that mineral resources are available in almost infinite amounts in the earth crust, the actual availability of a mineral primarily depends on ore grades (Gerst 2008). The impact patway of mineral resource extraction is illustrated in Figure 13.1 and described in equation 13.1. When a mineral is extracted (ME), the overall ore grade of that mineral declines (OG) (Mudd 2007; Prior et al. 2012). This mechanism can be captured by cumulative grade-tonnage relationships, as shown by Vieira et al. (2012). The smaller the ore grade, the larger the amount of ore that needs to be produced for extracting the same amount of mineral resource (OP). According to Prior et al. (2012), ore grade decline can be used as an indicator for a range of societal impacts. For instance, larger amounts of ore produced for the same unit of mineral output, implies more waste (waste rock, tailings) to be handled. The larger the future mineral resource extraction (R) the larger becomes the overall increase of ore produced. Consequently, the future metal extraction is relevant and should be considered. The average increase in ore amount per kg of mineral extracted considering all future mineral resource yet to be extracted is defined as the surplus ore potential, here the life cycle impact indicator.

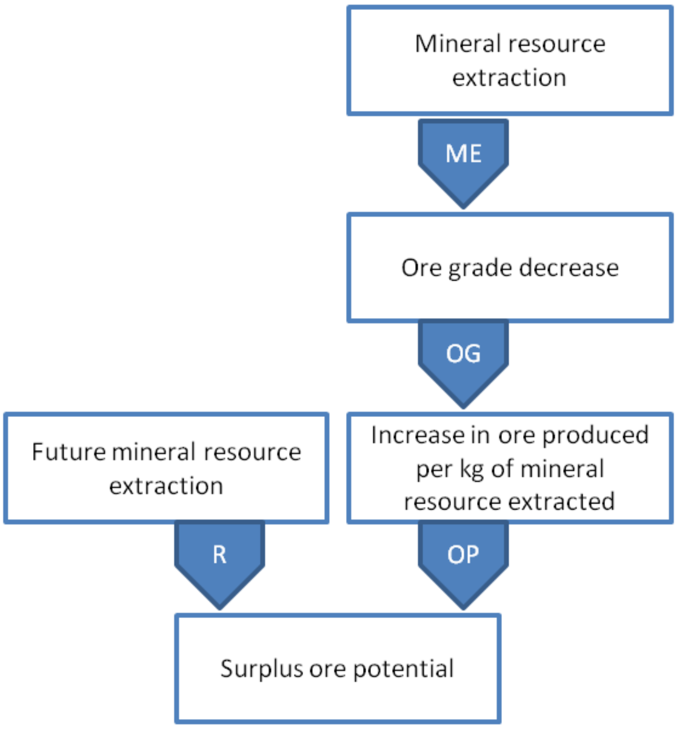

Figure 13.1: Cause-effect chain for natural resource impacts caused by mineral resource extraction. The interim steps of the impact pathway are depicted and the factors leading to them are described in equation 13.1.

Description of all related AoPs

This impact pathway only affects natural resources.

Methodological choice

An average approach is used to calculate the characterization factors. By calculating on basis of cumulative grade-tonnage relationships the increase in ore amount for all future mineral extraction and then dividing it by the future mineral extraction, average CFs are derived. These CFs are used to assess the potential impacts of mineral resource extraction worldwide.

Spatial detail

Mineral resource scarcity is a global phenomenon because there is a global market for these type of resources. As a result, no spatial detail was defined for this method.

13.2. Calculation of the characterization factors at endpoint level

The endpoint CF, expressed as the surplus ore potential (SOP), is defined as the extra amount of ore produced in the future per unit of mineral extracted, which is calculated by Equation 13.1.

$$\mathrm{CF}_{\mathrm{end},x} = \frac{\int_{CME}^{MME} (\Delta \mathrm{OP}_x) dCME}{R_x} = \frac{\int_{CME}^{MME} (\Delta \mathrm{OP}_x) dCME}{MME_x - CME_x}$$

Equation 13.1.

where $CF_{end,x}$ (kg_{ore}/kg_x) is the average Surplus Ore Potential of mineral x, OP_x is the ore produced per amount of mineral resource x extracted (kg_{ore}/kg_x), and R_x (kg_x) is the actual reserve of the mineral x, defined as the maximum amount to be extracted of that mineral (MME_x) and the difference between the current amount of mineral x extracted (CME_x).

The ore extracted per amount of mineral resource x produced (OP_x in kg_{ore}/kg_x) is equal to the inverse of the ore grade of the mineral (OG_x in fraction). The ore grade of a mineral can be derived with a cumulative grade-tonnage relationship, as previously shown by Musgrove (1965), Gerst (2008), and Vieira et al. (2012). A cumulative grade-tonnage relationship reflects the relationship between the cumulative extraction of a mineral x and its ore grade and can be derived as (Vieira et al., 2012):

$$\mathrm{OG}_x = \frac{1}{\mathrm{OP}_x} = \exp(\alpha_x) \cdot \left(\frac{\mathrm{MME}_x - \mathrm{CME}_x}{\mathrm{CME}_x}\right)^{\beta_x}$$

Equation 13.2.

where OG_x is the ore grade of mineral x (in kg_x/kg_{ore}), MME_x (in kg_x) is the maximum amount of mineral x that can be extracted, CME_x (in kg_x) is the cumulative amount of mineral x extracted, and α_x and β_x are respectively the location parameter and scale parameter of the loglogistic distribution of the cumulative grade-tonnage relationship for the mineral x.

There is sufficient information to derive SOP values for 18 mineral resources, namely aluminium, antimony, chromium, cobalt, copper, gold, iron, lead, lithium, manganese, molybdenum, nickel, niobium, phosphorus, silver, tin, uranium, and zinc (Vieira et al. 2016). For the minerals for which SOP values could not be derived on the basis of empirical cumulative grade-tonnage relationships, we used the price of the mineral resource to estimate its SOP value. These are indicated in Table 13.2. with an asterisk. Price data of 2013 was retrieved from Kelly and Matos (2013) in U.S. dollars reference year 2013 (USD2013) except for the platinum group metals and uranium. For palladium, platinum, and rhodium, average price data for 2013 was retrieved from Kitco Metals Inc. (2015). The ESA spot U_3O_8 data (a weighted average of triuranium octoxide prices paid by EU utilities for uranium delivered under spot contracts during the reference year) published by the Euratom Supply Agency (2015) was used to calculate the price for uranium. As shown in figure 13.2, the price of a mineral can be considered as a good predictor for SOP (explained variance of the regressions equals 90-91%).

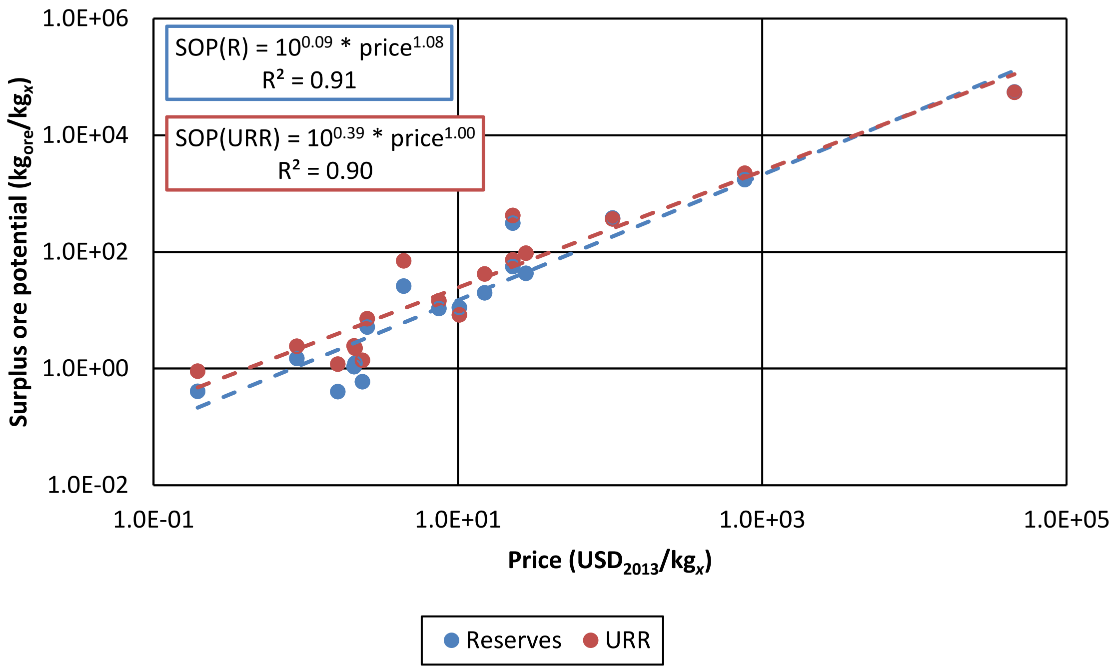

Figure 13.2: Relationship between average price in 2013 (USD_{2013}/kg_x) and surplus ore potential (kg_{ore}/kg_x). The surplus ore potential have been calculated for two different future production estimates, reserves (R) and ultimate recoverable resource (URR).

13.3. Uncertainties

The uncertainty of the characterization factors was not calculated. However, there is information of the coefficient of correlation (R^2) of the cumulative grade-tonnage curves of each mineral resource covered and these provide a good indication of the uncertainty in the CFs derived. As such, we decided to qualitatively cluster all minerals in the three classes of uncertainty depending on each R^2:

- low uncertainty if $0.9 \leq R^2 \leq 1$: aluminium, cobalt, iron, molybdenum, nickel, and phosphorus
- medium uncertainty if $0.8 \leq R^2 < 0.9$: antimony, chromium, gold, lead, and uranium
- high uncertainty if R2 < 0.8 or derived on basis of price: remaining mineral resources.

13.4. Value choices

Time horizon

There is no value choice related to the time horizon considered as this is infinite for this method. This means that all mineral resources to be extracted in the future are considered. No discounting to future effects is applied.

Future mineral resource extraction

One value choice that has to be made for this method is the definition of the maximum amount of a mineral resource *x* to be extracted (MME_x) as this is dependent on the future mineral resource to be extracted. Two different reserve estimates were applied in the calculations of the endpoint characterization factors to understand to what extent the results depend on the definition of mineral reserves. The first type of reserve estimate, used to calculate CF with “certain effects”, is the ‘Reserves (R)’ which is defined as that part of a mineral resource “which could be economically extracted or produced at the time of determination”, meaning at current prices and state of technology (U.S. Geological Survey 2015). The ‘Ultimate recoverable reource (URR)’, used to calculate the CFs with “all effects”, refer to “the amount available in the upper earth’s crust that is ultimately recoverable”. The definition of URR as used by UNEP (2011), there called ultimately extractable reserves, will be used here which is 0.01 % of the total amount in the crust to 3 km depth.

Table 13.1: Included effects with CF certain effects and CF all effects.

Choice category	CF certain effects	CF all effects
Reserve estimate	Reserves	Ultimate recoverable resource

Table 13.2: Characterization factors for natural resources.CFs with an * are derived based on prices. The others are based on empirical data.

Elementary flow	CF certain effects [kg_{ore}/kg]	CF all effects [kg_{ore}/kg]
Aluminium	1.09E+00	2.48E+00
Antimony	1.11E+01	8.36E+00
Arsenic*	9.59E-01	1.92E+00
Ball clay*	4.16E-02	1.04E-01
Barite*	1.46E-01	3.34E-01
Bauxite*	2.60E-02	6.69E-02
Bentonite clay*	6.55E-02	1.58E-01
Beryllium*	9.09E+02	1.12E+03
Bismuth*	2.99E+01	4.68E+01
Boron*	8.39E-01	1.69E+00
Cadmium*	2.51E+00	4.68E+00
Cesium*	2.05E+05	1.73E+05
Chromium	6.01E-01	1.39E+00
Chrysolite*	2.38E+00	4.46E+00
Clay, unspecified*	6.31E-02	1.53E-01
Cobalt	4.32E+01	9.60E+01
Copper	1.08E+01	1.46E+01
Diamond (industrial)*	1.10E+03	1.34E+03
Diatomite*	3.32E-01	7.14E-01
Feldspar*	9.60E-02	2.25E-01
Fire clay*	2.10E-02	5.50E-02
Fuller’s earth*	9.29E-02	2.19E-01
Gallium*	1.00E+03	1.23E+03
Germanium*	4.19E+03	4.64E+03
Gold	5.52E+04	5.46E+04
Graphite*	1.44E+00	2.80E+00
Gypsum*	1.55E-02	4.14E-02
Hafnium*	1.17E+03	1.41E+03
Ilmenite*	2.59E-01	5.68E-01
Indium*	1.25E+03	1.50E+03
Iodine*	7.02E+01	1.04E+02
Iron	4.12E-01	9.06E-01
Iron ore*	1.10E-01	2.55E-01
Kaolin*	1.58E-01	3.58E-01
Kyanite*	3.40E-01	7.31E-01
Lead	5.21E+00	7.18E+00
Lime*	1.28E-01	2.95E-01
Lithium	2.61E+01	7.10E+01
Magnesium*	6.63E+00	1.16E+01
Manganese	4.06E-01	1.20E+00

Mercury*	9.03E+01	1.31E+02
Molybdenum	3.13E+02	4.27E+02
Nickel	2.00E+01	4.23E+01
Niobium	4.81E+01	7.61E+01
Palladium*	6.88E+04	6.25E+04
Perlite*	5.48E-02	1.34E-01
Phosphorus	1.51E+00	2.44E+00
Platinum*	1.49E+05	1.28E+05
Potash*	7.48E-01	1.52E+00
Pumice and pumicite*	3.33E-02	8.42E-02
Rhenium*	7.25E+03	7.72E+03
Rhodium*	1.05E+05	9.27E+04
Rutile*	1.34E+00	2.62E+00
Selenium*	1.38E+02	1.94E+02
Silicon*	3.43E+00	6.26E+00
Silver	1.74E+03	2.24E+03
Strontium*	6.21E-01	1.28E+00
Talc*	2.52E-01	5.53E-01
Tantalum*	6.10E+02	7.74E+02
Tellurium*	1.99E+02	2.73E+02
Thallium*	1.76E+04	1.76E+04
Tin	5.65E+01	7.35E+01
Titanium*	7.43E+00	1.28E+01
Titanium dioxide pigment*	4.18E+00	7.53E+00
Tripoli*	2.30E-01	5.09E-01
Tungsten*	7.75E+01	1.14E+02
Uranium	3.86E+02	3.69E+02
Vanadium*	3.76E+01	5.81E+01
Wollastonite*	2.38E-01	5.24E-01
Zinc	1.25E+00	2.24E+00
*Garnets**	3.23E-01	6.97E-01
*Gemstones**	1.35E+05	1.17E+05
Platinum-group metals	5.99E+04	5.50E+04
*Rare earth metals**	2.97E+01	4.66E+01
*Zirconium minerals**	1.31E+00	2.56E+00

13.5. References

Euratom Supply Agency. 2015. ESA average uranium prices. Accessed 3 June 2015 at http://ec.europa.eu/euratom/observatory_price.html.

Gerst, M.D. 2008. Revisiting the cumulative grade-tonnage relationship for major copper ore types. *Economic Geology* 103(3): 615–628.

Kelly, T. D., Matos, G. R. 2013. *Historical statistics for mineral and material commodities in the United States (2013 version)*: Reston, Virginia: U.S. Geological Survey Data Series 140. Accessed 3 June 2015 at http://minerals.usgs.gov/minerals/pubs/historical-statistics/.

Kitco Metals Inc. 2015. Historical Charts and Data – London Fix. Accessed 3 June 2015 at http://www.kitco.com/charts/.

Mudd, G. M. 2007. An analysis of historic production trends in Australian base metal mining. *Ore Geology Reviews* 32(1-2): 227-261.

Musgrove, P. 1965. Lead: grade-tonnage relation. *Mining Magazine* 112(4): 249–251.

Prior, T., D. Giurco, G. Mudd, L. Mason, and J. Behrisch. 2012. Resource depletion, peak minerals and the implications for sustainable resource management. *Global Environmental Change* 22(3): 577-587.

UNEP. 2011. *Estimating long-run geological stocks of metals*. Working paper, April 6, 2011. Paris: UNEP International Panel on Sustainable Resource Management, Working Group on Geological Stocks of Metals.

U.S. Geological Survey. 2015. Mineral commodity summaries 2015. U.S. Geological Survey, 196p.

Vieira, M. D. M., T. C. Ponsioen, M. J. Goedkoop, and M. A. J. Huijbregts. 2012. Ore Grade Decrease As Life Cycle Impact Indicator for Metal Scarcity: The Case of Copper. *Environmental Science & Technology* 46(23): 12772-12778.

Vieira, M. D. M., T. C. Ponsioen, M. J. Goedkoop, and M. A. J. Huijbregts. 2016. Surplus Ore Potential as a Scarcity Indicator for Resource Extraction. *Journal of Industrial Ecology*. Advance online publication. doi: 10.1111/jiec.12444.