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Measurement of mineral supply diversity and its importance in assessing risk and criticality

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ABSTRACT

The diversity of supply, or conversely its concentration, has become one of the key factors in measuring the criticality of minerals. The premise is that if supply is limited to just a few major suppliers the risk of supply disruption is increased, although in reality it depends on many more factors that can be complicated to measure. In addition, there is a wide range of possible methods for measuring supply diversity or concentration, some involving the use of complicated formulas, which can easily become bewildering to the non-statistician. Often the intricacies of their use, the data inputs and sources, and the resulting indices, are not fully understood with the consequent risk of misinformed decisions being based upon them. This paper examines a selection of the available indicators, discusses their limitations and illustrates how a simple index, such as concentration ratio, can be as informative as more complicated approaches. Further, it uses the trends in supply diversity for five minerals (fluorspar, lithium, coal, copper and nickel), taken at decadal intervals over the past century, to demonstrate that a snapshot index taken at a single point in time does not accurately determine whether the level of supply concentration is a cause for concern.

1. Introduction

The concept of raw materials 'criticality' is not new (see Glöser et al., 2015 for a useful summary, particularly of the 20th and 21st centuries) but it has become one of the most frequently discussed topics in recent times with, for example, the number of papers on the subject published in 2000–2011 more than treble that of 1990–1999 (Speirs et al., 2013). The dictionary definitions of the term 'criticality' state that these materials are those of "highest importance", which implies a usefulness that would make them almost essential. In recent years materials have been described as 'critical' usually because there is some perceived risk that they might become scarce or not routinely available for modern technology. Graedel et al. (2014) provide a useful introduction to the subject and describe some of the associated complexities.

A significant number of studies have been conducted to assess whether a range of metals or materials can be defined as 'critical', each using different sets of criteria and diverse methodologies (e.g. National Research Council, 2008; European Commission, 2010, 2014 and 2017; British Geological Survey, 2015; Graedel et al., 2015; Gemechu et al., 2015; McCullough and Nassar, 2017). However, one aspect that is common to all these studies is an assessment of 'supply risk' or the 'risk of supply disruption' and the assessment of this factor always includes some measure of 'supply concentration' (Speirs et al., 2013). The premise is that if the supply of a material is limited to a few countries the risk of supply disruption is increased, although in reality the situation is much more complicated than this.

The concentration of the supply of a material to a few countries can cause prices to rise or become more volatile as competition for the material increases and concerns grow about possible supply constraints (De Groot et al., 2012). Rising or volatile prices and concerns about supply restriction may also result in consuming industries seeking to make significant changes such as material substitution, redesign of products to use less of the material or increased use of alternative sources e.g. from recycled products (Graedel et al., 2014). These kinds of industrial changes can have serious consequences for costs and profitability (McLelland et al., 2014; Hendricks and Singhal, 2005). Some of the 'criticality' studies have attempted to incorporate market volatility into the assessment of whether a mineral is critical (e.g. McCullough and Nassar, 2017). There are also a number of actions that may be taken at government level such as funding research to improve processing technologies, supporting exploration or legislation aimed at improving recycling rates (Graedel et al., 2014).

Most of the 'criticality' studies that have been carried out should be considered as providing an 'early warning' of potential problems. The actual supply of materials is a complex web of interconnected companies and countries with a wide variety of influencing factors, which requires more detailed analysis if a full understanding of the system is

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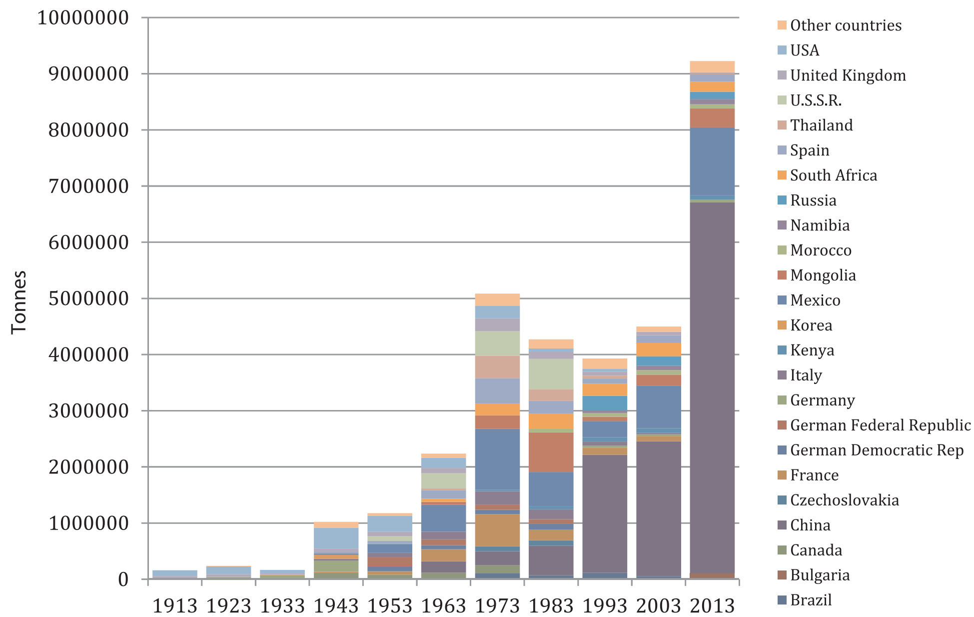


Fig. 1. Global production of fluorspar at decadal intervals from 1913 to 2013 (data from BGS, 2017).

to be obtained (McCullough and Nasser, 2017).

In the context of global studies 'production' is used a proxy for 'supply' and potential supply from stockpiles is ignored. For clarity, the term 'production concentration' is the direct opposite of 'production diversity' (Acar and Bhatnagar, 2003).

In many cases the measure used for 'production concentration' is the Hirschman-Herfindahl Index (HHI), which is described more fully later in this paper. But the use of HHI has its complexities and there are also other measures that can be used to make comparable assessments. Furthermore, it could be argued that it is not the production concentration itself that is the issue in determining a mineral's criticality but rather the potential geopolitical issues associated with the supply concentration. Statistical measures also exist that quantitatively measure dominance in a market and, as this paper demonstrates, these can also be applied on a global scale.

This paper uses a dataset from the British Geological Survey (BGS) known as "World Mineral Statistics" to examine the diversity or concentration of production for five mineral commodities: fluorspar, lithium, coal, copper and nickel. This dataset contains over 100 years of annualised production data by country and consequently enables the examination of how mineral supply diversity has changed over the last century. A range of established statistical measures are presented and compared in order to draw conclusions about their usefulness and usability in the context of mineral commodities.

The World Mineral Statistics dataset commenced with the publication of "The Mineral Industry of the British Empire and Foreign Countries, Statistical Summary (Production, Imports and Exports)" by the Imperial Mineral Resources Bureau in 1921 (IMRB, 1921). This first volume, containing statistics for 43 mineral commodities for the years 1913–1919 listed by country worldwide, was the direct result of supply restrictions incurred during the First World War. The Imperial War Conference of 1917 recommended the formation of the Bureau, which received a Royal Charter in 1919, expressly for the purpose of collecting and disseminating information relating to mineral resources for the benefit of defence and industry (Imperial War Conference, 1918).

Over the subsequent decades the annual publication incurred many changes, not least the removal of references to the "British Empire" and the somewhat disparaging "Foreign Countries" in the 1950s. Many countries have become unified, dissolved into constituent parts or adopted new names, reflecting 100 years of social and political change. The number of commodities covered by the dataset has increased such that recent volumes, now called "World Mineral Production", contain statistics for more than 70 mineral commodities (e.g. Brown et al., 2017). Metrication of units occurred in the early 1970s followed by the introduction of a storage database in the early 1990s and the digital dissemination of the statistics via an online archive in 2012 and data download tool in 2014.

Today, the World Mineral Statistics dataset continues to be maintained by the BGS and "World Mineral Production" is still published annually. The entire series of publications have been scanned and made available online and the statistics from 1970 onwards can be downloaded directly into MS Excel. The dataset itself is almost unique globally, with only the United States Geological Survey having one that is comparable in terms of the numbers of years encompassed.

2. Supply statistics

The five commodities discussed in this paper were selected on the basis that they would likely reveal different levels of production concentration. These include commodities where supply appears to have become more concentrated over time, with one producer believed to be dominant (fluorspar, lithium) and commodities for which supply appears to have become more diverse in recent years, albeit still with one notably large producer (coal, copper). Production of the fifth commodity (nickel) does not appear to be significantly concentrated in any single country. The data presented here are based on 'mine production' of these commodities (reported as metal content for lithium, copper and nickel) and are shown against the country in which they were extracted.

Due to the size of the dataset, sample intervals of 10 years have been used to display and assess how the output of producing countries have changed with time. It is assumed that these sample years are reflective of the entire decade from which they are taken, but these samples do not represent an amalgamation of the entire decade and it is possible that additional countries may have started and then ceased production in between the selected years. Countries producing smaller quantities of the commodity have been grouped as 'Other countries' in Figs. 1–5 to improve the clarity of the graphs. The data used to generate the graphs in this paper are available in the supplementary information (Tables S1 to S10) and, specifically, the total numbers of producing countries in any sample year are shown in Table S6.

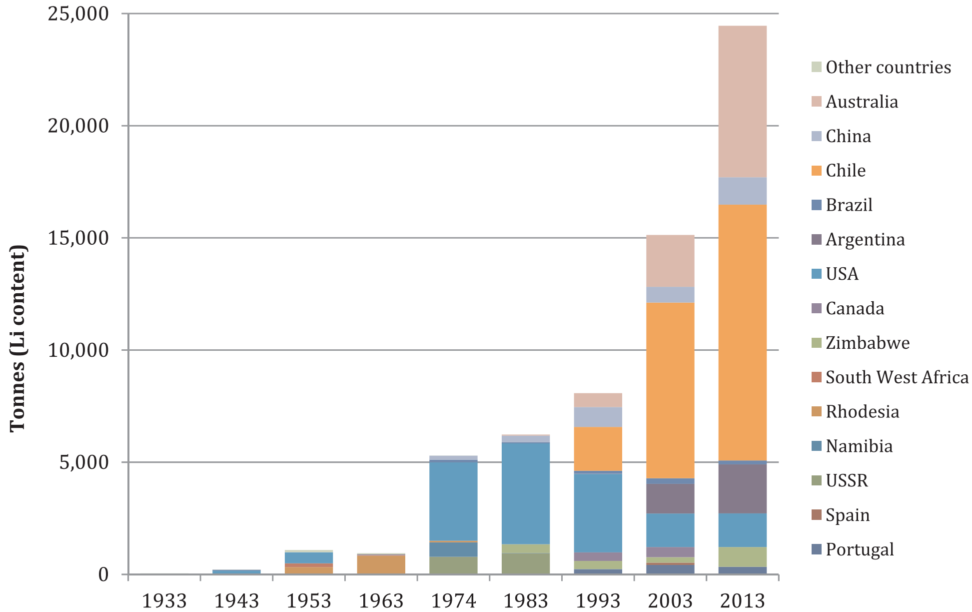


Fig. 2. Global production of lithium at decadal intervals from 1933 to 2013 (data from BGS, 2017).

2.1. Fluorspar

Fluorspar is an industrial mineral predominantly consisting of calcium fluoride, also known as fluorite (CaF_2) (Bide, 2011; Fulton and Miller, 2006). As shown in Fig. 1, in 2013 China was the largest producer of fluorspar with 72% of the world's total output, but in 1963 China only produced 9% of the world's total and Mexico was the largest producer with 22% (Table S1). However, China's growing dominance becomes clear from 1993 because, although total global production reduced compared to 1983, China's share of production increased to 53%.

2.2. Lithium

Lithium is a soft, highly reactive alkali metal with excellent electrical conductivity (Brown, 2016; Evans, 2014). The global production of lithium was first recorded in the World Mineral Statistics dataset in 1925 and was absent from the editions covering the early 1970s. Nevertheless, as demonstrated by Fig. 2, the data show that the world's total output has increased dramatically since 1993. The figures are shown on a tonnes lithium content basis in order that comparison can be made between two contrasting production sources. Prior to the late 1960s all lithium was extracted using conventional mining and processing techniques from ores containing minerals such as spodumene, petalite, lepidolite, amblygonite and eucryptite. However, since 1966 another source of lithium has been utilised in the form of brine waters from beneath salt pans, or salars, at a significantly lower production cost. Lithium from this source was first extracted in California, USA and resulted in a noticeable increase in production as shown in the data from 1974 onwards. Subsequently brine waters have been utilised for lithium extraction in the Andes of Chile and Argentina, as evident in the later decades on Fig. 2. Chinese production is derived from both sources. Production by conventional mining has generally declined in most countries, with the exception of Australia where the

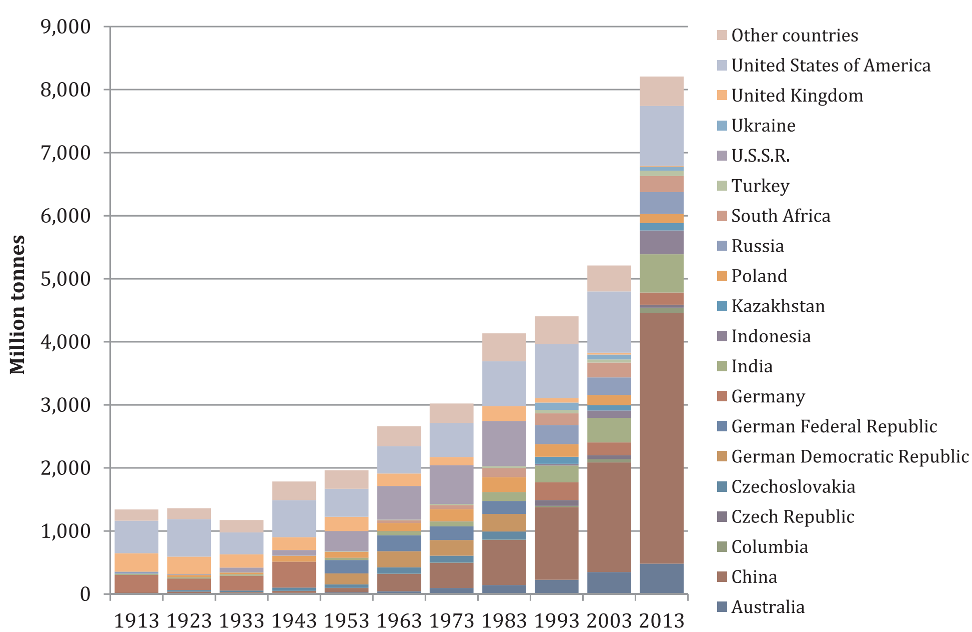


Fig. 3. Global production of coal at decadal intervals from 1913 to 2013 (data from BGS, 2017).

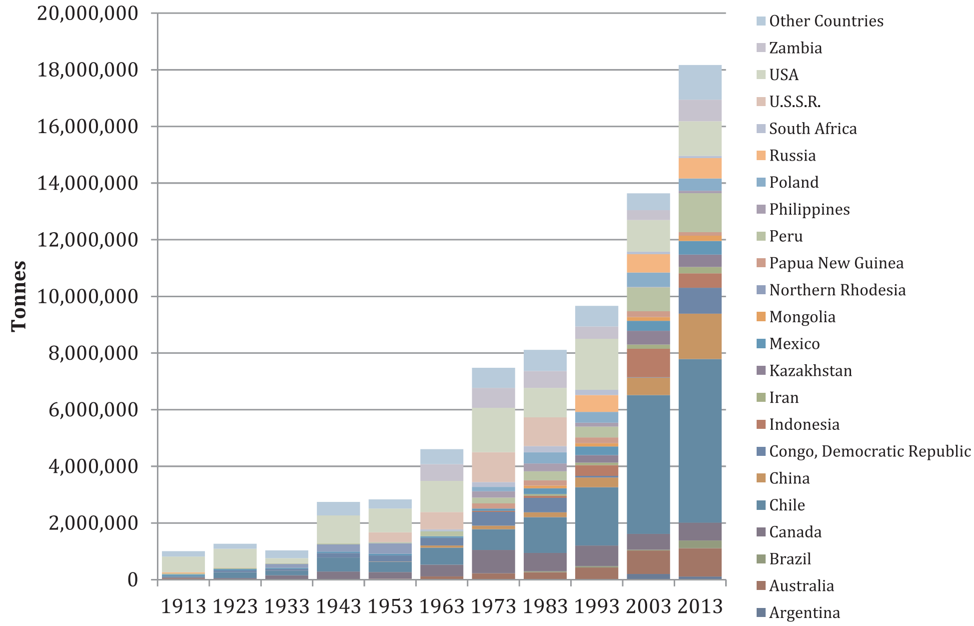


Fig. 4. Global mine production of copper at decadal intervals from 1913 to 2013 (data from BGS, 2017).

commencement of lithium production in 1983 from a large, relatively high-grade deposit has sustained production growth.

In 1933 the world's largest producer was Portugal with 78% of global production. This was followed by several decades when the USA was the leading producer with up to 72% of the global total in 1983. Since then Chile and Australia have overtaken the USA and in 2013 Argentina also produced more lithium, as shown in Table S2.

2.3. Coal

Coal is an energy mineral, comprised of lithified plant remains with mineral impurities and water (Kendall et al., 2010; Speight, 2013). As shown in Fig. 3, some of the most notable changes over the last century are the decline in output from the United Kingdom from 292 million tonnes in 1913 to less than 13 million tonnes in 2013, the emergence of the Soviet Union as a major coal producer between the 1950s and 1980s followed by its separation into smaller republics and the growth of production from countries such as India and Indonesia. However, the dominant feature of the graph is the enormous growth in production from China.

This growth is also evident in Table S3, which shows the percentage contribution to global production by the world's leading producers. In 1913 China contributed 1% to the world's total output of coal but had risen to 48% in 2013. In contrast, although production tonnages have increased, the USA's contribution to the global total reduced from 39% in 1913 to 12% in 2013.

2.4. Copper

Copper is a non-ferrous base metal and is the third most consumed industrial metal (after iron and aluminium) (Lusty and Hannis, 2009; Ayres et al., 2002). In 2013 Chile was the largest global miner of copper

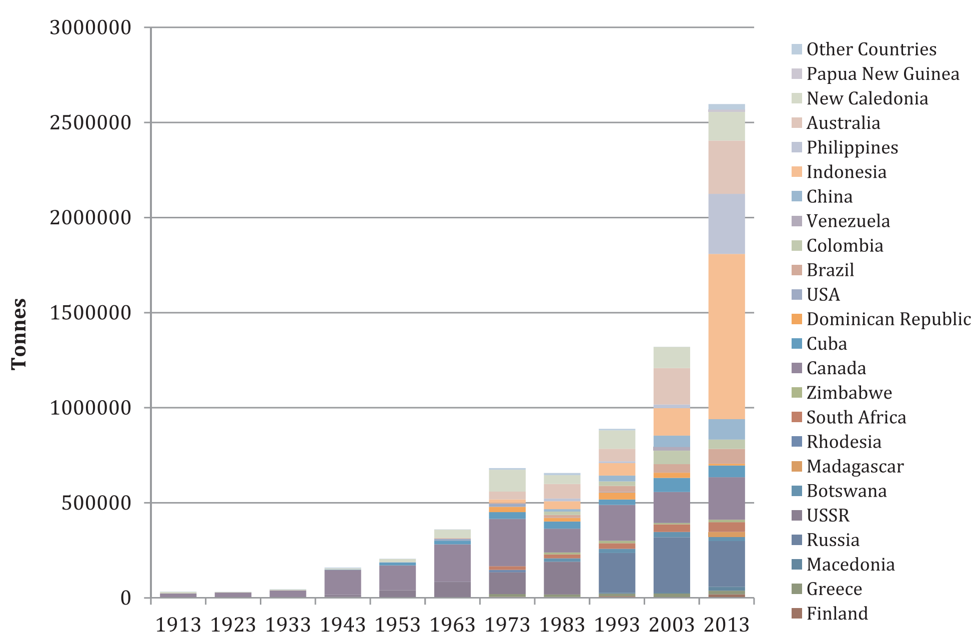


Fig. 5. Global mine production of nickel at decadal intervals from 1913 to 2013 (data from BGS, 2017).

(measured here by copper content) but, as Fig. 4 shows, this is a relatively recent development. From 1913 to the 1970s the world's largest producer was the USA. However, since the 1970s whilst the USA's output has remained relatively consistent, slightly declining in some decades, mine production from Chile has grown significantly. Other countries have also increased output or started producing with the effect that the USA's contribution to the global total production has declined from 56% in 1913 to just 7% in 2013 (Table S4). By contrast, Chile's contribution to the world's total mine output has grown from 4% in 1913 to 32% in 2013. It is also notable that in 2013 the world's second largest producer of mined copper was China but its contribution to the global total production was only 9%, although that has increased from less than 1% in 1953.

2.5. Nickel

Nickel is a hard, ductile and malleable base metal that readily forms alloys (Bide et al., 2008; Reck and Rotter, 2012). The world's total production of mined nickel has increased considerably in the most recent decade reaching nearly 2.6 million tonnes of contained nickel in 2013, a 97% increase compared to 2003. In 2013 the largest producing country was Indonesia but Russia, Canada, the Philippines, Australia and New Caledonia also made a significant contribution to supply (Fig. 5). In previous decades, Canada had been the dominant producing country with contributions to the world's total output ranging from 37% in 1973 to 91% in 1923 (Table S5). In terms of global production, Canada was overtaken by the USSR in 1983, by Russia in 1993, Australia in 2003 and by Indonesia and the Philippines in 2013.

3. Measuring supply concentration or diversity

The data presented in the previous section clearly shows how the largest mineral producing countries have changed over time, but does not quantify the degree of production concentration of a particular commodity. Furthermore, they do not explicitly indicate whether a producing country is ‘dominant’ in the supply of a commodity nor provide a quantitative measurement of how dominant a particular country may be. This information is necessary to determine whether there should be any cause for concern as production concentration is generally considered to increase the risk of supply disruption, a major factor in determining criticality (Buijs and Siever, 2011).

Supply can be restricted on a variety of scales. Events such as natural disasters, political upheaval, industrial accidents or employee strikes can all cause the supply from a single mine, region or country, to be disrupted (Long et al., 2012). Furthermore, a dominant position by one producer, whether a company or a country, can have impacts on commodity pricing or result in supply restrictions associated with export quotas or taxes. An example of the latter situation is evident from a dispute brought before the World Trade Organisation (WTO) by the USA and others against China with regards to rare earths, tungsten and molybdenum (WTO, 2015). These kinds of issues are not inevitable but, depending on which country is dominant, when they do happen they may give rise to concern. Increased risk of supply disruption can lead to changes in government policies or regulations and may influence decisions on the need for strategic stockpiles.

As mentioned in Section 10.0, a number of studies have incorporated production concentration into calculations of ‘supply risk’, an essential part of assessing the ‘criticality’ of a mineral. For example, production concentration is one of the seven criteria used in the ‘Risk List’ published by BGS to determine the relative supply risk of 41 elements. In the calculations used to produce this list, the percentage of world supply from the top three producers was determined and concentration was considered as ‘high’ if it was greater than 66.6%, ‘medium’ if it was between 33.3% and 66.6% and ‘low’ if it was below 33.3% (BGS, 2015). Other studies on raw material criticality have incorporated production concentration, alongside many other factors, by using statistical indices (e.g. European Commission 2011 and 2014; Coulomb et al., 2015).

A number of statistical measures have been developed for measuring concentration in a market at a company level. Governments and regulators worldwide have used these measures as part of their policy-making processes to ensure effective competition in specific markets (e.g. Competition and Markets Authority, 2010). Acar and Bhatnagar (2003) briefly describe the evolution of these statistical measures and identify a range of techniques that could be used. The following section applies some of these measures to assess the concentration of mineral production on a global scale.

3.1. Number of producers

Acar and Bhatnagar (2003) describe the simplest measure of diversity within a company as the number of product lines that it produces. It follows that the simplest measure of diversity in a market is the number of producing companies (Competition and Markets Authority, 2010). The same principle can be used to describe diversity in mineral supply on a global scale by examining the number of producing countries.

For the five commodities considered in this paper, Table S6 shows the number of producing countries for each sample year, which is also shown graphically on Fig. 6. Whilst in general the number of producing countries has increased during the century, there are some significant differences in the trends between the earlier and later decades. The perception may be that the supply of fluorspar and lithium has become less diverse but this is only true in the latter part of the century, with both minerals showing significant increases in the number of producers in the earlier decades. Although there has been an obvious increase in the number of countries producing copper between 2003 and 2013 there was a comparable reduction in the number of producing countries between 1983 and 1993. Only for nickel is the number of producing countries higher in 2013 than at any other point during the last century.

However, this measure does not consider the size of a single producer relative to the total amount produced and it will also be affected by the unification of countries or the separation of single jurisdictions into multiple independent states. The number of producers does have an impact on the results calculated using many of the other statistical indices and this is discussed in Section 4.1.

3.2. Concentration ratio (CR)

Economists and competition authorities have traditionally used concentration ratios to measure the extent of market control by the largest companies in a particular industry. This ratio measures the relative size of the largest group of companies compared to the size of the entire market (Pettinger, 2012). It will identify whether a market is monopolistic, oligopolistic or diversified and can be calculated based on any number of the largest companies (often the top three, four or five). It is also relatively simple in that it requires only the calculation of the

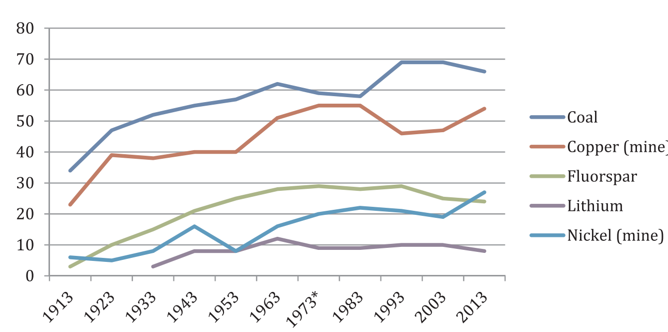


Fig. 6. Trends in the number of producing countries, data at decadal intervals * 1974 for lithium (Data from BGS, 2017).

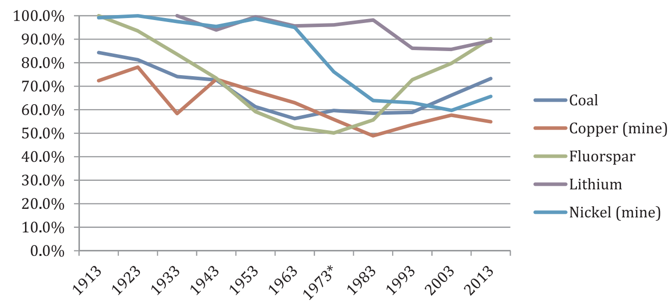


Fig. 7. Trends in concentration ratios for the top 4 producing countries, data at decadal intervals *1974 for lithium (Data from BGS, 2017).

total market share held by these top producers (Eq. (1)).

$$CR_n = S_1 + S_2 + \dots S_n \quad (1)$$

Where n represents the number of producers included in the calculation and S represents the market share of each producer. Values close to 100% indicate markets that are close to monopolistic (a monopoly would have a CR_1 value of 100%), CR_5 values greater than 50% are likely to be considered oligopolistic (although the threshold may vary) (Pettinger, 2012), whereas the most diversified markets will have values closer to 0%. This measure can be applied to producing countries on a global scale by considering the percentage of the world total contributed by the top producing countries instead of company market shares.

For the five commodities considered in this paper, Table S7 illustrates how the concentration ratio has changed over the century based on the top 4 producing countries and these data are shown graphically in Fig. 7. The data appear to show that the production of nickel, copper and lithium have become less concentrated over time. Production of fluorspar became less concentrated between 1913 and 1973 but since then has become considerably more concentrated. Concentration ratios do not fall below 49% for any of these commodities in any year, which suggests that the supply of all these commodities could be considered oligopolistic in most years.

This measure is less illustrative when there are fewer producing countries overall than when there are many countries because the results are naturally closer to 100% when there are fewer producers. Increasing the number of producers included in the calculation will result in higher percentages so the selection of how many is particularly important. It also does not provide any information regarding the scale of production of the top producing countries relative to each other and consequently it does not indicate the dominance, or otherwise, of a single country. This measure is, however, simple to calculate and the results are straightforward to interpret.

3.3. Hirschman-Herfindahl Index (HHI)

The HHI has become one of the standard tools used to assess the concentration of companies within a market and is therefore used frequently by competition authorities and economists. It was proposed independently by A.O. Hirschman in 1945 and O.C. Herfindahl in 1950 as a measure of concentration in an industry and therefore of competition between companies (Hirschman, 1945; Herfindahl, 1950). It is calculated as the sum of the squares of company market shares (Eq. (2)).

$$HHI = S_1^2 + S_2^2 + \dots S_n^2 \quad (2)$$

Where S represents the market share of each producer in turn and n represents the total number of producers. The market share figures resulting from this 'un-normalised' HHI can be quoted either as a decimal or as a whole number (i.e. a market share of 35% may be shown as 0.35 or 35). If decimal numbers are used the HHI calculation results in a number between 1/n and 1. If whole numbers are used the HHI results in a figure between 1/n and 10,000.

According to the United States Department of Justice (2010), HHI calculated using whole numbers resulting in a figure above 2500 represents a market that can be considered to have high concentration, a value between 1500 and 2500 represents a market of moderate concentration and a value below 1500 represents a market that is not concentrated. The equivalent figures if HHI is calculated using decimals are over 0.25 (high concentration), between 0.15 and 0.25 (moderate concentration) and below 0.15 (low concentration).

In the UK, the Competition and Market Authority (CMA) guidelines (2010) provide slightly different thresholds for HHI (again calculated using whole numbers) of 1000 for a concentrated market and 2000 for a highly concentrated market. These guidelines also provide thresholds for changes in HHI as a result of a merger between two companies, stating that a change of less than 250 in a concentrated market, or less than 150 in a highly concentrated one, would be unlikely to cause concern (Competition and Market Authority, 2010).

HHI can also be calculated on a 'normalised' basis such that the results range between 0 and 1 when the calculation is performed using decimal figures to represent the market shares (Eq. (3)).

$$HHI^* = (HHI - 1/n)/(1 - 1/n) \quad (3)$$

Where HHI* represents the normalised version, HHI is the un-normalised version of the index and n is the total number of producers. Normalising the index has both advantages and disadvantages as described in Section 4. HHI (or HHI*) can be applied to mineral producing countries on a global scale by considering their share of the total world production instead of company market shares. This index was previously used in a similar context, in the European Commission raw material criticality assessment (EC, 2010, 2014). Table S8 shows the calculated HHI values for the five commodities and the 11 sample years considered in this paper, with part a) containing the un-normalised HHI values and part b) the normalised HHI values. These are illustrated graphically in Fig. 8.

Notably, for all five of the selected commodities the un-normalised HHI values are 'highly concentrated' for 1913 and 1923 based on the thresholds set by the UK CMA. Copper and coal fall into the 'concentrated' range from 1933 and generally remain in this range for the

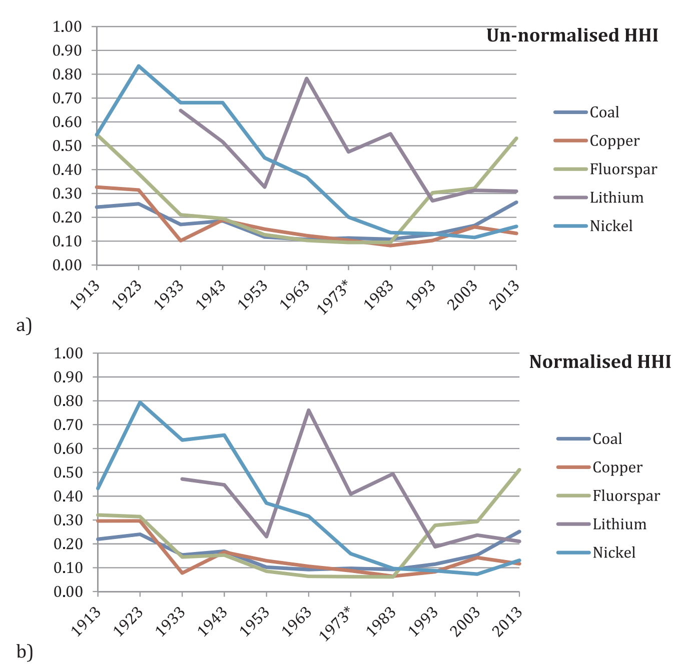
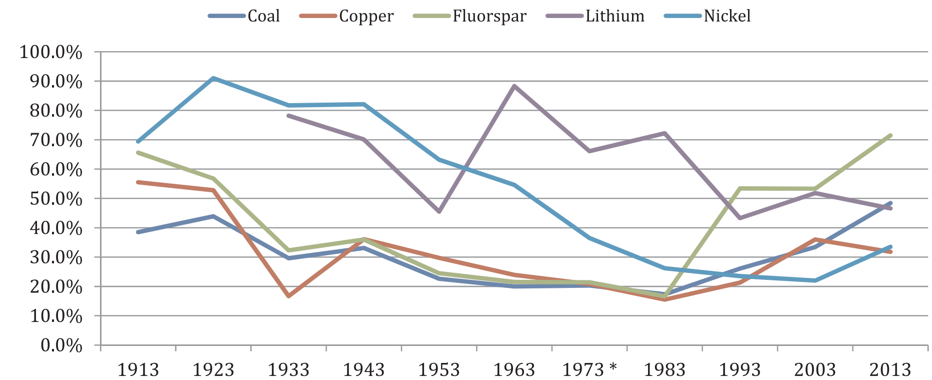


Fig. 8. Trends in HHI, data at decadal intervals, part a) are un-normalised, part b) are normalised; both calculated using market shares expressed as decimals. *1974 for lithium (Data from BGS, 2017).



	1913	1923	1933	1943	1953	1963	1973 *	1983	1993	2003	2013
Coal	U.S.A.	U.S.A.	U.S.A.	U.S.A.	U.S.A.	U.S.S.R.	U.S.S.R.	U.S.S.R. & China	China	China	China
	38.5	43.9	29.6	33.1	22.6	20.0	20.3	17.3	26.1	33.4	48.4
Copper	U.S.A.	U.S.A.	U.S.A.	U.S.A.	U.S.A.	U.S.A.	U.S.A.	Chile	Chile	Chile	Chile
	55.5	52.8	16.7	36.1	29.7	23.9	20.8	15.5	21.3	36.0%	31.8
Fluorspar	U.S.A.	U.S.A.	U.S.A.	U.S.A.	U.S.A.	Mexico	Mexico	Mongolia	China	China	China
	65.6	56.8	32.3	36.0	24.5	21.5	21.4	16.6	53.4	53.3	71.5
Lithium	n/a	n/a	Portugal	U.S.A.	U.S.A.	Rhodesia	U.S.A.	U.S.A.	U.S.A.	Chile	Chile
			78.2	70.1	45.5	88.3	66.1	72.2	43.3	51.8	46.6
Nickel	Canada	Canada	Canada	Canada	Canada	Canada	Canada	U.S.S.R.	Russia	Russia	Indonesia
	69.4	91.0	81.7	82.1	63.2	54.6	36.5	26.2	23.5	22.0	33.5

Fig. 9. Trends in the market share of the leading producer at decadal intervals. The identity of that leading producer has changed over time as shown in the data table. In the table dominant producers based on market share are coloured red, producers with strength but not dominance are coloured orange. *1974 for lithium (Data from BGS, 2017).

remainder of the period considered. The HHI value for fluorspar falls into the 'concentrated' range in 1953, crosses into the 'not concentrated' range in 1973, but then rises above the 'highly concentrated' threshold from 1993 onwards and continues to increase. Fluorspar has the highest HHI value in 2013 of all five commodities considered. The HHI for nickel shows the most significant decrease in values across the century, having the highest values of the five commodities in all the sample years up to 1953 and only falling below the 'highly concentrated' threshold from 1983. Its HHI value has remained above the 'concentrated' threshold in each subsequent decade.

The HHI appears to be a useful tool for assessing the concentration of global supply of these minerals. However, it is more complicated to calculate than concentration ratio and there is the potential for some misunderstanding due to there being both normalised and un-normalised versions of the index, as discussed further in Section 4.

This analysis clearly demonstrates that the production of nickel, in particular, has become significantly less concentrated in supply since 1943 despite the small increase in concentration in 2013. In contrast, production of fluorspar has become much more concentrated in supply since 1983, but the perception of how significant this change is could be partially affected by the low HHI values in the middle of the century and the speed at which this increase happened. Comparing the un-normalised HHI value of fluorspar in 2013 (0.53) with that in 1913 (0.55) suggests it may not be as significant as it first appears.

These HHI figures do not identify which country or countries are the largest producers or whether any of the leading producers are likely to be able to exercise dominance in the market.

3.4. Percentage market share (S)

In economics the term 'dominance' is a measure of the strength of a particular product or company in the market place. This is relevant to the global supply of minerals because a dominant producing country could exert influence over prices by restricting supplies to other countries. Furthermore, a country could use a dominant position to provide an unfair advantage to its domestic industry or to apply export restrictions or tariffs (e.g. WTO, 2015; Bradsher, 2010). However, the presence of dominance does not itself result in anti-competitive practices rather it is the abuse of dominance that causes problems (Competition Bureau, 2015). On a global scale, useful indices have been developed to give an indication of which countries may be more or less inclined to this kind of behaviour, e.g. the World Bank's Worldwide Governance Indicators (World Bank, 2018) and the Fraser Institute's Investment Attractiveness Index (Stedman and Green, 2018). The former includes indicators for: 'political stability', 'government effectiveness', 'regulatory quality' and 'control of corruption', amongst others. The latter includes indicators for 'policy perception' (which itself consists of sub-indicators for undertainty surrounding regulations, the legal system, political stability, trade barriers, etc.) and 'mineral potential' (which relates to geology).

There are a number of ways of calculating dominance; the simplest is the percentage of the total market supplied by one company or product (Eq. (4)). In the world of commerce, a company with a market share exceeding 60% would be considered to have market dominance. A company with a market share of more than 35% but less than 60% would have market strength but not necessarily dominance. A market in which no company has more than a 35% market share would suggest no company has strength or dominance and is unlikely to raise concerns with competition regulators (Competition Bureau, 2015).

$$S_i = (P_i/T)*100 \quad (4)$$

Where S is the percentage market share, i represents the individual producer, P is the production from that producer and T is the total quantity produced in the market. This can be applied to global mineral supply by examining the percentage contribution of the top producing countries to the world's total output. Tables S1-S5 contain the percentage shares of the top producing countries for the five minerals considered. Fig. 9 contains the percentage share of just the single top producer in each country and the identity of this country is shown in the data table below the graph.

For fluorspar, two countries have had market dominance at different times during the century: the USA in 1913 (66% of the world's total production) and China in 2013 (72%). In two other years each of these two countries have also had market strength: the USA in 1923 and 1943 and China in 1993 and 2003. It is notable that the three years mentioned for China are the most recent.

With regards to lithium, market strength and dominance have varied over the sample years for which statistics are available. In 1933, Portugal had market dominance but by 1943 this had changed to the U.S.A. In 1963 it had changed to Rhodesia (now Zimbabwe), probably due to the opening of the large Bikita Mine. However, this may be affected by the absence of data for the U.S.A. in that year. Market dominance switched back to the U.S.A. in 1974 and 1983. In the most recent two decades, no country has had dominance but the growth of production in Chile has provided it with market strength.

Market dominance for mine production of nickel rested with Canada for the first half of the century with its contribution to global production of nickel reaching as high as 91% in 1923. Canada continued to have market strength in 1963 and 1973 but since then no country has produced a sufficient quantity of nickel to cross that threshold.

It is significant to note that the trend lines for market shares in Fig. 9 are very similar to those for HHI in Fig. 8. This is not surprising when you consider that HHI is calculated based on market shares (see Eq. (2)). The difference with HHI is that the market shares are squared and all producers are included whereas in Fig. 9 only the largest producer in each year is shown.

3.5. Kwoka's Dominance Index (D)

This index was developed by John E Kwoka Jr in 1977 (Kwoka, 1977) with the intention that it would be an improved measure of ‘inequality’ in the size of companies within a market. The performance of commercial markets would appear to be dependent not only on the individual company's market share but on the size of the gap between the market share of the largest company and its competitors. A greater size inequality enables the largest company to exploit market pricing more effectively and thereby enhance its profitability.

Kwoka's index is calculated as the sum of the squares of market share differences when companies are ranked by size (Eq. (5)).

$$D = \sum_{i=1}^{n} (S_i - S_{i+1})^2 \tag{5}$$

Where S means the market share of each producer ranked by size, i represents each individual producer in turn and n is the total number of producers. The values range from $1/n^2$ to 1. A result of 1 represents a monopolistic market while values close to 0 mean that no single company can exercise power in the market. The literature is unclear on how high the value needs to be to indicate a dominant producer (e.g. d’Outreville, 1998; Ruthenberg, 2006). However, the trends produced using the index are informative for the purposes of this paper.

This index can be used to analyse global minerals supply by replacing market shares with each country's percentage contribution to the world's production of a mineral. Table S9 shows the calculated values for Kwoka's dominance index for the five commodities and eleven years considered and these values are shown graphically in Fig. 10.

With regards to lithium, the dominance index is quite variable and with values above 0.3 in 1933, 1943, 1963 and 1983 there have clearly been countries with greater dominance of global supply than for copper or coal. For these years, the largest producers were Portugal, the USA, Rhodesia and the USA, with shares of global supply of 78%, 70%, 88% and 72%, respectively. In contrast the dominance index has reduced to about 0.1 in the three most recent sample years, which coincides with the emergence of Chile and Australia as significant producers.

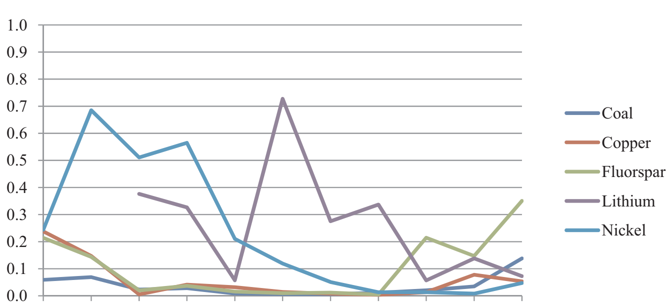


Fig. 10. Trends in Kwoka's dominance index, data at decadal intervals * 1974 for lithium (Data from BGS, 2017).

The dominance index for fluorspar shows comparable values to copper for each year until 1993, with the largest producer being the USA until 1953, Mexico in 1963 and 1973 and Mongolia in 1983. However, from 1993 the emergence of supply from China becomes apparent with its share of global production increasing sharply from 12% in 1983 to 53% in 1993 and the dominance index increases from 0.01 in 1983–0.22 in 1993. A small dip in the dominance index for 2003 is related to a rise in the global share from the second producer, Mexico (from 7% to 17%), which had the effect of keeping China's contribution to global production at 53% despite a rise in actual production quantity. However, a very large increase in China's production of fluorspar by 2013 has caused its share of the global total to increase to 72% in 2013. In comparison Mexico's proportion of the total global production reduced to 13% in 2013 despite an overall rise in production from the country. These two factors combined have caused the dominance index to rise to 0.35.

The dominance index for nickel shows a completely different pattern with values in excess of 0.3 only in 1923, 1933 and 1943 when Canada was the largest producer with a share of global supply greater than 80% in each decade. A significant decline in Canada's percentage of the total, caused initially by the emergence of supply from other producers rather than an actual fall in production, reduced the dominance index from 0.57 in 1943–0.21 in 1953. Since then the index has continued to decline, reaching a low in 2003 of just 0.01. In that period Canada has been overtaken as the largest producer by Russia, then Australia and more recently by Indonesia and the Philippines.

3.6. Entropy measure of diversification (E)

Unlike the other statistical measures reviewed, the use of entropy is a direct measure of diversity rather than concentration. Consequently, whereas calculated values for the concentration ratio or HHI are lower where a market place is more diverse and higher when it is more concentrated, calculated values of entropy are larger when a market place is more diverse and lower when it is closer to a monopoly.

Entropy is calculated by multiplying the market share of a company or product by the logarithm of that market share and then summing the results (while also converting the negative number that results into a positive number) (Eq. (6)).

$$E = -\sum_{i=1}^{n} S_i * log S_i \tag{6}$$

Where S represents the market share, i the individual company within the market and n the total number of producers. If a company or market has a monopoly the index would calculate to 0 and the maximum value that can be calculated is the logarithm of n. As with the other measures, it is adapted for the context of this paper by using a country's contribution to the total production of each commodity instead of a company or product market share.

Table S10 shows the calculated values for the entropy measure of diversification for the five commodities and eleven years considered and these values are presented graphically in Fig. 11. The literature on this topic does not reveal a classification system by which these values can be defined as indicating a ‘highly concentrated’ market, nor a threshold below which concern should be raised. However, the table and figure do reveal that the closest there has been to a monopoly situation for these five commodities was in 1923 when the supply of nickel has an entropy value of 0.14. As indicated previously, in that year the largest producer of nickel was Canada with a share of the global total output of mined nickel of 91%. Since then the entropy value for nickel has risen in almost every decade, reaching a high of 1.05 in 2003.

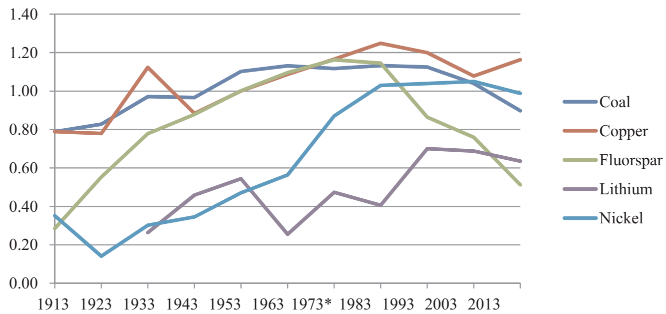


Fig. 11. Trends in entropy measure of diversity, data at decadal intervals *1974 for lithium (Data from BGS, 2017).

Lithium too appears to be moving gradually away from a monopoly situation, although the trend line is more variable than for nickel with noticeable dips in 1963 and 1983. The former is likely due to the opening of a new large mine in Rhodesia (now Zimbabwe) while the latter is the result of a significant increase in production in the U.S.A. Despite these dips, the entropy measure has not fallen below 0.26 in any of the years assessed.

The trend for fluorspar is perhaps the most concerning of the five commodities because although the entropy measure has risen steadily from 0.29 in 1913–1.16 in 1973, since then it has fallen sharply to 0.51 in 2013. This indicates that the supply was becoming increasingly diverse up until 1973 but has subsequently become more concentrated. The latter coincides with the emergence of China as the largest producer.

4. Discussion

4.1. The effect of changes in the number of producers

A number of measures have been described and calculated to examine the variation in concentration of the global supply of coal, copper, fluorspar, lithium and nickel. As previously mentioned, the number of countries producing each commodity has generally increased across the century and this will have an effect on indices such as HHI, Kwoka's dominance index or entropy, irrespective of other factors. In order to assess how significant an impact this has on these three measures, Fig. 12 show the effect of three scenarios:

1) If the number of producers increases but all producers have equal market shares;
2) If one producer retains 50% market share but an increasing number of producers equally share the remaining market; and
3) If two producers retain the majority of the market share but an increasing number of new entrants take small market shares away from one of them.

A number of observations can be drawn from this scenario analysis. Firstly, whist an increase in the number of producers intuitively creates a more diverse market place, the normalised HHI remains at zero if all the producers continue to have the same market share (red line in Fig. 12, part 1). In contrast the un-normalised HHI falls markedly as the number of producers increases (dark blue line in Fig. 12, part 1). Consequently, where the number of producers changes over time, there is a clear advantage to using un-normalised HHI rather than the normalised version of the index.

Secondly, where one or two producers remain dominant in a market despite new entrants, the normalised HHI increases noticeably while the un-normalised HHI decreases (compare red and dark blue lines in Fig. 12, parts 2 and 3). The normalised HHI would therefore suggest that the market is becoming less diverse even though the number of producers is increasing, which is counter intuitive. Again the un-normalised HHI would appear to have an advantage over the normalised version of the index.

However, the minimum value that the normalised HHI can reach is always zero whereas with the un-normalised HHI the minimum value it can reach varies depending on the number of producers. Therefore, if the latter is to be used accurately, it is important to plot both the calculated value and the minimum value (based purely on the number of producers) in order to visually determine the difference between the two (compare dark blue and light blue lines in Fig. 12, parts 2 and 3). In scenario 2 or 3, for example, it can be observed that if one producer retains 50% of the market whilst new entrants take market share away from its competitor, the calculated HHI is considerably higher than the minimum HHI. This means that overall the market is more concentrated than it would have been if the new entrants had taken market share away equally from both the original producers.

A similar argument can be made for also plotting the minimum possible value of the Kwoka's dominance index (compare dark green and light green lines in Fig. 12, parts 2 and 3). In scenario 2, Kwoka's dominance index actually rises as the number of producers increases from 3 to 10, which is a reflection of the increasing market share gap between the largest producer and the others. This situation in the real world would suggest that the largest producer is increasing in dominance and could therefore exert more influence than other producers. However, in scenario 3 Kwoka's dominance index falls slightly as the number of producers increase, which indicates a reduction in the dominance of the largest producer. But it is important to recognise that the reduction is considerably smaller than would be observed if market shares of all producers remained equal indicating that the new entrants have not improved the competitive dynamics of the market as much as the simple increase in the number of producers would suggest.

Plotting the calculated values and maximum values for the entropy measure of diversification is also informative (compare dark purple and light purple lines in Fig. 12, parts 2 and 3). In Scenario 2 or 3 it would at first appear that the market is naturally becoming more diverse as more producers enter because the calculated values are increasing. However, comparison with the maximum entropy values reveals that the increase is notably smaller (especially in scenario 3) than it would have been if all market shares had remained equal.

4.2. Interpreting the assessment measures for specific commodities

Returning to the five commodities considered by this paper and examining the indices in turn the following observations can be made.

4.2.1. Fluorspar

The number of fluorspar producers increased significantly during the first half of the century, from 3 in 1913 to a maximum of 28 or 29 in 1963–1993, but the number has decreased slightly in the most recent decades to 24 in 2013. The concentration ratio of the top 4 producers fell notably between 1913 (when it was 100%) to a low in 1973 of 50%. However, it has subsequently risen equally notably to 90% in 2013 (Fig. 13, part a). This would imply that the decrease in supply diversity in recent decades is much more significant than the number of producers metric would suggest. Examination of the percentage market shares reveals that the dominant producing country in 2013 is China, contributing 72% to the global total production. The former largest producer, the USA, has fallen from 66% in 1913 to zero production one hundred years later.

In the early decades of the century, the gap between the calculated HHI (un-normalised) and the minimum value possible based on the number of producers remains relatively constant until 1953 when it narrows significantly. This implies that supply diversity was fairly constant in the early decades and improved in the middle of the century. However, after 1983 the minimum HHI remains flat whilst the calculated HHI rises considerably, demonstrating that supply has become significantly less diverse in recent decades (Fig. 13, part a).

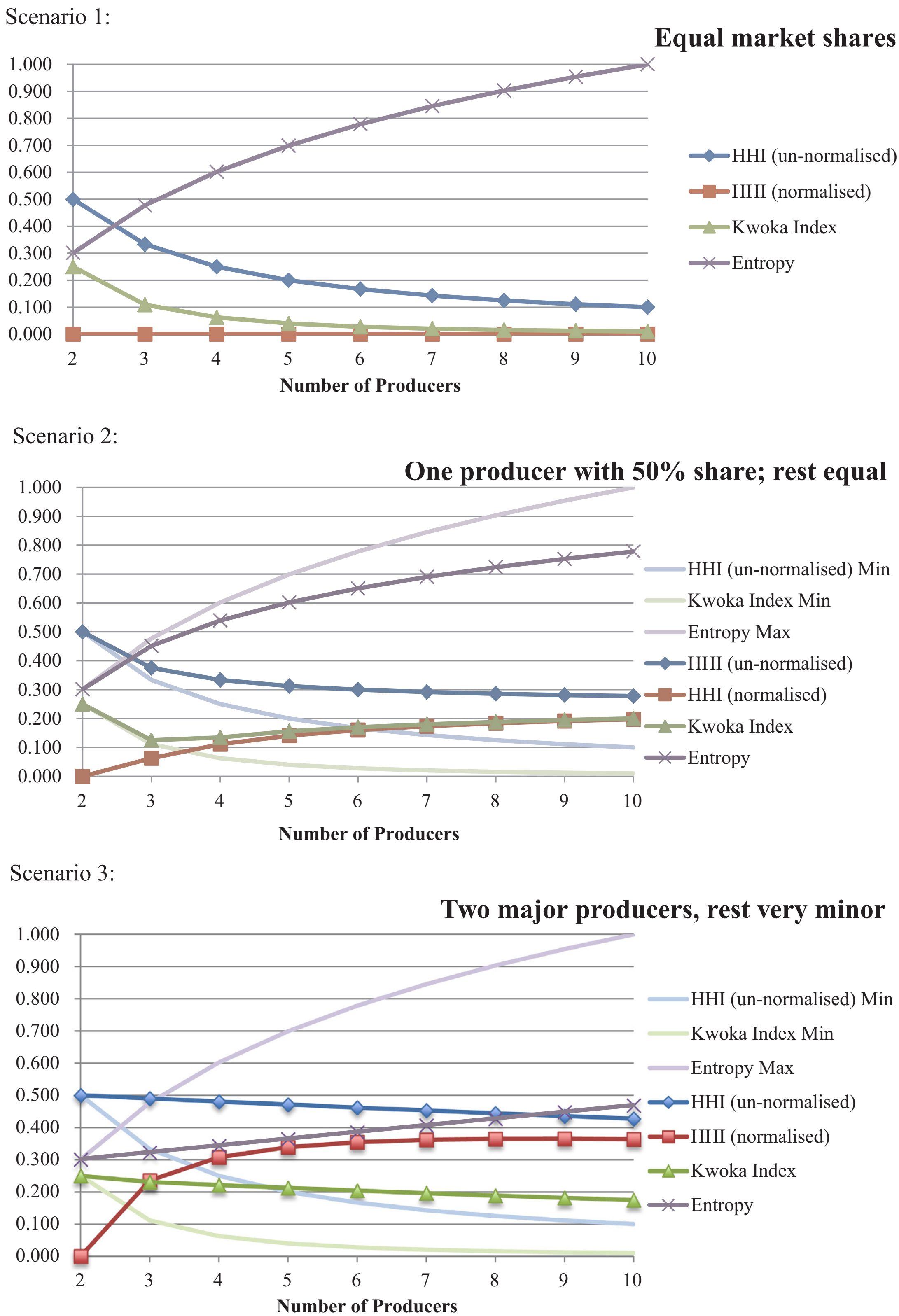


Fig. 12. The effects of increasing numbers of producers on 3 scenarios (see text for details).

Kwoka's dominance index shows a similar pattern to HHI and clearly demonstrates that one producer has become dominant in global supply (Fig. 13, part a). The significant change in 1983, is also illustrated in the calculations for the entropy measure of diversity by a significant widening of the gap between the maximum value based on the number of producers and the actual calculated value (Fig. 13, part b).

The hypothesis for fluorspar at the outset of this paper was that supply had become considerably less diverse, with a significant shift to the leading producer and this is clearly supported by the calculations presented here for the decades since 1983. All of the measures described support the same conclusions, although examination of the number of producers alone would appear to underestimate the scale of

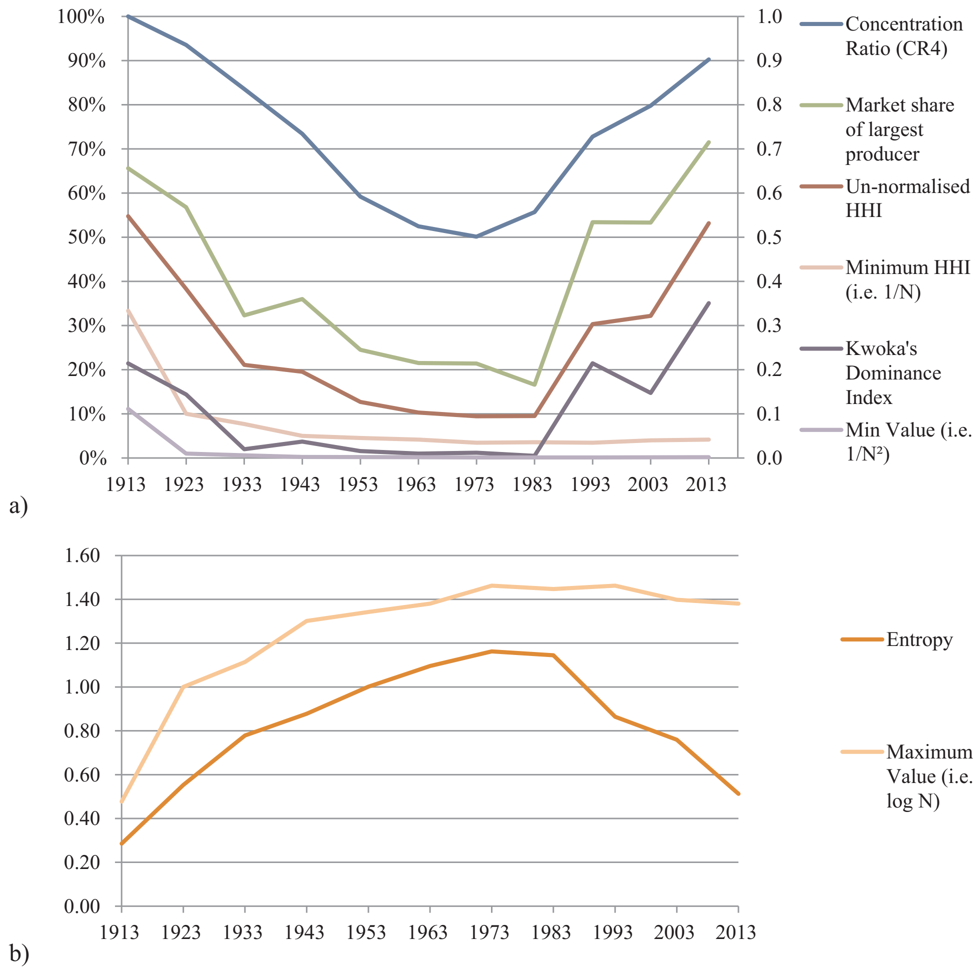


Fig. 13. Indices for fluorspar, part a) concentration ratio and market share of largest producer (left hand axis) with un-normalised HHI and Kwoka's dominance index (right hand axis), part b) entropy measure of diversity (Data from BGS, 2017).

the issue.

4.2.2. Lithium

The number of producing countries for lithium increased notably between 1933 and 1943 but has since remained relatively constant at about 10 ± 2. The concentration ratio for the top 4 producing countries has remained high (above 85%) in all years, but declined noticeably between 1983 (98%) and 1993 (86%) indicating that supply has become more diverse (Fig. 14, part a). This correlates well with the commencement of production of lithium from brines beneath saltpans.

The HHI values are considerably more variable for lithium than the other commodities considered. This probably results from the smaller number of producers, which means that countries ceasing production or new entrants have greater impact on the index. However, since a peak in 1963 the HHI for lithium decreased considerably, which would indicate that global supply has become more diverse (Fig. 14, part a). The variability seen in HHI is also reflected in the data for market share, with the largest producer varying between four different countries since 1933. In 2013 the largest producer was Chile with 47% of global supply and Australia was the second largest with 28%.

Kwoka's dominance index shows a similar pattern to HHI (Fig. 14, part a) and this indicates that the dominance held by the largest producer in 1963 has largely been eliminated. The index also suggests that since 1993 no single producer dominated despite Chile's market share being so significant. This is likely to result from Australia's percentage of global supply increasing since production started in the early 1980s. The comparison of the calculated entropy with the maximum possible values suggests that supplies became less diverse between 1943 and 1983 (because the gap is wider) but that since then supplies have diversified as the gap has narrowed (Fig. 14, part b).

At the outset it was thought that the global supplies of lithium had become less diverse because of the emergence of Chile as a major producer but the various measures reviewed suggest that the reverse is true in since 1993. Although examination of market shares would suggest Chile has a position of strength, Kwoka's dominance index reveals that supplies from other countries (e.g. Australia and Argentina) are preventing Chile's position from becoming dominant.

4.2.3. Coal

The number of coal producers has increased from 34 in 1913 to 69 in 1993 and 2003, with a slight reduction to 66 in 2013. This implies there has been an increase in supply diversity throughout most of the last century, albeit with a slight reduction in the most recent decade. This is supported by the figures for concentration ratio for the top 4 producers, which has fallen from 84% in 1913 to 56% in 1963 but subsequently has risen to 73% in 2013 (Fig. 15, part a). The countries contributing the greatest proportion to the world total supply of coal in 1913 were the USA and the United Kingdom; production from both have declined over the century although the USA remains the second largest producer. The leading producer is now China with a market share of 48% (compared to just 1% in 1913).

HHI (un-normalised) for coal has fallen during the first half of the century, becoming closer to its minimum value for the corresponding number of producers (Fig. 15, part a), but in the most recent three

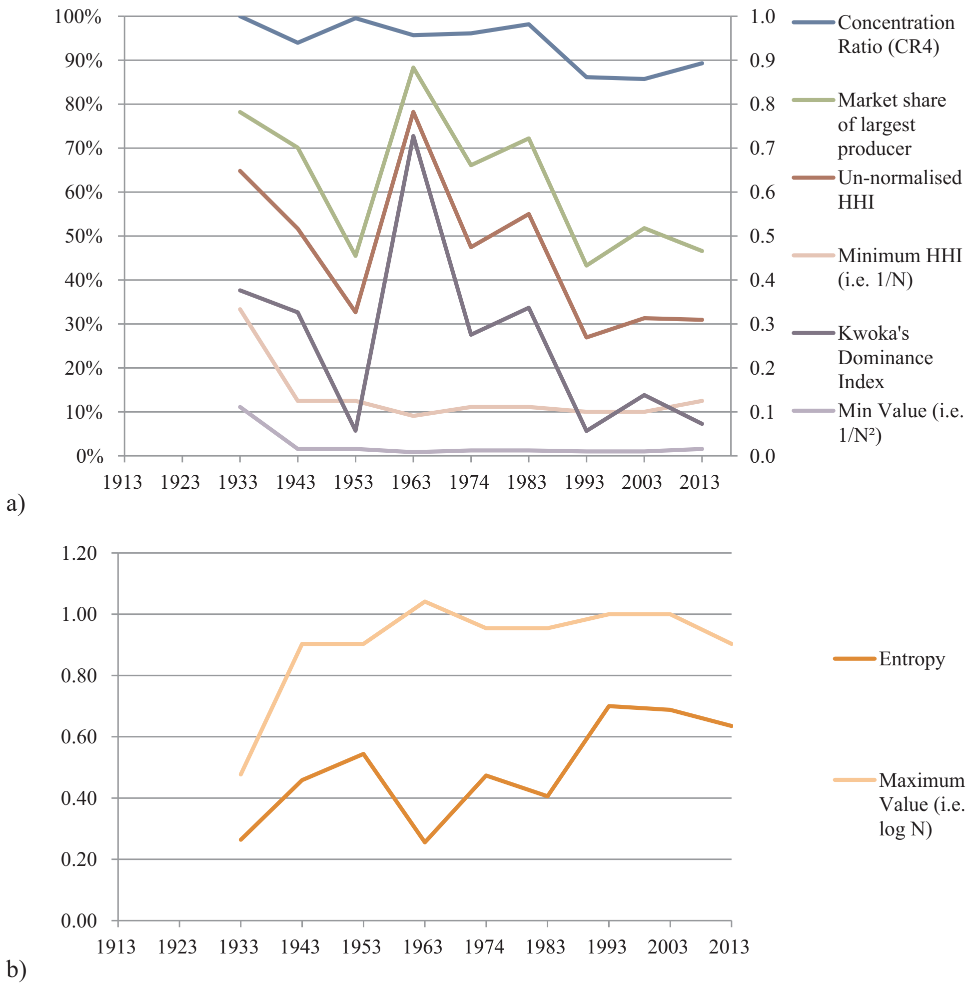


Fig. 14. Indices for lithium, part a) concentration ratio and market share of largest producer (left hand axis) with un-normalised HHI and Kwoka's dominance index (right hand axis), part b) entropy measure of diversity (Data from BGS, 2017).

decades the index has increased. This suggests that global supply was becoming more diversified up until the middle of the century but since 1983 it has become more concentrated. Kwoka's dominance index has also fallen during the first half of the century (Fig. 15, part a) but has increased in more recent decades, particularly between 2003 and 2013. This indicates that the global supply was free from any producer dominance in the middle of the century but the largest producer (i.e. China) is becoming more dominant.

The entropy measure of diversification is more challenging to interpret than the other measures because there is a significant gap between the calculated values and the maximum value in all years (Fig. 15, part b), which implies that the supply of coal was not as diverse as the number of producers implied it should be. However, this gap is widening in 2003 and 2013, which implies a further reduction in supply diversity in those decades.

At the outset, it was hypothesised that the situation for coal would be an increase in supply diversity with perhaps one important but not necessarily dominant producer (i.e. China). However, the results suggest that global supply has become slightly less diverse since 1993 and that China is becoming more dominant than was previously considered. However, this conclusion is unlikely to cause concern due to the relatively large number of coal producing countries.

4.2.4. *Mine production of copper*

Despite a significant fall in the number of producing countries between 1983 and 1993, the general trend has increased, from 23 in 1913 to 54 in 2013. This would imply that global supply is becoming more diverse. This is supported by the concentration ratio of the top 4 producers, which despite some variation over the century has a general trend that indicates supply has become more diverse (Fig. 16, part a).

A generally declining trend in HHI is interrupted by notable increases in 1943 and 2003 (Fig. 16, part a). A declining trend in HHI suggests that global supply is becoming more diverse, but the analysis indicates that this has not been uniform throughout the century. Kwoka's dominance index shows a significant fall over the first three decades of the century, generally low values in the middle of the century, but a notable rise in 2003 (Fig. 16, part a). The latter has been caused by the emergence of Chile as an important copper producer although it has not yet crossed the threshold to be described as 'dominant'.

Comparing the calculated entropy measure of diversification with the maximum possible value reveals that there has been only a slight narrowing of the gap during the middle decades of the last century, but the gap has subsequently widened again in 2003 and 2013 (Fig. 16, part b). This indicates that changes in diversity over most of the decades have not been significant.

Although the original hypothesis was that global supply of copper has become more diverse over the century, this analysis indicates that in reality the situation is more complicated. Although there are more countries producing copper in 2013 than in many previous decades, the emergence of Chile as a major producer appears to have reduced the overall diversity of supply since 1993.

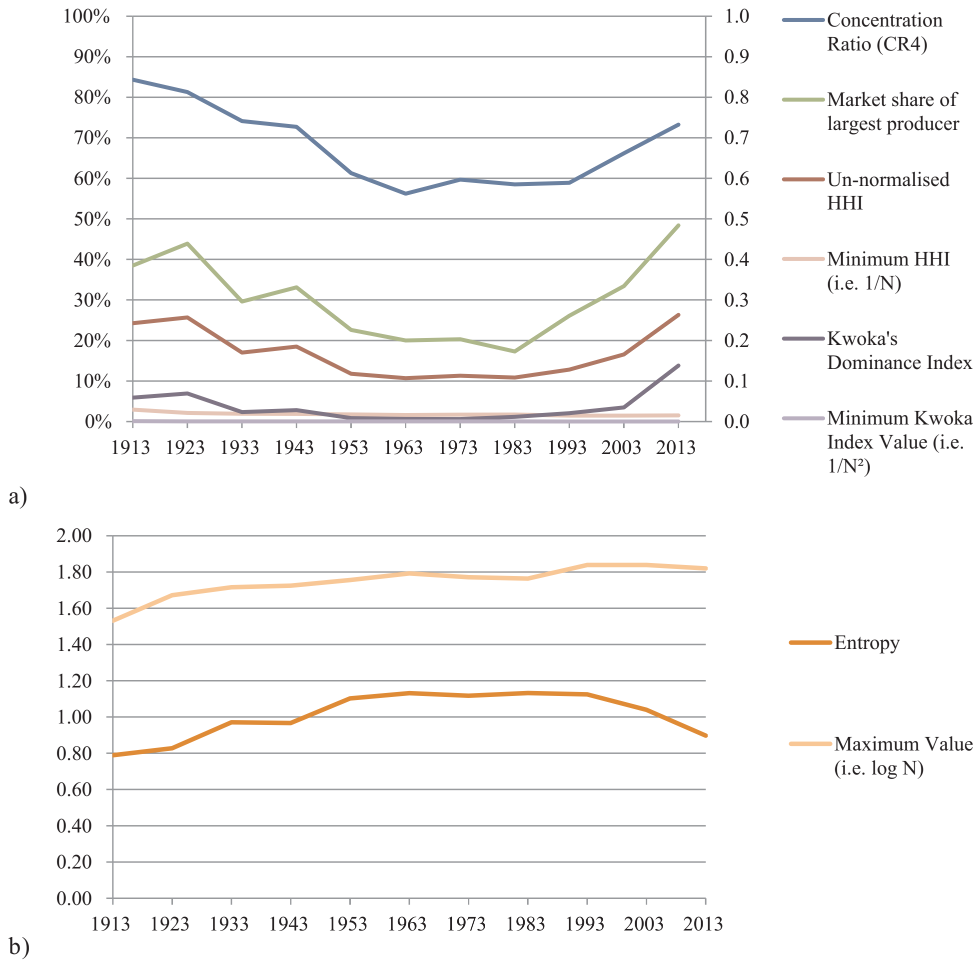


Fig. 15. Indices for coal, part a) concentration ratio and market share of largest producer (left hand axis) with un-normalised HHI and Kwoka's dominance index (right hand axis), part b) entropy measure of diversity (Data from BGS, 2017).

4.2.5. *Mine production of nickel*

The number of countries where nickel is mined has increased over the century from six in 1913 to 27 in 2013, suggesting that supplies have become much more diverse. Although the number of producers rose quite quickly, the concentration ratio of the top four producers did not decline significantly until after 1963. Since then it decreased to a low of 60% by 2003, but has risen to 66% in 2013 (Fig. 17, part a). This suggests that global supply has become much more diverse, albeit with perhaps a reduction in diversity in 2013. This conclusion is reinforced by examination of the market shares of the different countries, which reveals that the proportion of global production supplied by the dominant producer (Canada) has been repeatedly eroded by new entrants. In 1923 Canada supplied 91% of the global market for mined nickel but in 2013 it supplied just 9% and was the fifth largest producer.

Values for HHI (un-normalised) show a significant drop from a peak of 0.83 in 1923 to 0.14 by 1983 and then a levelling off with a slight rise to 0.16 in 2013 (Fig. 17, part a). This suggests supplies have become considerably more diverse during the century. The notable reduction in Canada's dominance of global supplies of mined nickel is also clear in the values for Kwoka's dominance index (Fig. 17, part a). In 1923 this index had a value of 0.69 but by 2003 it had dropped to 0.01. This is very close to the minimum calculated value for the index of 0.002, which suggests that the market was almost ‘fully diversified’ in that year. However, since then the value for Kwoka's dominance index has risen slightly to 0.05, which reflects the growth in the proportion of the global total supplied by Indonesia (up from 11% in 2003 to 34% in 2013).

A comparison of the calculated value for the entropy of diversification measure with the maximum possible value suggests that the market for mined nickel was not as close to being ‘fully diversified’ in 2003 as the Kwoka's index value suggests (Fig. 17, part b). However, the gap between these two values does narrow, particularly when comparing 1943 with 2003 for example. The gap widened again in 2013 suggesting supplies became slightly less diverse in the most recent decade.

The hypothesis was that global supplies of mined nickel had diversified over the century but with no individual country being dominant in recent decades. This is clearly supported by the indices presented in this paper, albeit with a suggestion of increasing market strength in 2013 by Indonesia. The situation changed significantly in 2014 due to the introduction of new policies in Indonesia that restrict the exports of unprocessed ores and which have caused a fall in production output from that country.

4.3. *Sustainability of supply*

The supply of minerals has been described as “the end product of geology” (Institute of Geological Sciences, 1978) and several others have quoted the phrase “minerals can only be worked where they naturally occur” (e.g. Weston, 1997; Wrighton et al., 2011); both these statements are true. Diversity of mineral supply is a direct function of the variation in geology. Although, in general most mineral commodities are not ‘scarce’, certain mineral deposit types only occur in a restricted number of geographic locations. Therefore, whether a country is able to supply a particular mineral commodity fundamentally depends upon its geology and the degree to which its land area has been

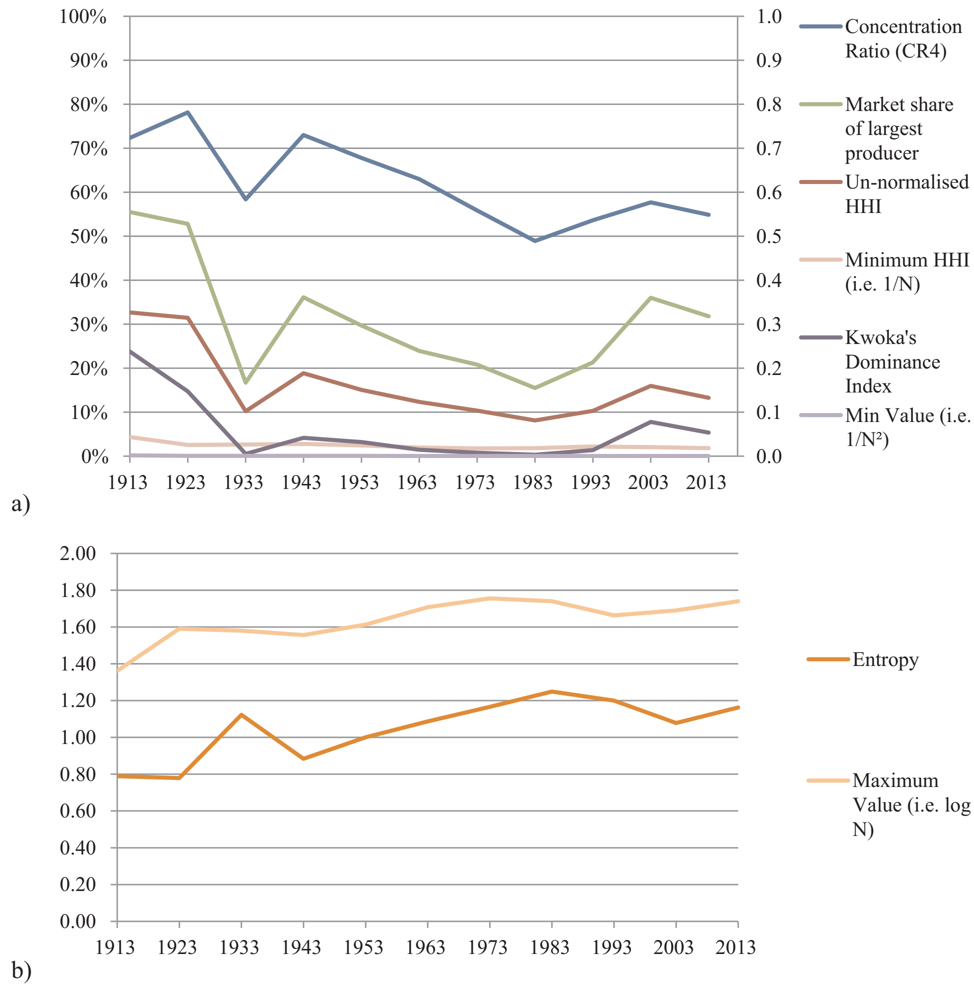


Fig. 16. Indices for mine production of copper, part a) concentration ratio and market share of largest producer (left hand axis) with un-normalised HHI and Kwoka's dominance index (right hand axis), part b) entropy measure of diversity (Data from BGS, 2017).

explored. However, these are just two factors amongst many others that determine whether a deposit can be mined. Other significant factors include production capacity, material prices, economic or technical feasibility, environmental policies and geopolitics.

In open-market economies it is usually the companies operating within a country that determine if it is economically feasible to develop a mineral resource, but a country's government can strongly influence those investment decisions using a range of financial or regulatory instruments. Many countries have successfully used their mineral resources as a method of improving the standards of living of their population, although history suggests this is not always a straightforward process and the distribution of mineral wealth remains problematic in many parts of the world. Furthermore, the presence of, or desire to develop, a particular industry within a country will influence the range of minerals considered to be 'important' to a particular country. Consequently even if a mineral is assessed as being at risk of supply disruption it may not necessarily be of concern to a country if it does not have an industry that uses that material. However, even if a mineral is only used in small quantities this does not necessarily indicate that it is 'unimportant', it may actually be vital to the functioning of a particular industry or technology, and the requirement for that commodity can sometimes grow significantly and rapidly.

Economic growth generates increased demand for mineral raw materials. The development of domestic industries, especially in the so-called 'emerging' economies, increases demand further and this has been particularly important in the last two decades. It is logical for a nation rich in minerals to encourage the development of domestic industries that are further along the processing chain because these industries create employment for the local population and generally create higher profits and tax revenues. However, the imposition of policies to accomplish this are often derided as 'resource nationalism' because all countries are dependent to some degree on supplies of raw materials from other countries. If one country chooses to conserve its mineral production for its own domestic industry, this inevitably means a reduction in supply for other countries. Ensuring a sustainable and 'fair' supply of raw materials is highly topical with many countries developing policies and strategies to improve raw material security of supply, for example the European Commission's Raw Materials Initiative (European Commission, 2008).

Statistical measures of supply concentration or diversity, such as those described and assessed in this paper, can make a useful contribution to the development and monitoring of policies or strategies by indicating which minerals these should focus on. The use of these indices are an effective 'early warning' mechanism that will highlight which minerals would benefit most from more detailed analysis (McCullough and Nasser, 2017). However, it is important that the conclusions drawn from indices such as those in this paper and the associated messages to decision-makers are not misleading. Furthermore, this paper demonstrates that applying a single diversity measure might not provide sufficient information for the position to be completely understood and as a consequence an important change in the market for a particular mineral could potentially be missed. For example, simply looking at the number of producers for a mineral is insufficient to determine whether supply risk could be increasing. HHI is

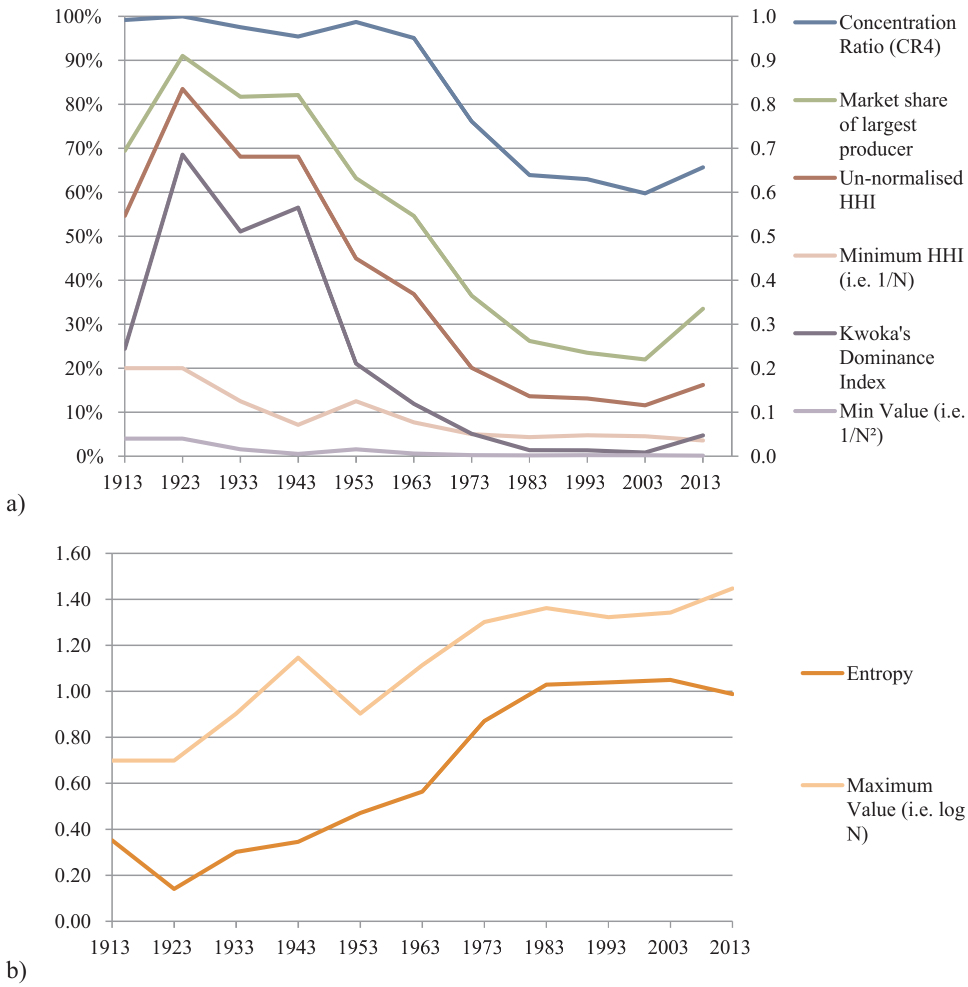


Fig. 17. Indices for mine production of nickel, part a) concentration ratio and market share of largest producer (left hand axis) with un-normalised HHI and Kwoka's dominance index (right hand axis), part b) entropy measure of diversity (Data from BGS, 2017).

a useful tool for examining supply concentration but the complications described previously may not always be fully understood by non-specialists. Kwoka's dominance index goes further than HHI in that it identifies whether a market has a producer with a position of strength or dominance that could be exploited. Changes in the index over time can serve to highlight whether a producer is increasing in dominance, which may be cause for concern and thereby serve as an early warning that policy actions are necessary. The entropy measure of diversification could also be used to determine whether a market is becoming more or less concentrated but the effect of increasing the number of producers is much more significant than with other indices and consequently it is vital that the maximum value is calculated to enable a comparison to be drawn between this and the observed value.

When considering changes in mineral supply diversity, it is important to avoid the issue of false precision. Calculating a figure using a complicated index may make the result appear to be very precise and there is a tendency to assume that greater precision is the same as greater accuracy. However, the interpretation of a complicated index will lead to the same basic conclusion as that reached using a simpler calculation, as illustrated by comparing the trends in Figs. 13–17, and the accuracy is no different. The index figure calculated using HHI, for example, is not providing anything really different than a figure calculated more quickly using a simpler concentration ratio or the market share of the largest producer.

The setting of thresholds is of greater importance for determining whether a market is 'concentrated' or 'highly concentrated'. If these are set too low the position for many minerals will appear to be more concerning than would otherwise be the case. Conversely, if the thresholds are set too high then important supply risks could be missed. Although the setting of these thresholds is inevitably arbitrary, it is a crucial step and it is vital that the thresholds applied in any study are always clearly stated to allow objective comparison with other studies that have been completed or may be undertaken in the future. The thresholds mentioned in Section 3.3 in relation to the UK's CMA are established by laws and regulations for company mergers at both national and European levels (Competition and Market Authority, 2010). In contrast, the reasoning behind the selection of thresholds for the EU's criticality studies is not specified (EC, 2010, 2014, 2017).

The setting of thresholds is directly related to the use of a 'criticality matrix' whereby the risk of supply disruption is plotted along one axis of a diagram against some measure of the impact of that disruption on the other. In EC (2010, 2014 or 2017) this second axis is 'economic importance' but other studies refer to it as 'impact' or 'vulnerability' (NRC, 2008; Glöser et al., 2015). The use of linear thresholds for the two axes in such a diagram divides the matrix into four blocks as illustrated by Frenzel et al. (2017) but in reality the level of criticality is a graduated scale and not something that is binary, i.e. 'critical' or 'not critical' (Graedel et al., 2014). Furthermore, both Frenzel et al. (2017) and Glöser et al. (2015) suggest that a line linking points of equivalent 'criticality' in such a matrix ideally should not be linear but curved, which suggests that the thresholds used in such diagrams should similarly be curved. As noted earlier, a statistical index for mineral supply diversity can be used on its own as an 'early warning' mechanism and for that a set of thresholds similar to the ones specified by the UK's CMA

Index / Measure	Complexi ty of calculation	Risk of false precision	Ease of interpretation	Effect of changes in number of producers
Number of producers	√ √	√ √	√	√
Concentration ratio	√ √	√	√ √	√ √
Normalised HHI	X X	X	X	X X
Un-normalised HHI	X	X	X X	X
Percentage market share (of largest producer)	√ √	√	√ √	√ √
Kwoka's dominance index	X X	X	X X	X
Entropy measure of diversification	X X	X X	X X	X

Fig. 18. Relative comparison of the statistical measures considered by this paper. Key: √ √ best (for this factor), √ acceptable, X not good, X X worst.

would be adequate. However, studies that consider two or more dimensions simultaneously would benefit from a more detailed examination of the appropriateness of any thresholds selected.

Although the calculation of a mineral supply diversity indicator at one point in time may reveal a 'snapshot' of the position in that market at that particular time, it is the trend in the indicator that is most informative. The perception that the supply of a mineral has become more concentrated may not represent the reality if the position is examined over a longer time frame. A gradual change in an indicator to suggest that one supplying country is becoming more dominant may not require any particular policy action to be taken, but over a longer time period that gradual change may appear more significant. Conversely, a dramatic or significant change in an indicator over a short time period may suggest that an urgent response is required whereas in the context of a longer time frame the change may not seem as severe. Datasets containing annualised data over long time periods, such as the World Mineral Statistics dataset used in this paper, are essential to allow these trends to be calculated over sufficient time periods.

5. Conclusions

The examination of mineral supply concentration or diversity is important because increased concentration will increase the risk of potential supply disruption, whether due to a natural causes (e.g. earthquake or volcanic eruption), social upheaval (e.g. worker strike) or geopolitics (e.g. resource nationalism). However, supply concentration only becomes an issue if a supplier holds a dominant position in a market because that country could potentially exert influence over the availability or price of that mineral. The presence of dominance does not itself result in anti-competitive practices rather it is the abuse of dominance that causes problems.

Statistical measures of concentration and dominance, such as those assessed in this paper, are useful for determining which minerals are at greater relative supply risk or for providing an early warning mechanism. As a consequence of these kinds of results, national or international policies or strategies can be focussed on reducing the risk either by increasing supply diversity or mitigation actions. However, it is important that they are used and interpreted correctly and that different measures are applied in combination to ensure the full complexity of global mineral supply is considered.

Analysis of the global production for five mineral commodities at key intervals over the last 100 years provides new insight into how mineral supply concentration has evolved over the last century. This analysis is only possible due to the existence of continuous and consistent datasets such as the BGS "World Mineral Statistics".

A number of statistical measures were used to examine supply concentration and dominance: the number of producers, concentration ratio of the top 4 producing countries, normalised and un-normalised HHI, percentage market share, Kwoka's dominance index and the entropy measure of diversification. Although HHI, Kwoka's index and the entropy measure appear to provide greater precision, they are more complicated to calculate and more difficult to interpret correctly, particularly when the number of producers is changing over time. Similar trends can be observed by calculating concentration ratios and market shares, which are simpler to calculate and more intuitive for non-specialists. A relative comparison of the different measures is summarised graphically in Fig. 18.

The setting of an appropriate threshold for determining levels of 'high concentration' is of greater importance than the selection of a particular index. Although this is generally done arbitrarily, on the basis of 'expert' opinion, the level at which it is set will have a significant impact on the interpretation of the results.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.resourpol.2018.05.007.

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