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Can ultimate recoverable resources (URRs) be assessed? Does analyzing declining ore grades help?

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Abstract

Inspired by a paper by Teseletso and Adachi (Miner Econ 8(10):21, 2021), the hypothesis regarding the declining grade of mined copper ore and its possible use as a guide to the future of ultimate recoverable resources (URRs) is tested. As a time axis, cumulative production is taken. Grades can be either grade of cumulative tonnage or annual production grade. Correlation can be linear (grade and tonnage) or semi-logarithmic (grade linear, tonnage logarithmic). We first show that the assumption that the highest correlation is the best guide to the future may be a fallacy. This is the linear correlation between grades of cumulative tonnage and cumulative tonnages since 1959, i.e., 85% of all copper mined historically with a near-perfect correlation approaching one ($R^2=0.97$). This leads to implausibly low results of the URR, clearly demonstrating that this trend must shift in the future. Moreover, Teseletso and Adachi's (Miner Econ 8(10):21, 2021) approach using a linear or semi-logarithmic correlation between annual grades with cumulative production leads to erroneous results. Here, the later the calculation of the correlation begins, the lower the extrapolated tonnages are at predetermined, postulated ultimate cutoff grades. This contradicts the accepted knowledge that with lower grades, the resource base is broadened—not narrowed. The only reasonable finding results from the correlation between linear grades of cumulative production with logarithmic cumulative production, i.e., the Lasky relationship, indicating a URR of 7.5 GT Cu, of which 6.7 GT remain to be mined, which is equivalent of close to 325 years of present production. The trend towards declining Cu grades with constant real Cu prices shows the potential for creative solutions for other metal as well.

Keywords Ultimate recoverable resources (URRs) · Grade–tonnage relationships · Grade of cumulative tonnage · Grade of annual tonnage · Linear correlation and extrapolation · Semi-logarithmic correlation and extrapolation

Introduction

Aristotle's concept of *horror vacui*—that nature abhors a vacuum—and the related fear of emptiness has been adopted by psychology (O'Donnell et al. 2021; Roux et al. 2015; Zhao and Tomm 2018). This is countered by humankind's and nature's desire to avoid or fill a vacuum. In the natural resource field, a typical example of a fear of empty spaces is the wish to have concrete quantifiable "facta et data" of mineral resources available for the future, not only for the near

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future but also for the far future — if not until eternity. But the assumed vacuum can be avoided by trusting in human creativity leading to revolutionary innovations fulfilling human's raw material needs (see Box 1 below).

Box 1: The fixed stock and opportunity cost paradigms: Two avenues for approaching the unknowable future

As the philosopher Karl Popper stated, the future is unknowable, at least for radically new inventions (Popper, 1969), and with these, we have to plan for future developments in the field of natural resources. On the eve of the Iraq War, US Secretary of Defense Donald Rumsfeld talked about the known knowns, the known unknowns, and the unknown unknowns (CNN Transcripts, 2002), words that can also apply to the future reserves and resources situation. Known knowns are the presently known reserves from mines and deposits; known unknowns are reserves that can be developed from known resources; and unknown unknowns are reserves that can potentially be developed using currently unavailable and unrealized technologies and from yet-to-be discovered deposits and/or technologies. Shale oil and shale gas development with newly developed horizontal drilling and fracking technology is a useful example of how radical and unforeseeable the resource picture for a commodity can be (Scholz & Wellmer, 2021). Because actual future development is unforeseeable, futurologists (aka futurists) speak of futures in the plural (Nowotny, 2002) and work with scenarios. To understand the future of raw materials development, the two camps—the fixed stock and opportunity cost paradigms—take different approaches, as described below.

Fixed stock paradigm: The proponents of this paradigm search for limits. Three examples are provided of where and how limits are seen:

- Gordon et al. (2006, 2007) saw a discrepancy between the discovery rate and the extraction rate of copper, pointing to a coming scarcity. They followed Skinner's (1976) bipolar grade-tonnage curve, which limits the amount of copper above the mineralogical barrier. The mineralogical barrier arises from the fact that, with lower grade, copper is no longer present in separate sulphide minerals but built into the lattice of silicate minerals, thereby making it impossible to recover using economical beneficiation methods.
- Based on a concept assuming that the size of extractable ore deposits is directly proportional to the crustal occurrence of the relevant metal (Rankin, 2011; Henckens, 2021), a working group of the International Resource Panel of the UN Environment Program (UNEP) (2011) concluded that 0.01% of the total amount of a material in the upper 1 km of the continental Earth's crust is a reasonable estimate for the upper limit of the "extractable global resources."
- Shoji and Kaneda (1998) use ore value–tonnage diagrams for different ore deposit types for resource assessment. Shoji (2002) applies the enrichment ratio (ER) defined as the ratio of grade of a metal element in a deposit to crustal abundance of the metal again for different deposit types to assess mineral resources.
- Singer (2017) used the geologic knowledge of copper distribution in certain ore deposit types and the statistical knowledge of the grade–tonnage relationship and the highly skewed copper distribution and probabilistic estimates of the number of undiscovered deposits by type.

Opportunity cost paradigm: The proponents of this paradigm start from a different angle (Tilton, 2003; Tilton & Lagos, 2006). Earth certainly has limits; these are the background values in the crust. However, quantity of an element is practically limitless and the fundamental recognition that unlike fossil fuels, most metals are not destroyed by use and might be recovered with appropriate technologies. For the example of copper, Tilton et al. (2018) calculated that, given the current rate of exploitation and using Earth's crust as the ultimate resource, this would result in 84 million years of consumption, far beyond the most probable existence of humankind.

To be useable, enrichments are necessary. These exist in nature with a wide variety of grades and tonnages and can become deposits to be exploited. They offer humankind substances for finding solutions for functions. Basically, raw materials have to become products of the human brain, which will help identify these solutions (Zimmermann, 1933; Wellmer & Scholz, 2017). Naturally, in the mining process, humans begin with the least-costly (known) solution, i.e., the highest-grade deposits accessible. These are rare. Although the example of copper, shown in the text below, illustrates that humans have learned to cope with increasingly lower-grade deposits in the long term and constant prices in real terms over 100 years, there are cost limits to what they are willing or able to pay for extracting and converting metal content from rock in order to convert it to useable products. At a certain cost limit, humans look for alternatives in the form of either direct substitutions or other solutions for a needed function, i.e., technological substitutions.

Repeatedly, attempts have been undertaken to fill this emptiness (herein, the knowledge void regarding future available resources). These have included efforts to quantify the ultimate limit of resources, either by using the known mineral reserves and resources in relation to consumption and manipulating and extrapolating the relationship, by applying the fixed stock concept, or by utilizing the statistical grade and tonnage distribution (see Box 1 below). Another idea has emerged from experiences showing that the lifetime curve of a deposit, a mining district, or even larger entities roughly follows a bell-shaped curve (Hewett 1929; Hubbert 1956; critical comment by Tilton 2018). Yet another approach assumes that an arbitrary fraction of the available material in the crust, i.e., the ultimate upper limit, can be used as a resource (Box 1 below).

Recently, Teseletso and Adachi (2021) have taken a new approach to filling the emptiness of the *horror vacui* in their paper titled "Future availability of mineral resources: Ultimate reserves and total material requirements." It provides an interesting nudge and an impetus that leads us to a principal discussion of how and even whether the "knowledge void" can be filled. In their paper, the authors claim to be able to forecast the ultimate recoverable resources (URRs) (all the resources which have been mined and ultimately will be mined) for copper (Cu), nickel (Ni), lead (Pb), zinc (Zn), gold (Au), and iron (Fe). They extrapolated grade trends of cumulative production between 1991 and 2019 for Cu, Ni, and Pb, and between 2000 and 2019 for Au, Fe, and Zn to a postulated predetermined ultimate cutoff grade (COG), which Teseletso and Adachi refer to as COG. They carefully and commendably analyze smaller units such as continents or countries as a basis for extrapolation, and then, they compile the extrapolated data for the entire world. They apply an innovative approach by extrapolating the declining grades of cumulative tonnages observed with many commodities over time to a predetermined COG to estimate future available reserves above this cutoff grade. This new approach attempts to counteract the *horror vacui* and considers a new argument in the dispute between the fixed stock paradigm (e.g., Meadows et al. 1972; Gordon et al. 2006) and the opportunity cost paradigm, which takes into account the inherent dynamics of market forces and technological developments and their impacts on changing and continuous demands (e.g., Tilton 2003; Tilton and Lagos 2007; see Box 1).

Considering the new approach suggested by Teseletso and Adachi (2021), we have certain reservations. In particular, we do not share their assumptions regarding postulating a technological limit (of ore grade) based on our current knowledge and extrapolating it linearly into the future. Because this touches upon several principal questions about the future outlook, we take Teseletso and Adachi's approach as an incentive to address the question of how—and how far—present knowledge can be extrapolated into the future and whether it really is a method that can fill the *horror vacui*.

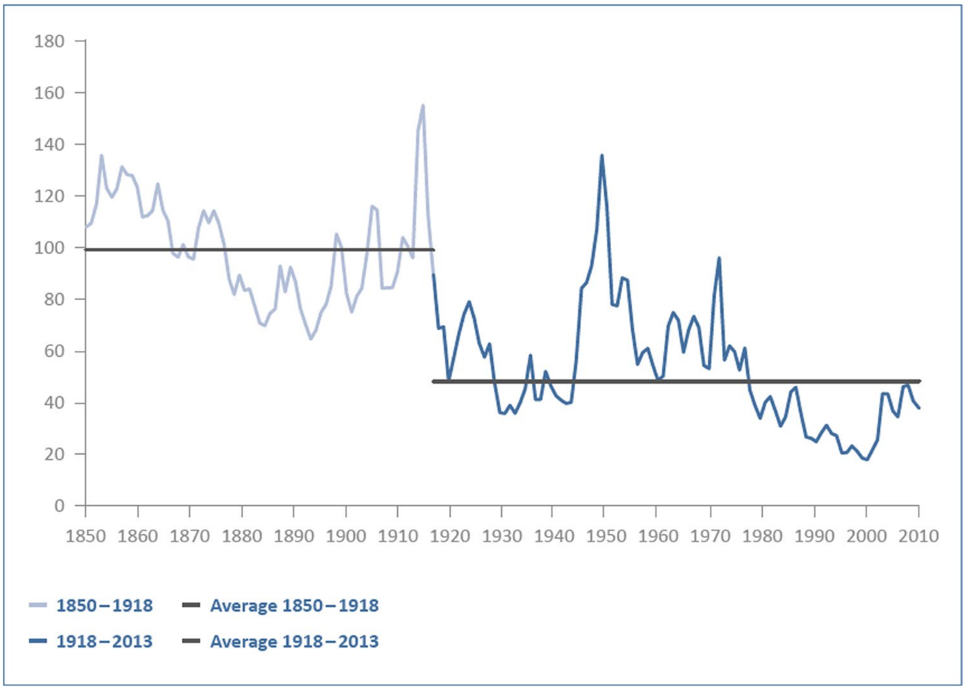
In 1952, the Chief Economist of the British Government, Sir Alexander Cairncross, said, "A trend is a trend. But the question is: Will it bend? Will it alter its course through some unforeseen force and come to a premature end?" This well-known rhyming quotation is true not only for economics but also for the world of raw materials, an essential component of economics. Is the assumption that there will be no bend in the future really justified? It might be justified to linearly extrapolate trends if technological improvements were only incremental. These build on existing technologies and continuously improve them. However, "leaps" or disruptive innovations may also occur (Kagermann et al. 2013; Harhoff et al. 2018), abruptly changing the technological situation and offering entirely new technical possibilities. These often come with the consequence of a new cost structure; for example, in mining, lower grades can be exploited. For the authors of this paper, it is highly doubtful that such developments can be simulated by a simple direct, linear model or via a logarithmic-transformation linear model. An example of such a disruptive intervention is the common and ubiquitous transistor that replaced the vacuum tube; another in the realm of mining is the introduction of low-cost bulk mining technology and the invention of flotation. These latter inventions coincided with the slump in global demand for metals following WWI that created a new lower-price plateau that, since then, has remained more or less constant in real terms (Fig. 1) (Buchholz et al. 2020; Wellmer 2022). The break in the price plateau in real terms after WWI is not only obvious for the sum of all base metals, as shown in Fig. 1, but also distinct in the case of copper alone (see Fig. 15 in Wellmer 2022).

We focus particularly on copper because long time series are observed over years and are available (e.g., Ayres et al. 2002; Gerst 2008; Crowson 2012; and the newest data from Schodde 2019). With Schodde's (2019) grade data from 1900 and due to the exponential increase of copper production since then, data about grade and tonnage are available for about 98% of all copper mined since the beginning of the copper age (Hong et al. 1996; Wellmer 2022). It is our opinion, however, that results from the example of copper can be generalized to other commodities. Figure 2 illustrates the development of worldwide copper grades since the end of WWI (Schodde 2019), i.e., with the beginning of the new price plateau in comparison to the copper-price development in nominal and real terms.

In this context, we add that copper is of special significance with regard to future economic and technological developments:

- Because of copper's widespread applications in most sectors of the economy, the copper price is seen as an early warning indicator of the development of the global economy. This is the reason that this base metal has been nicknamed "Doctor Copper" (e.g., FAZ 2021).
- Of those metals that will be used in the future in increasing quantities for the energy changeover (*energiewende*), copper is expected to be used in the largest quantity (IEA 2021). A recent study demonstrated that, for emergent technologies that currently use only 19% of the mining

Fig. 1 Index of real prices of non-ferrous metals, 1850–2013 (normalized to 1900). The prices for aluminum, copper, lead, zinc, and tin are weighted by means of the real value of the production. The data are derived from the London Metal Exchange and its predecessors (after Stuermer 2013/2018; Stürmer 2013; Stürmer M. 2021, Personal Communication). The corrections for inflation are based on the British Consumer Price Index (from Wellmer 2022)



production of 2018, this figure could increase to 35% by 2035 (Marscheider-Weidemann et al. 2021).

Examination of URR approaches

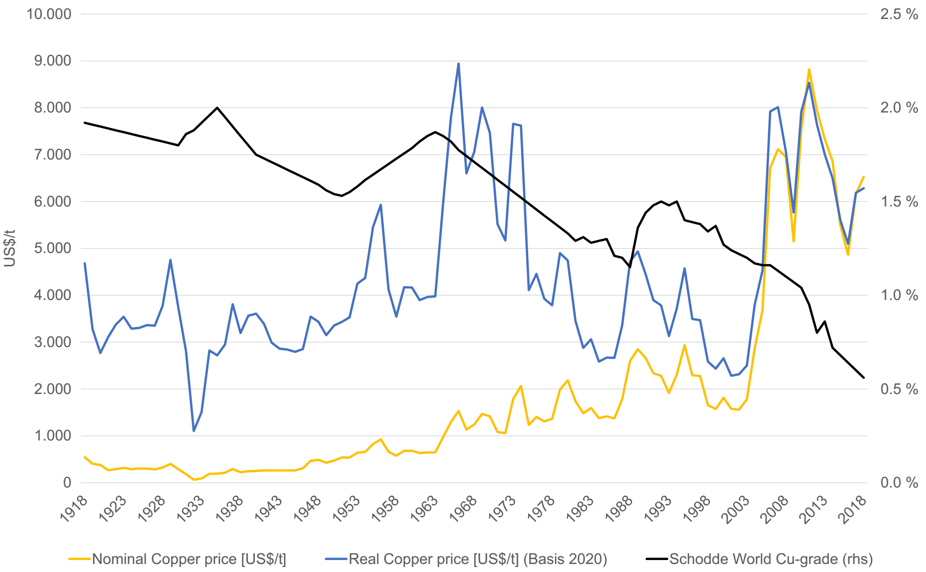
Our analysis will proceed using the following steps.

The ultimate COG and URR

Teseletso and Adachi (2021) introduced a new interpretation of ultimate recoverable resources (URRs). Generally, a URR is understood in the scientific community as the amount of a resource that will *ultimately* be exploited (see, e.g., Berger et al. [22 international authors], 2020, or Wikipedia 2021, the definition of URR). Teseletso and Adachi (2021) have stated, "The URR is the maximum limit of metal resources that can be extracted and exploited; therefore, metal production can never exceed [the] URR, i.e., $\text{URR} \geq Q_{i(t)}$," whereby Q is the cumulative production. However, they introduce a new element—a predetermined ultimate cutoff grade (COG).

Of course, the authors are free to introduce a new definition, but now, it must be understood that a new

Fig. 2 Development of the global copper grade (Schodde 2019) and copper prices in nominal and real terms (BGR 2021). Correlation coefficients between nominal copper price and copper grade development are −0.776 and real copper prices and copper grade development are −0.271



element is introduced and, thereby, the meaning of URR has changed. The border is no longer infinity (the word "ultimate" in URR) but rather a predetermined ultimate cutoff grade under the assumption that it will never be reached or exceeded. In the following, we critically examine this new definition.

In investigations dealing with average grade developments and cutoff grades, cutoff grades are of course the weighted mean of a multitude of mines reflecting different economic and technological conditions. With the following example, we want to illustrate how much a single mine, which could well be an example for others, has been successful in lowering the cutoff grade. Presently, the producing mine exploiting the lowest copper concentration in the world is the open pit Aitik Mine in Sweden, mining 0.22% Cu with a cutoff grade of 0.06% (Karlsson 2020). (The mine produces also some gold and silver as by-products which has an influence on the cutoff grades. The problem is solved by calculating metal equivalents. This is explained in detail in Appendix 1). The cutoff of copper is just 9 times the geological background of 68 ppm (Greenwood and Earnshaw 1984). This means that this mine's average grade is just above Teseletso and Adachi's (2021) predetermined COG and that the applied cutoff grade is only about a third of that assumed by those authors (2021), clearly illustrating that their assumption is far too pessimistic. There is no reason to assume that, as a result of technological advances, the cutoff grade cannot be further reduced, thus calling to mind the "known unknowns" (West 2020).

Furthermore, we must also consider unknown—and entirely unsuspected—innovations, i.e., Popper's (1988) "unknown unknowns." Popper claimed that, for radically new innovations to occur at all, the future must be unknowable. Otherwise, an innovation would, in principle, already be known and would thus occur in the present—not in the future.

Linear extrapolation

We want to examine various approaches of linear or semi-logarithmic extrapolation of declining grades, whereby the grades themselves are always linear. First, we study the relationship between cumulative production and grade of cumulative production, both by linear and semi-logarithmic extrapolation. Then, we consider Teseletso and Adachi's (2021) approach of cumulative production and grade of annual production, also by linear and semi-logarithmic extrapolation; in each case, cumulative production is used as the time element.

Limits of linear extrapolation

To look into the future and extrapolate trends, it is tempting to select trends with a high coefficient of correlation related to the time variable. One such highly tempting trend with a coefficient of determination of 0.9725, unusually high for geological data, even taking into account the effect that with accumulation correlation is induced, is shown in Fig. 3, which illustrates a "hyperbolic" curve representing the cumulative grade of cumulative production against cumulative production since 1900. Since an approximate cumulative production of 100,000,000 t (tonnes) that occurred in 1959, the curve shows a very linear trend with this high coefficient of determination of 0.9725. This holds for a cumulative production from 100,000,000 t to today (764,000,000 t in 2020 (BGR 2021), i.e., for the last 87% of cumulative production since 1900 or 85% of all copper mined worldwide historically (Hong et al. 1996; Wellmer 2022). From 1959 to 2018, the average grade of copper produced worldwide decreased from 1.76% Cu to 0.56% Cu, and production increased from 3.4 million t to 20.6 million t (Schodde 2019; BGR 2021).

Working with cumulative production, there is the problem—as noted by DeYoung Jr (1981) and later discussed in detail in this article with the examination of Lasky's relationship—that these trends cannot be extrapolated to zero because they would require negative metal values. However, they can be useful for determining the maximum of metal in tonnes for URR under the assumption that the linear relationship holds (DeYoung Jr 1981); see Appendix 2. The maximum URR under this linear relationship is 1.09 GT copper; this, of course, is a highly theoretical value because no company would mine to a copper grade of + 0.00%. Every mining company would apply a cutoff grade, which would reduce this value. Without going through the exercise of reducing this theoretical maximum tonnage to a reasonable cutoff value, the figure of 1.09 GT (Giga tonnes) copper as a maximum value is already far too low:

> The cumulative production from 1900–2020 is already 0.76 GT copper (BGR 2021), leaving a difference of only 0.33 GT copper for the future. This represents just 38% of the reserves given in the Mineral Commodity Summaries of the US Geological Survey (Flanagan 2021), not taking into account any of the identified 2.1 GT resources, of which a major proportion will, in all probability, be developed as reserves.

This clearly illustrates that even trends with a high degree of correlation in the past can be broken, or to quote Chief Economist of the British Government Sir Alexander Cairncross analogously, the trend will bend (1952).

Extrapolating with the help of the semi-logarithmic Lasky's relationship

The most well-established relationship between grade and tonnage is that of Lasky, which is thought by many to be suitable for extrapolation (Lasky 1950). It states that a linear decrease in grade is related to a logarithmic increase in the cumulative

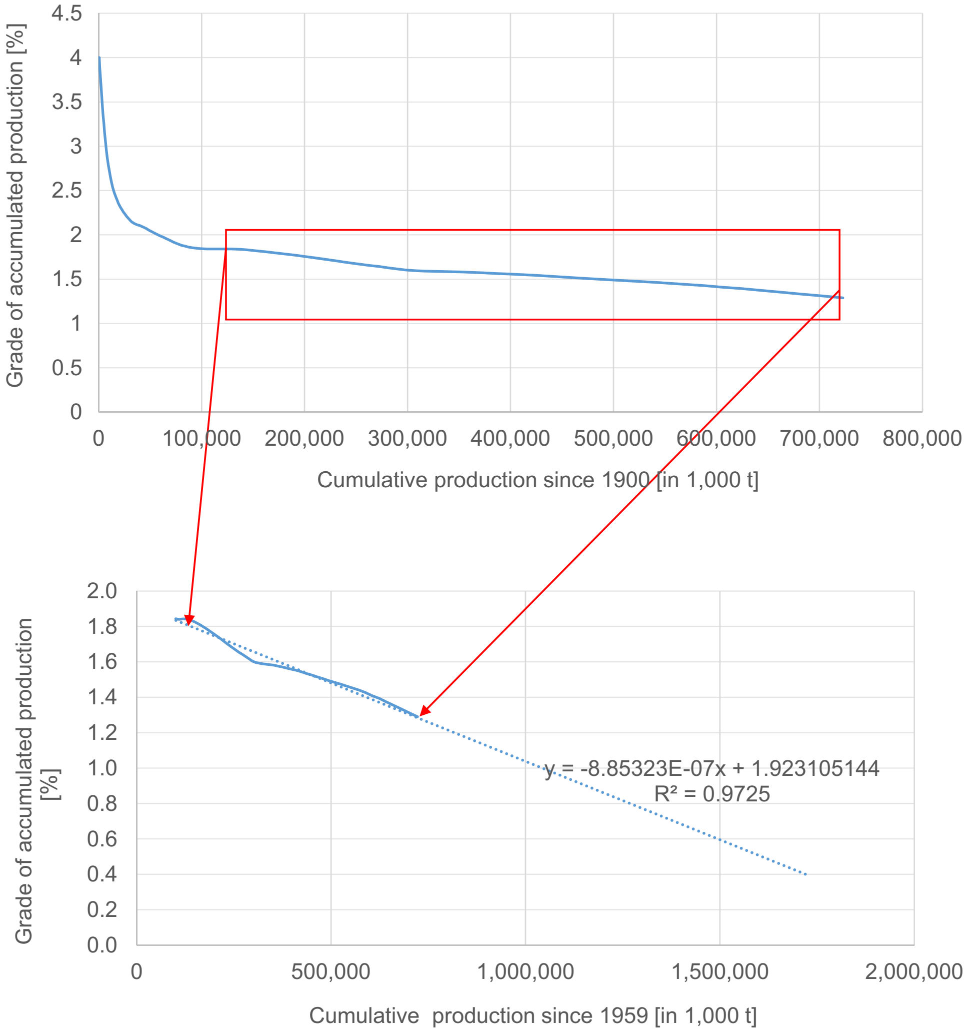


Fig. 3 Upper part — copper grade (y-axis) of cumulative production (copper from mine production) (*x*-axis) since 1900 (in 1000 t) (data: Cu grade of annual production since 1900, Schodde 2019; cumulative copper production, BGR raw materials data bank, 2021). Lower part — extrapolation of cumulative production (since 100 million t) was reached in 1959 (linear slope with a coefficient of determination of 0.9725)

tonnage of the ore. Lasky's relationship was critically "re-examined" by DeYoung Jr (1981), who pointed out that there are limits, and that the straight line—the linear relationship between accumulated tonnage and the grade of this accumulated tonnage—cannot be mathematically extrapolated to increasingly lower accumulated grades because doing so would require physically impossible negative metal values. This is logical since we are considering the grades of accumulated tonnage. Theoretically, every positive grade of prior accumulated tonnage has to be compensated by negative grades to be able to ever come close to zero grade of the accumulated tonnage, which, of course, is unrealistic. This relationship, however, as outlined above, is useful for determining the maximum amount of metal available assuming the validity of Lasky's relationship (see Appendix 3). This maximum would be 9 GT copper, an unrealistic value because no mining company would mine copper to the limit of + 0.00% Cu. Taking a realistic cutoff value, which has already been achieved at 0.06% Cu (Karlsson 2020), results in a maximum 7.5 GT copper, about 10 times the amount of copper mined thus far. Subtracting 0.76 GT Cu mined between 1900 and 2020 (see above), we arrive at a figure of 6.7 GT Cu. This would be the equivalent of close to 325 years of present production.

Interestingly, this is nearly identical to other estimates using different approaches:

- One example is Singer's (2017) estimate of 6.4 GT Cu. The method Singer (2017) used relied on global probabilistic estimates of the number of undiscovered deposits (not now known) by deposit type and the distribution of contained copper in each deposit type (4.3 GT Cu). To this number was added known reserves of each deposit type and past production for a total of 6.4 GT Cu.
- Henckens (2021) estimated 6 GT copper on the basis of the approach used by the International Resource Panel of the UNEP (UNEP 2011) for extractable global resources (EGR) in the upper 3 km of Earth's crust. It is not difficult to imagine that, in the future, the mining of copper will also take place to such a depth using remote-control

mining methods like those used in Sweden's Kiruna iron ore mine (Cai and Brown 2017; Lawson 2021).

- At a similar order of magnitude, a recent study by the US Geological Survey's Global Copper Mineral Resource Assessment Team identified undiscovered copper resources (Hammarstrom et al. 2019). As of 2015, the results of the study were 2.1 GT of copper of identified resources and 3.5 GT of undiscovered resources, for a total of 5.6 GT.

For the sake of completeness, other studies are mentioned that also arrived at a URR in the order of 10^9 t Cu, i.e., GT, but with lower numbers:

- A comparable study by Mudd and Jowitt (2018) of only identified resources resulted in 3 GT copper.
- Using various models, including peak models, Sverdrup et al. (2014) arrived at a URR of 2.8 GT, of which 2 GT remains to be mined.
- Ali et al. (2017) arrived at 2.2 GT for the URR, of which 1.6 GT remains to be mined.
- Teseletso and Adachi (2021), to be discussed below, arrived at the lowest figure, 1.34 GT.

Linear extrapolation — Teseletso and Adachi's (2021) approach

In an attempt to avoid the problem of mathematically possible—but realistically impossible— negative metal values, Teseletso and Adachi (2021) took a new approach that involved working with cumulative production. However, they did not refer to the grade of cumulative production but rather to the annual grade. The incremental view of marginal increase is used for an analysis of stepwise changes. In this way, they were able to extrapolate the grade tonnage curve to the value of their predetermined ultimate cut-off grade (COG). They also used a linear as well as an exponential interpolation of the historic production data and extrapolated it into the future. For copper, nickel, and lead, they used the last 28 years from 1991 to 2019 and the last 19 years for gold, iron, and zinc. In regard to how the extrapolation was performed, an element of arbitrariness exists, as the authors themselves stated ("Furthermore, URR was extrapolated *arbitrarily* at the given metal COG, …"; italics by the authors of the present paper). For copper, they used the exponential inter- and extrapolation and arrived at a URR of 1.34 GT copper at a predetermined ultimate cutoff (COG) of 0.2% Cu. Because of the element of arbitrariness, in the following exemplary case of copper, we use both linear and the exponential inter- and extrapolation (interpolation = for given data finding a function of the form $y = a + b\,x$ (if linear) or $y = a\,x^b$ (if exponential); extrapolation = continuation of interpolated functions).

We disagree, in particular, with the Teseletso and Adachi (2021) paper's consideration of the annual change. By considering the incremental grade change of cumulative production, the averaging effect is lost, while the impact of metal prices immediately becomes noticeable. This can be seen clearly by comparing the real value of the copper price and the grade development (change in average copper grade mined) as depicted in Fig. 2. The average grade did not decrease but rather increased from 1990 to 1994 after the nominal and real price had been in a relative trough.

Figure 2 illustrates the general trend of a linear decline with three bumps up, with the last bump showing a *convex* descent. This means the later one starts to linearly interpolate, the steeper the gradient will be, i.e., the lower the cumulative production at a predetermined COG will be (Appendix 4). In Table 1, moving 28 years' steps are taken for comparison. This number was chosen analogous to the 28-year time span of Teseletso and Adachi (2021). The steepening of the grade curve becomes even more obvious in Table 1 in the third column, considering the grade differences of the cumulative production, which evens out the annual fluctuations due to metal price movements.

Table 1, in connection with Fig. 2, clearly shows a continuous trend of increasing grade differences, i.e., decreasing grades with increasing production at more or less constant real prices. This suggests that increasingly lower grades are not mined because they *must* be mined to fulfill demand but rather because they *can* be mined due to technological advances, i.e., a higher tonnage can

Table 1 Copper grade differences for the 28-year period 1950–2018 and corresponding cumulative tonnage (data sources Schodde 2019; BGR 2021)

28-year period in 5-year steps	Difference in copper grade of global production (source: Schodde 2019)	Difference in copper grade of cumulative production since 1900	Accumulated copper production during period in million tonnes
1950–1978	0.15% Cu	0.19% Cu	143.0 mt
1955–1983	0.36% Cu	0.20% Cu	168.8 mt
1960–1988	0.64% Cu	0.24% Cu	192.8 mt
1965–1993	0.35% Cu	0.26% Cu	215.3 mt
1970–1998	0.31% Cu	0.26% Cu	241.3 mt
1975–2003	0.29% Cu	0.25% Cu	272.7 mt
1980–2008	0.23% Cu	0.24% Cu	309.9 mt
1985–2013	0.44% Cu	0.25% Cu	351.9 mt
1990–2018	0.88% Cu	0.30% Cu	406.9 mt

be mined at the same cost. This is the conclusion reached earlier by other authors including Rötzer and Schmidt (2018), Schodde in Wellmer et al. (2019, p. 76, Fig. 3.22), and West (2020). In the opposite case, prices in real terms would also have increased.

The generally convex course of the grade curve in Fig. 2 has the consequence that the later the interpolation starts, the lower the accumulated tonnages will be when extrapolating the trend (see Appendix 4) and, in general, the higher the coefficient of correlation will be. This certainly contradicts the geological experience that, with lower grades, tonnages increase nonlinearly, meaning the lower the grade, the broader the resource base. This leads to the conclusion that assuming one can extrapolate annual grade trends produces paradoxical results.

As a concrete example, the bending of the grade curve of production in Fig. 2 in 2011/2012 happened at about 0.6 Gt cumulative production since 1900 (BGR 2021) as a reaction to the price increase. This illustrates that lower grades *can* be mined due to a positive price development and does not indicate an argument for the depletion of resources. There is no geologic reason that the grade curve at a particular stage cannot bend toward the opposite direction and flatten out.

Discussion

The results of the model developed by Teseletso and Adachi (2021) and our two models are summarized in Table 2.

It is beyond our ability to predict to what extent and for what functions mined copper will be needed in a few hundred years. Nor can we know the price, i.e., the economic value, of a specific mineral in a socio-technological environment in a few hundred or even thousand years. We mention these long time frames—for example, in relation to the bioessential element phosphorus—because the concept of intergenerational justice demands that we do and calls for further discussion, particularly as there is an asymmetric relationship with future generations (Persson and Savulescu 2019; Scholz and Steiner 2022). While we can look back, we cannot see several centuries ahead. We do not know how far into the future humankind will continue to exist on Earth, what metal resources will be needed, or the extent to which such resources will be geotechnically accessible. These unknowns result in challenging and difficult moral questions that are likely to have different answers from the perspectives of different cultures. And although these critical questions and topics far exceed the scope of this paper, URRs represent a critical concept in this context.

The URR describes the amount of a minerals, in this case, copper, that humankind has mined in the past and that can be mined economically in the future at a reasonable cost that does not threaten the viability of societies. We should note that these costs include the costs of environmental degradation, which increase nonlinearly with declining cutoff grades (Koppelaar and Koppelaar 2016; Priester et al. 2019; Rötzer and Schmidt 2018). The history of human development has been associated with increasing resource consumption for which the availability of mineral raw materials has been and will continue to be of critical importance. Against this background, a *horror vacui* of approaching a *lack of minerals (in a relatively near future)* is a significant concern for the future of humankind in the opinion of certain circles of the population or scientists who have not studied the dynamics of reserves in detail. However, taking into account that resources are geoeconomic entities, atoms do not disappear and the store of copper in the technosphere constantly increases that can at least in part be recycled, it is highly improbable that the world will run out of copper.

It is impossible to make an exact prediction about (mined) future mineral-resource consumption, yet the URR is not a "completely unknown unknown." We have data, knowledge, models, and theories about the past that allow us to make certain statements about future availability—at least on the order of magnitude—with the caveat of totally new technological developments, the unknown unknowns. However, all these models share one problem: They are significantly incomplete and, thereby, incorrect. But some models are better than others and, thus, more useful for building an understanding of a challenging problem. Moreover, we have to remain aware that most of them work with ceteris paribus assumptions regarding most aspects of the environment and few assumptions about what information is included in certain variables, the relationships between variables, and the fact that few make

Table 2 Models for estimating remaining URR by extrapolating grades

Model	Grade	Tonnage	Correlation	Results
Teseletso and Adachi (2021)	Annual since 1991	Cumulative tonnage since 1991	Semi-logarithmic: –Grade linear –Cumulative tonnage logarithmic	URR: 1.34 GT Cu Assumption of predefined ultimate cutoff grade of 0.2% Cu
Model 1: best correlation $R^2 = 0.97$	Grade of cumulative tonnage since 1959	Cumulative tonnage since 1959, i.e., 85% of all Cu mined historically	Linear: –Grade linear –Cumulative tonnage linear	URR: 0.33 GT Cu
Model 2: based on Lasky's relationship	Grade of cumulative tonnage since 1900	Cumulative tonnage since 1900, i.e., 98% of all Cu mined historically	Semi-logarithmic: –Grade linear –Cumulative tonnage logarithmic $R^2 = 0.94$	URR: 6.7 GT Cu Assumption of cutoff of 0.06% Cu, lowest cut-off presently realized

assumptions about changes in the environment (e.g., with relation to availability or costs of energy, water, or demand and, therefore, the future costs of a specific mineral itself). The publication of the paper by Teseletso and Adachi (2021) provides us with an opportunity to test whether the observed declining grades of copper and assumed relationships between grade and tonnage mined can be a guide to the future for filling the *horror vacuum cuprum*.

We have approached the *horror vacui cuprum* with two types of models in comparison to Teseletso and Adachi's (2021) model; all three models work with cumulative production in place of time. However, in contrast to Teseletso and Adachi (2021), who used data only from 1991 onward, we used the longest-possible data series, starting in 1900. Like Teseletso and Adachi (2021), we have used linear and semi-logarithmic extrapolations. Whereas our two models work with grades of cumulative production vs. cumulative production alone, Teseletso and Adachi (2021) used annual grade vs. cumulative production (see Table 2).

Our first model began with the assumption that the better the correlation, the more trustworthy the extrapolation. The linear correlation of grades of cumulative tonnage as opposed to cumulative tonnage since 1959 shows a significantly high degree of correlation with $R^2 = 0.97$ (see Fig. 3). Our calculation for the world data amounted to an estimate of the URR of 1.09 GT copper, of which 69.7% has been consumed in the last 120 years. Only 0.33 GT would be left, which certainly may cause a *horror vacui* concern with respect to copper. Given an average mine production of 0.021 Gt t/a of 2021 (Flanagan 2021), this would mean the possibility of a rapid end to the copper supply in less than 16 years—a highly improbable scenario and one that sharply contradicts the most reliable reserve forecast of the US Geological Survey (Hammarstrom et al. 2019).

The second model is based on Lasky's (1950) much-tested and "re-examined" relationship, which states that a linear decrease in grade is related to a logarithmic increase in the cumulative tonnage of the ore. We also introduce and discuss an estimate of the lowest economically mineable ore grade. Here, an estimate of the lowest cutoff grade of 0.06% Cu is taken; this estimate is based on a successful Swedish mine that currently plans with a measured concentration of 0.22% Cu (Karlsson 2020). Our model is based on production since 1900, meaning 98% of all the copper ever mined by humankind. Actually, this modeling also provided a very good curve fit (see Fig. 5 in Appendix 3) of the logarithm of cumulative tonnage against the ore grade of the cumulative tonnage with a coefficient of determination of $R^2 = 0.94$. This resulted after correcting for past production of a remaining resource of 6.7 Gt Cu, which is in the same range of between 5 to 7 Gt Cu as estimates by Singer (2017), the US Geological Survey (Hammarstrom et al. 2019), and Henckens (2021).

Applying Teseletso and Adachi's (2021) model to our longer-range time series, we can show that the later the extrapolation begins, the lower the predicted URR; this applies to linear as well as semi-logarithmic extrapolation. Moreover, it certainly contradicts the observation that with lower grades that *can* be mined—as opposed to *must* be mined—despite constant real prices in the long term, the resource base is enlarged rather than restricted (Schodde 2019).

A differentiated analysis showed that the (absolute) differences of ore grades are increasing (see Table 1), meaning that the decline of ore grades is steepening. Between 1990 and 2018, we were facing a decline of ore grades of 0.88%, and the global average ore grade in 2018 was 0.56% (Schodde 2019). Just by relating these two numbers, we may learn that mining will enter a new age, whereby rock with very low concentrations will become the subject of mining in many places. This implies an increase in the total volume of ores and waste mined and will undoubtedly call for an extensive environmental evaluation. It is the task of good scientific models to reveal such trends and to develop proper knowledge and technological means that may compensate for this.

We argue that the cumulative production and ore grade are variables of a special value. They comprise the historic data and even out (widely) idiosyncratic, short-term biases due to relatively brief geopolitical crises, economic crises, etc. In addition, they are dynamic in the way that the major trends of mineral consumption due to technology development, population demand, and long-term lifestyle changes as well as geo-economic properties are included. One could say that due to long-time integration, they are curves of a "historic memory." The variables of cumulative production and ore grades are, thus, an underlying principle of geoecological modeling (DeYoung Jr 1981; Gerst 2008; Tilton 2018; Yaksic and Tilton 2009). They cannot be extrapolated, which Northey et al. (2014) earlier cautioned against, but via the equation for Lasky's relationship, the maximum amount of extractable copper can be estimated. Recalling once again the words of British Chief Economist Sir Alexander Cairncross in 1952, the trend will certainly bend.

Final comments

Would it not be wiser to accept that the longer-term future cannot be projected (West 2020) or can be forecast only to a certain degree, and to observe the reserve/production-ratio as an early warning indicator if the ratio continuously decreases (Scholz and Wellmer 2013)? Speaking of the future, the famous German philosopher Hannah Arendt (1906–1975) described, "the unpredictability of the future, this fog of the uncertain and unknowable, which the act of promising illuminates and disperses here and there …" (Arendt 2007), thus underscoring the uncertainty and only once in a while offering glimpses into the future we will have to live with. An example of such a glimpse into the future in relation to the field of raw materials might be the history of the conversion of nitrogen in the air to fertilizers. In 1898, the incoming president of the British Academy of Sciences, Sir William Crookes, charged the community of chemical researchers with the task of inventing "chemical manure" to avoid starvation due to lack of natural nitrogen fertilizer (Hager 2008), a problem solved by the Haber-Bosch process in 1913 (Erisman et al. 2008).

But despite the uncertainty we face, we have the knowledge that Earth holds vast geopotential (Fig. 4) from which reserves can be generated with humankind's most important resource—creativity (McKelvey 1972; Meinert et al. 2016) and the circular economy can certainly be improved. As stated earlier, there will always be "unknown unknowns" that take the form of technological breakthroughs that no one can predict today (Popper 1988). We cannot predict when these might appear, but we can be certain that unexpected "black swans" and technological breakthroughs as unknown unknowns will occur (Taleb 2007). Just to speculate about breakthroughs with the potential to have an immense impact on copper consumption, there might be developments in the temperature range of superconductivity or in carbon nanotube technology (Pasquali and Mesters 2021). These nanotubes have properties that could make them substitutes for copper in numerous applications. Today, they are far too expensive, but with the possibility of cost decreases due to rapidly increasing carbon production by producing hydrogen from natural gas, which is far more effective than electrolysis, who knows what the future will hold? Thus, forecasting is uncertain and should be accompanied by conservative precautionary thinking for securing resilient future development that properly acknowledges what is known. The general trend of declining copper grades with over the long run constant copper prices in real terms, i.e., the grade decrease was compensated by technological improvements, indicates the creativity potential also for other metals in future.

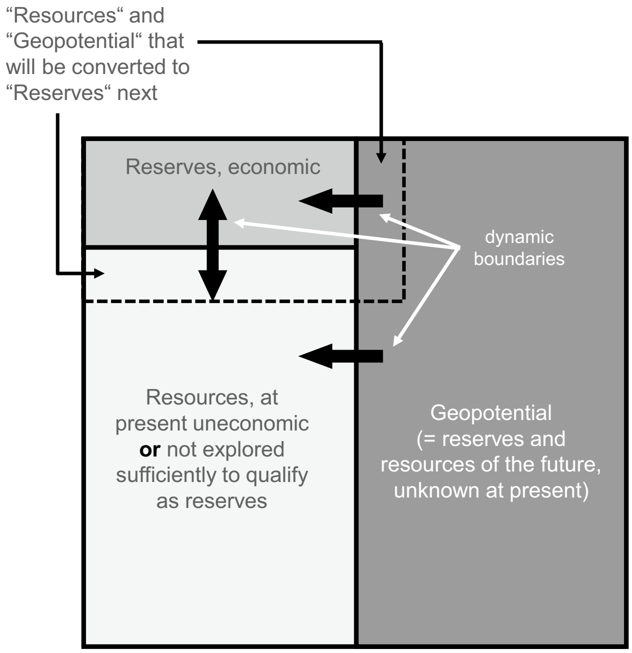


Fig. 4 Total Resource Box (Scholz and Wellmer 2021, amended from Scholz et al. 2014); x-axis: general trend of increasing knowledge, going from left to right; y-axis: general trend of increasing economic viability going from bottom to top

Appendix 1

Calculating cutoff grades of multi-element mines

In multi-element mines, cutoff grades are usually calculated via metal-equivalents, i.e., the revenue contributions of each element are brought to a common denominator, which normally is the revenue of the main revenue earner (see Wellmer et al. 2008, p. 50–52). For this purpose, the revenues of each element have to be calculated via the calculation of the net smelter return (NSR) (Wellmer et al. 2008, p. 72–77). For these calculations, metal prices and in addition smelting and refining charges have to be assumed and smelting losses considered. These somehow complicated calculations can be simplified in general reflections, working with net-smelting-return-factors, the NF-factors (Wellmer et al. 2008, p. 765, Table 7.1). The Aitik mine is taken as an example:

Karlsson (2020) gives the following data (Table 3) for the Aitik mine:

Now the calculation of the NSR. Because gold and silver occur as bound to copper minerals, we can assume the same recovery for copper, gold, and silver and omit the recovery in the mill for our calculations.

1. For copper: 0.22% Cu means 2.2. kg of copper, i.e., a value of 14.52 US$/t. The NF-factor for Cu is 0.65, i.e., the NSR for 0.22% Cu is $14.52 \times 0.65 = 9.44$ US$/t.
2. For Ag: 1.2 g/t has a value of 0.66 US$/t, the NF-factor for Ag is 0.95, i.e., the NSR for Ag is 0.62 US$/t.
3. For Au: 0.14 g/t has a value of 5.85 US$/t, the NF-factor for Au is 0.95, i.e., the NSR for Au is 5.56 US$/t.

Table 3 Grades and planning prices 2020 (Karlsson 2020)

Metal	Grade	Planning price
Copper	0.22%	6600 US$/t
Silver	1.2 g/t	17 US$/oz
Gold	0.14 g/t	1300 US$/t

This means the total NSR of the mine is 9.44 + 0.62 + 5.56 = 15.62 US\$/t, i.e., 60% of the revenue comes from copper and 40% from the precious metals.

From the NSRs, now metal-equivalents can be calculated.

It is reasonable to assume that this ratio also applies to the cutoff of 0.06% Cu, i.e., to the value of 0.06% Cu; the relative value of the precious metals has to be added to get a monetary cutoff value.

Appendix 2

Determination of maximum metal according to the relationship of Fig. 3

The linear relationship starting with a cumulative production of 100,000 t (BGR 2021) in Fig. 3 is as follows:

$$y = -8.85323 \times 10^{-7} x + 1.923105144 \tag{1}$$

The total metal content

$$\begin{aligned} M_{\mathrm{t}} = y \times x &= (-8.85323 \times 10^{-7} x + 1.923105144) \times x \\ &= -8.85323 \times 10^{-7} x^2 + 1.923105144 x \end{aligned} \tag{2}$$

The maximum metal content can be determined via the 1. First derivation:

$$M_{\mathrm{t}}{}' = -17.6 \times 10^{-7} x + 1.923105144 \tag{3}$$

To find the maximum, M_{t}' has to become 0, i.e.,

$$M_{\mathrm{t}}{}' = 0. \tag{4}$$

Then follows:

$$x = 1.09 \times 10^{6} \tag{5}$$

The unit of x is 1000 t, so the solution is 1.09 GT Cu.

Appendix 3

Determination of maximum metal according to Lasky's relationship

The relationship between the accumulated production and the grade of this accumulated production is as follows (Fig. 5):

$$y = -0.351603 \ln x + 5.98883697 \tag{6}$$

The total metal content

$$M_{\mathrm{t}} = y \times x = (-0.351603 \ln x + 5.98883697) \times x \tag{7}$$

The maximum metal content can be determined via the 1. Derivation:

$$M_{\mathrm{t}}{}' = -0.351603 \ln x - 0.351603 + 5.98883697 = -0.351603 \ln x + 5.63723397 \tag{8}$$

To find the maximum, M_{t}' has to become 0, i.e.,

$$M_{\mathrm{t}}{}' = 0. \tag{9}$$

Then follows:

$$\ln x = 16.03 \text{ or } x = 9,183,802. \tag{10}$$

The unit of x is 1000 t, so the practical solution is 9 GT Cu.

This, of course, is an unrealistic value because no one would mine copper to a cut-off grade of 0% Cu. If one uses the above Eq. (6) to calculate the grade for 7.5 GT, this would be 0.42% Cu, the grade for 7.6 GT 0.41% Cu, meaning that an incremental grade in the cumulative production from 7.5 to 7.6 GT would be 0.06% Cu (not considering by-product credits), which is the lowest cut-off grade achieved thus far by the Aitik Mine in Sweden (Karlsson 2020).

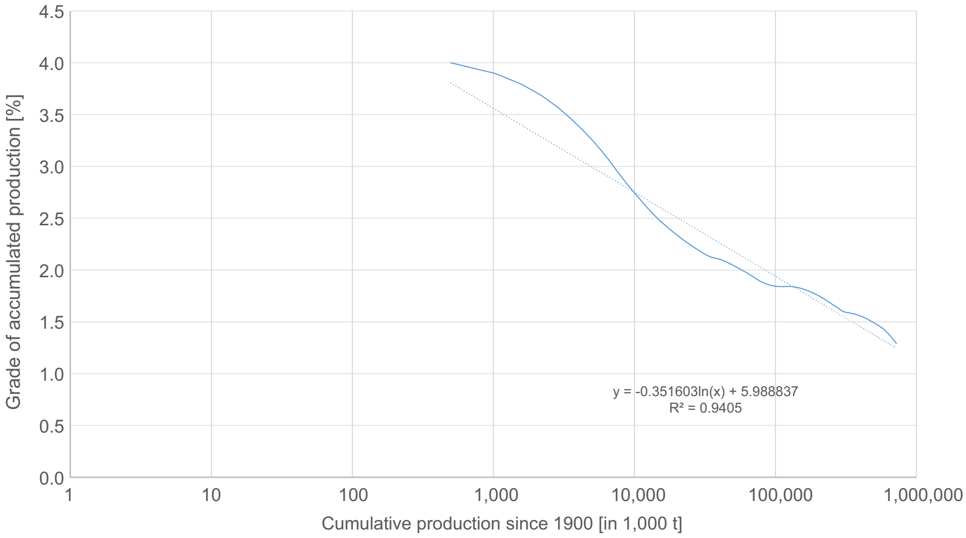


Fig. 5 Linear grade of accumulated tonnage against logarithmic of accumulated tonnage since 1900, showing a coefficient of determination of $R^2 = 0.94$ since 1900, i.e., 98% of all copper mined throughout history

Appendix 4

Extrapolation of grade-cumulative production curve for different time spans

In the following, the exponential and linear courses of the grade-cumulative tonnage curves are interpolated and then extrapolated to a value of 0.2% Cu for the following time spans:

- 1900–2020
- 1918 (end of WWI)–2020
- 1959–2020
- 1991–2020
- 2000–2020

The reasons for selecting these time spans are as follows:

1900–2020: data availability of world copper grades (Schodde 2019).

1918–2020: end of WWI, break in the trend of copper price development, and a new price plateau (Fig. 1).

1959–2020: start of the highly linear grade development of cumulative production (coefficient of correlation of 0.9725) (Fig. 3).

1991–2020: Teseletso and Adachi's (2021) time span for Cu, Ni, and Pb.

2000–2020, 1991–2020: Teseletso and Adachi's (2021) time span for Au, Fe, and Zn.

(The selection of the time spans is not influenced by breaks in the curves of Figs. 6 and 7, Table 4.)

If one omits the time span from 1900 but starts in 1918, the general trend is clearly observed that the shorter the time interval, the lower the expected tonnage up to a predetermined cutoff of 0.2% Cu and, in general, the better the coefficient of determination. The values before 1918 are at the older higher price plateau (see Fig. 1 and Wellmer 2022).

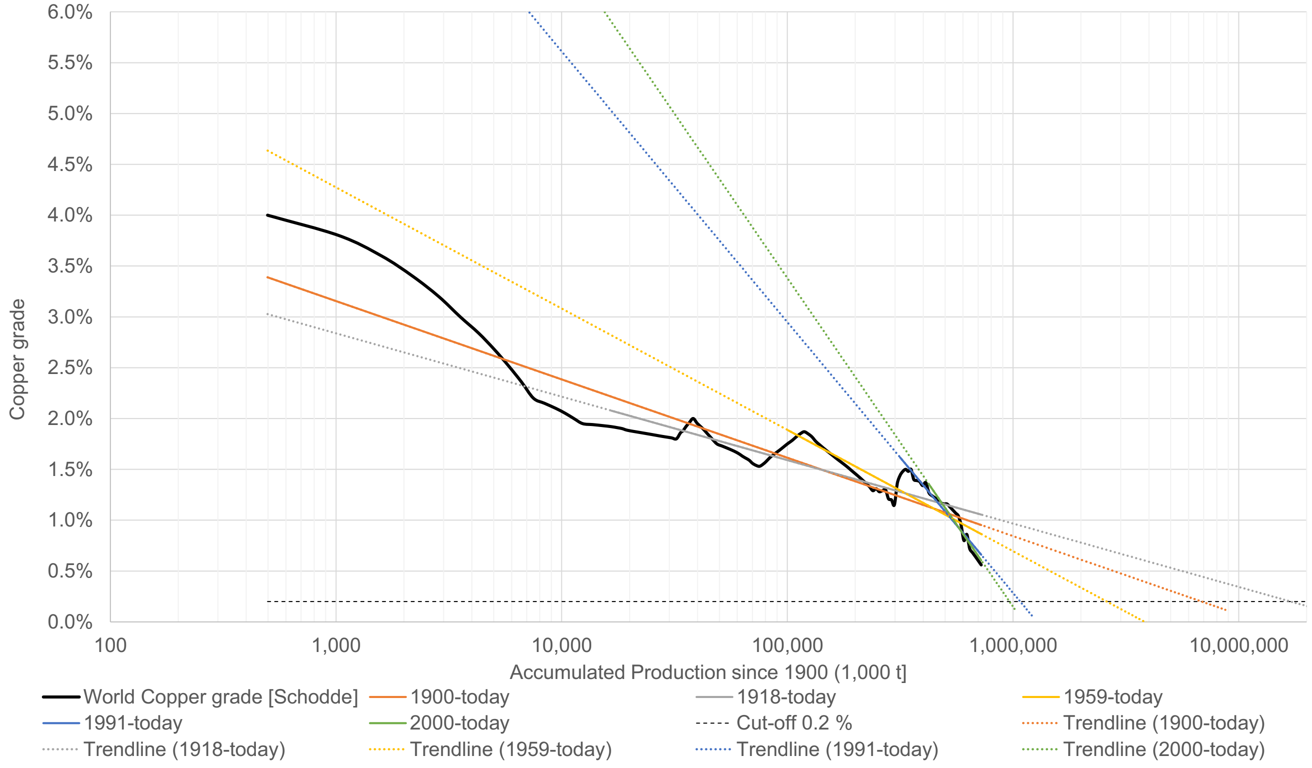


Fig. 6 World copper grade against cummulative tonnage semi-logarithmically inter- and extrapolated (data: Cu grade of annual production since 1900, Schodde 2019; cumulative copper production, BGR raw materials data bank, 2021)

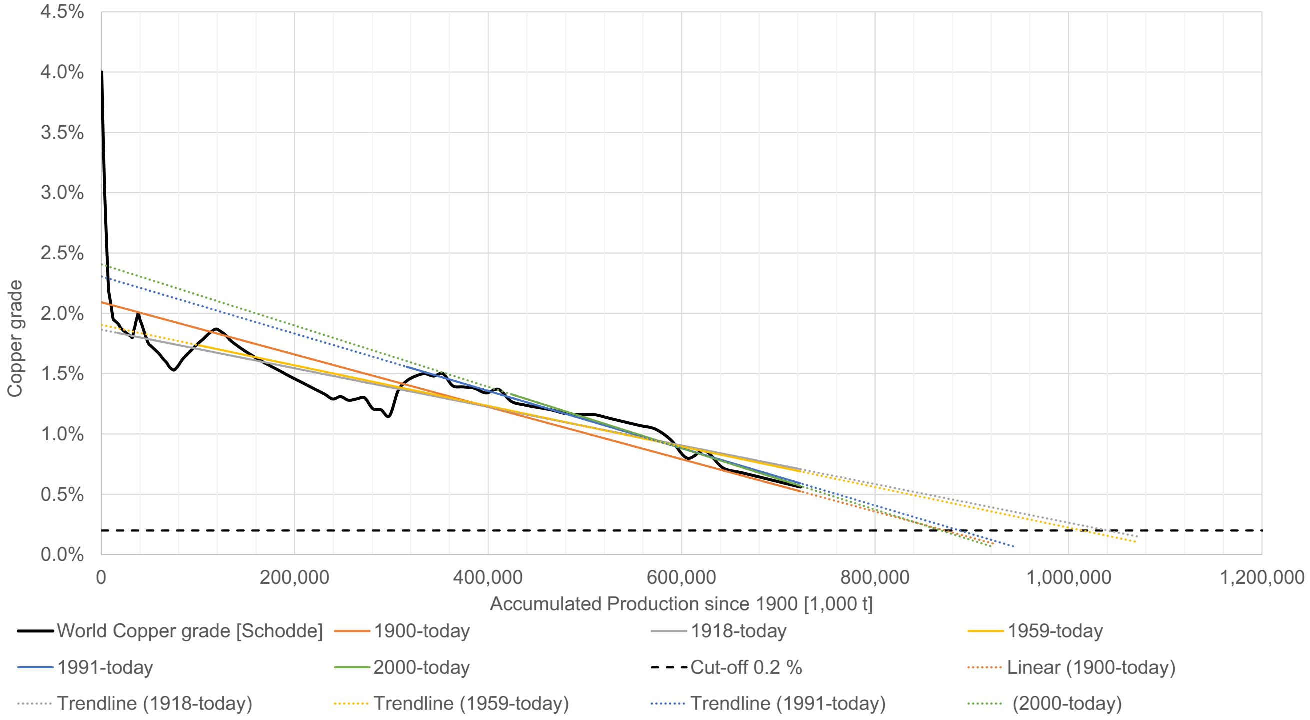


Fig. 7 World copper grade against cummulative tonnage linearly inter- and extrapolated (data: Cu grade of annual production since 1900, Schodde 2019; cumulative copper production, BGR raw materials data bank, 2021)

Table 4 Evaluation of Figs. 6 and 7

Time span	Logarithmic interpolation Coefficient of determination	Logarithmic interpolation Intercept at 0.2% Cu	Linear interpolation Coefficient of determination	Linear interpolation Intercept at 0.2% Cu
1900–2020	0.8537	6,844,909	0.5533	872,415
1918–2020	0.7566	16,982,199	0.8779	1,040,594
1959–2020	0.8226	2,606,002	0.8539	1,014,031
1991–2020	0.9437	1,075,758	0.9731	887,478
2000–2020	0.9292	966,131	0.9543	868,516

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Declarations

Conflict of interest The authors declare no competing interests.

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