China, the United States, and competition for resources that enable emerging technologies

Andrew L. Gulley[a,1], **Nedal T. Nassar**[a], **and Sean Xun**[a]

[a]National Minerals Information Center, US Geological Survey, Reston, VA 20192

Edited by T. E. Graedel, Yale University, New Haven, CT, and accepted by Editorial Board Member B. L. Turner February 27, 2018 (received for review September 29, 2017)

Historically, resource conflicts have often centered on fuel minerals (particularly oil). Future resource conflicts may, however, focus more on competition for nonfuel minerals that enable emerging technologies. Whether it is rhenium in jet engines, indium in flat panel displays, or gallium in smart phones, obscure elements empower smarter, smaller, and faster technologies, and nations seek stable supplies of these and other nonfuel minerals for their industries. No nation has all of the resources it needs domestically. International trade may lead to international competition for these resources if supplies are deemed at risk or insufficient to satisfy growing demand, especially for minerals used in technologies important to economic development and national security. Here, we compare the net import reliance of China and the United States to inform mineral resource competition and foreign supply risk. Our analysis indicates that China relies on imports for over half of its consumption for 19 of 42 nonfuel minerals, compared with 24 for the United States—11 of which are common to both. It is for these 11 nonfuel minerals that competition between the United States and China may become the most contentious, especially for those with highly concentrated production that prove irreplaceable in pivotal emerging technologies.

international resource competition | foreign mineral reliance | technology resources | mineral supply risk | critical minerals

New and innovative uses of materials have enabled technological advancements that have long been an important driver of human development. While previous ages of human history can broadly be defined by a single metal or alloy (i.e., Iron Age or Bronze Age), the material compositions of today's emerging technologies encompass almost the entire periodic table and are constantly evolving (1–4). As a result, previously unused elements are now required in unprecedented quantities for everyday artifacts including indium for cellular phones and cobalt for rechargeable batteries; renewable energy generation including dysprosium for wind power and tellurium for solar photovoltaic technologies; and applications important to national security including rhenium for jet engines and germanium for infrared goggles (1, 2).

As demand for these elements has grown, so too has the concern regarding the stability of their supply (5–7). These concerns stem from the fact that many of the elements required for advanced technologies are obtained from mineral commodities that are produced only in a few countries (8), recovered only or mainly as byproducts (9), and generally not recycled in significant quantities after use (10). Recent high profile cases of supply disruptions including China's rare earth element (REE) export quota reduction in 2010 (11) and the prolonged labor strikes in South Africa's platinum mines in 2012 (12) and 2014 (13) have only served to amplify these concerns.

To better understand and perhaps anticipate which raw materials might be at an elevated risk for a supply disruption, a number of organizations and individuals have developed assessments of "criticality" (1, 7, 8, 14–28). These assessments utilize a variety of methodologies and encompass varying temporal, geographic, and material scopes. They generally involve an examination of a number of indicators, including ones that attempt to quantify production concentration, substitutability, price volatility, and recycling, to name a few. Another aspect that is considered by some criticality assessments is net import reliance (NIR). By quantifying how much of a country's domestic consumption of a specific commodity is obtained from foreign sources, NIR indicators provide insights into that country's exposure to a potential supply disruption from foreign sources.

Given their varying scopes, only a few criticality studies have included an assessment of NIR for a wide range of mineral commodities for large economies such as the United States (28) and the European Union (14–16). In addition to these comprehensive studies, a small number of criticality assessments have examined NIR of other countries for a limited number of mineral commodities including the REE for China (29) and copper and a few of its byproducts for the United Kingdom (30). While these assessments consider the NIR of countries individually, this study has attempted to compare the NIR of countries concurrently. Doing so provides insights into interdependency and competition for mineral raw materials among the countries in question that would otherwise not be self-evident when assessed independently.

Here, we seek to inform international competition potential and interdependency for mineral resources by assessing and comparing current foreign mineral dependence for the world's two largest national economies, the United States and China. To measure foreign dependence, we calculate the NIR of China and

Significance

Expanding demand for nonfuel minerals that enable pivotal technologies has elevated concerns regarding supply security, especially for nations that are highly import reliant. Although import reliance has become a prominent concern, few studies assess import reliance and none compare import reliance of countries concurrently. Doing so provides insights into resource interdependency and competition potential. Here, we compare the net import reliance of 42 minerals for the two largest national economies, China and the United States. We find that China relies on imports for over half of its consumption for 19 minerals, compared with 24 for the United States—11 of which are common to both. It is for these 11 minerals that competition between the United States and China may become the most contentious.

Author contributions: A.L.G., N.T.N., and S.X. designed research, performed research, analyzed data, and wrote the paper.

Conflict of interest statement: N.T.N. is a former student of Thomas Graedel, and they have published together, most recently in 2016.

This article is a PNAS Direct Submission. T.E.G. is a guest editor invited by the Editorial Board.

[1]To whom correspondence should be addressed. Email: agulley@usgs.gov.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1717152115/-/DCSupplemental.

the United States (as a percentage of each country's consumption) for 42 mineral commodities—hereafter referred to as "minerals" for simplicity. NIR is calculated as a percentage of each country's consumption and, thus, ranges from a minimum value of zero when the country is a net exporter to a maximum value of 100 when net imports are required to fulfill all of the country's consumption.

To provide a further indication of competition potential, we estimate the concentration of global production for each mineral using the Herfindahl–Hirschman Index (HHI) (31). The HHI, calculated in this analysis as the sum of the squares of each producing country's production share, is a widely used metric for market concentration and is also the basis for the most widely used indicator in criticality assessments (6). It ranges from a theoretical minimum value of zero when production is evenly distributed among an infinite number of countries, to a maximum value of 10,000 when all production is concentrated in a single country. Incorporating this simple market concentration metric provides insights into whether the United States and China have a wide range of supplying countries to choose from or if they are restricted to one or two dominant suppliers. High market concentration will be especially indicative of competition potential for a mineral when both countries rely on foreign imports and their consumption is a large share of that mineral's world production.

A goal of the analysis was to be as comprehensive as possible with regards to mineral coverage in order to provide a broad understanding of the contemporary situation. To achieve this, a number of data sources of varying quality were utilized. Importantly, the analysis is for the year 2014—the most recent year for which a comprehensive set of necessary data are available. Despite these shortcomings, we believe that the results can generally be considered to be representative of the current situation. However, some minerals had to be excluded either due to lack of reliable data or because it was believed that 2014 was not a representative year for that mineral. Finally, it is important to note that the analysis of NIR examines the production, consumption, and trade of the mineral raw materials and does not consider minerals contained in semifinished goods or product components, such as sintered permanent magnets, or finished goods, such as computer monitors. Specifics regarding methodology, assumptions, and data sources, as well as a justification for the geographic, temporal, material, and system scope of the study, are provided in *Methods* and Dataset S1.

Results

The results of the NIR comparison are presented in scatter plot format in Fig. 1, which is divided into four quadrants to represent four states of import reliance. Each quadrant has its own implications for resource dependency and competition. Quadrant 1 contains minerals for which neither country is highly import-reliant. One would expect relatively less competition between the two economies for these minerals because each country's consumption is not significantly greater (and in some cases less) than domestic production. For example, both China and the United States mine more molybdenum (Mo) than they consume. Both countries are thus net exporters. Furthermore, the production of all minerals in this quadrant, except magnesium (Mg), is generally not highly concentrated, as reflected by the relatively moderate median HHI value of 2,245.

In contrast, quadrant 2 contains minerals for which the United States is highly import-reliant, but China is not. Notably, China is a leading source of US imports for 9 of 13 minerals in this quadrant: antimony (Sb), bismuth (Bi), refined cobalt (Co_r), low-purity gallium (Ga_L), germanium (Ge), indium (In), tellurium (Te), yttrium (Y), and REE (32). Aside from Co_r, In, and Te, the production of these minerals is extremely concentrated (i.e., HHI values >5,000), indicating that China is the dominant producer of these minerals globally.

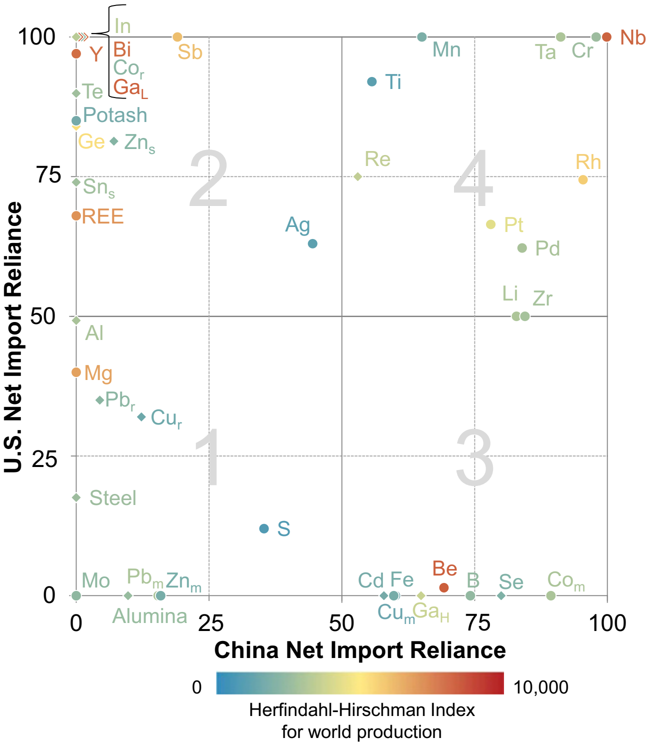

Fig. 1. Net import reliance of the United States (vertical axis) and China (horizontal axis) as a percentage of domestic consumption for 42 minerals for the year 2014. Data denoted by element abbreviation. Circles indicate mine production. Rhombuses indicate refinery or smelter production. Subscripts differentiate between multiple production stages (H, high-purity production; L, low-purity production; m, mine production; r, refinery production; s, smelter production). Each point is colored according to the concentration of that mineral's world production as measured by the HHI at the country level. See Dataset S1 for details.

The position of REE in quadrant 2 epitomizes concerns about Chinese control of raw materials (33). The United States has not always been a net importer of REE. From 1965 through the mid-1980s, the United States dominated REE mine production (34). In the early 1990s, however, China began to exploit its significant REE endowment (35). By the early 2000s, China produced more than 90% of world REE production (32). This shift in global REE production was felt most acutely when, during a 2010 diplomatic row with Japan, China reduced its export quota of REE (33) and exemplified the influence that supply economics and government policy can have on the temporal dynamics of foreign mineral supply dependence.

Reflecting the converse of quadrant 2, quadrant 3 contains minerals for which China is highly import-reliant but the United States is not. Of the eight minerals in this quadrant two, iron ore (Fe) and mined copper (Cu_m) are vital for China's continuing industrialization and urbanization. Their placement in this quadrant reflects unprecedented growth, rather than a lack of domestic resources. In fact, China is the third largest producer of Fe (36) and second largest producer of Cu_m (36).

Of all minerals in quadrant 3, only beryllium (Be) has highly concentrated production and the United States as the dominant producer. Beryllium's position represents a concerted effort by the US Government (most recently in 2005 through the Defense Production Act, Title III) to establish and maintain reliable domestic supply of a strategic mineral for military, aerospace, and nuclear applications (32). Aside from Be, the production of minerals in quadrant 3 is distributed relatively widely across the globe. This suggests that China has a number of countries from which to obtain these minerals. China's supply risk for these minerals is thus relatively lower and China may not need to develop its own resources for these minerals.

Mineral production is often comprised of distinct stages that can take place in different countries. For example, gallium (Ga) has one production stage in quadrant 2 ($\mathrm{Ga_L}$) and another in quadrant 3 ($\mathrm{Ga_H}$). To be used in a component for solar cells, smart phones, light-emitting diodes (LED), or electronic warfare applications (36), Ga must be greater than 99.999% pure (36). To achieve this, low-purity gallium ($\mathrm{Ga_L}$; 99.9–99.99% pure) is produced as a byproduct of processing bauxite and zinc ores (36). Low-purity gallium is then refined into high-purity gallium ($\mathrm{Ga_H}$; 99.999+% pure). $\mathrm{Ga_H}$ is subsequently used to produce gallium arsenide (GaAs) and gallium nitride (GaN) substrates, epiwafers, and devices that will be utilized in advanced technology components (36).

In 2011, China's government began to subsidize LED manufacturing (36), as well as domestic $\mathrm{Ga_L}$ and $\mathrm{Ga_H}$ production (36). Between 2010 and 2015, China's share of global $\mathrm{Ga_L}$ production rose from 33 to over 80% (36, 37). As for $\mathrm{Ga_H}$, China imported over half of the $\mathrm{Ga_H}$ utilized in production of advanced technology components in 2014 but has reportedly expanded $\mathrm{Ga_H}$ capacity such that China now leads the world and is capable of satisfying its $\mathrm{Ga_H}$ consumption needs domestically (37). As with REE, this shift exemplifies the ability of China's government to enact policies that expand domestic mineral production and dominate global mineral markets.

Lastly, quadrant 4 contains minerals for which both countries are highly import-reliant due to consumption in excess of domestic resources or processing capacity. China and the United States are therefore more likely to compete for the 11 minerals in this quadrant—all of which play an integral role in modern society. Niobium (Nb) serves as an alloying agent in high-strength low-alloy steel, which is ideal for bridges, skyscrapers, oil pipelines, and vehicles. Niobium is not mined in either China or the United States. Indeed, ~85% of world primary Nb production comes from a single mine in Brazil, with the remaining production split between a second mine in Brazil and a mine in Canada (36). As an example of recent overseas mineral acquisitions, in 2011 Chinese State-owned enterprises (SOEs) acquired a 15% equity share of the private company that owns Brazil's largest mine and in 2016 another Chinese SOE acquired 100% of the second Brazilian mine (36, 38). While these investments have not expanded the global supply of niobium, they likely reduce China's supply risk for niobium.

Another mineral in this quadrant is chromite ore (Cr), which is required to produce chromium—an essential element in stainless steel. Since 2000, China has greatly expanded its stainless steel production (39). China has been unable to mine sufficient Cr to satisfy its chromium needs for stainless steel production. To obtain the chromium required, China has significantly increased its imports of Cr since 2000. Chromite ore's location in quadrant 4 is thus a result of China's surge to dominance of the global stainless steel market, as well as a lack of Cr production in the United States (36, 39).

The three platinum group metals (PGMs) examined, platinum (Pt), palladium (Pd), and rhodium (Rh), are also in quadrant 4. These PGMs are mostly widely recognized for their use in catalytic converters, which are crucial to reducing exhaust emissions of vehicles with internal combustion engines. To fulfill their needs, both China and the United States rely on imports from South Africa, which is by far the largest PGM producer (36). The combination of high production concentration of PGMs in labor strike-ridden South Africa and China's tightening emissions standards of its growing vehicle fleet may further elevate competition potential for PGMs. Mass adoption of electric vehicles that do not require catalytic converters may, however, decrease the demand for these minerals, while their use in fuel cells may increase demand for Pt.

In addition to foundational applications in modern society (i.e., industrial gas turbines for power generation) (36), as well as environmental quality (i.e., catalysts that produce lead-free, high-octane gasoline), rhenium (Re) is integral to national security. The addition of Re to superalloys—used in turbine blades closest to the combustion zone of a fighter jet engine—allows for closer design tolerances, higher operating temperatures, and improved engine performance (36). Access to Re may thus be a deciding factor in future contests of air superiority.

Rhenium is predominately produced as a byproduct during Mo concentrate roasting, which itself is largely a byproduct of copper (Cu) porphyry production (36). Although the United States has considerable Re resources from its Mo and Cu operations, it does not have sufficient Mo concentrate roasting capacity to meet its own Re needs. Instead, the United States ships most of its Re-bearing Mo concentrate to a plant in Chile, which produces roughly half of the world's Re. The Mo concentrate is roasted; the Re is captured and then purchased by US firms for the production of superalloy turbine blades. In contrast, China's Mo resources contain very low concentrations of Re (40), making its recovery highly inefficient. To meet its needs, China either imports Re metal, Re chemical precursors, or Re containing Mo concentrates. Note that China and the United States are not likely to compete broadly for Mo concentrates to increase Re production because Re is only contained in specific forms of Mo concentrate.

Tantalum (Ta) is a mineral that has been credited with financing armed rebel groups accused of human rights violations in the resource-rich nation of the Democratic Republic of Congo (DRC) (36, 41). In 2010, to disrupt this financing source, the US government designated tantalum, tin, tungsten and gold produced in the DRC and neighboring countries as conflict minerals, the use of which publicly listed companies in the United States must disclose (36, 41). Tantalum appears in quadrant 4 because the United States has no Ta mine production and China has relatively little in comparison with that of Rwanda and the DRC (36). Given that China has no policy restricting the use of conflict minerals, and that over half of current global Ta mine production comes from Rwanda and the DRC, US firms are likely to be more restricted regarding Ta import sources than Chinese firms.

Discussion

The 13 minerals in quadrant 2 may pose a supply risk to US manufacturing industries for which Chinese industries are more insulated. This is especially the case for the nine minerals that the United States primarily imports from China. Conversely, the eight minerals in quadrant 3 may represent raw material vulnerabilities to Chinese manufacturing industries for which US industries are more insulated (only one of which the United States is China's primary import source).

China appears to have reduced its supply risk for several minerals in quadrant 3 including $\mathrm{Co_m}$, $\mathrm{Cu_m}$, and $\mathrm{Ga_H}$. Chinese SOEs have addressed prominent $\mathrm{Co_m}$ and $\mathrm{Cu_m}$ supply risks through so-called "infrastructure-for-minerals" deals with African governments (42, 43). China's potential vulnerability to $\mathrm{Ga_H}$ has likely already been eliminated through domestic capacity expansions.

Finally, the 11 minerals in quadrant 4 represent potential sources of resource competition between China and the United States. Unless reliance can be reduced through substitution, improved processing efficiencies, increased domestic production, or recycling, the United States and China will increasingly vie for access to overseas assets that produce minerals in quadrant 4. For each of the minerals that we identify for competition potential, one of the two largest producers is either African or

South American (South Africa for Cr, Mn, Pt, Pd, Rh, Zr; DRC and Rwanda for Ta; Chile for Re, Li; and Brazil for Nb). This indicates that, geographically, resource rivalry may be most contentious in South and Central Africa, as well as in Brazil and Chile. Increasing demand for minerals that enable sustainable and defensive technologies may intensify international resource competition during the 21st century—especially for minerals that cannot be substituted and have highly concentrated production.

While improvements in recycling, mineral processing, material efficiency, substitution, and domestic production may alleviate import reliance and resource competition in the long run, such factors are often constrained in the short run by existing technology, existing manufacturing capital, and long development timeframes (1, 3, 44, 45). In addition to these factors, increased global mineral production may also be constrained by current prices and the mining policies of host governments (45). Prolonged price increases or more favorable policies could potentially augment global mineral supplies, although such projects face long development timeframes. Given these market dynamics, the results likely reflect the near-term situation for the majority of minerals covered.

Methods

To assess foreign mineral dependence of the United States and China, we calculate NIR of each country for mineral i in year t based on the following equation, where $I_{i,t}$ represents that country's imports for consumption from other countries, $E_{i,t}$ represents its exports to other countries, $P_{i,t}$ represents its domestic production, and $\Delta S_{i,t}$ represents changes in its industry and government stocks:

$$\mathrm{NIR}_{i,t} = \frac{I_{i,t} - E_{i,t}}{P_{i,t} + I_{i,t} - E_{i,t} + \Delta S_{i,t}}. \qquad [1]$$

Note that the denominator of Eq. **1** represents an estimate for the country's consumption, which is referred to as "apparent consumption." In some cases, however, consumption ($C_{i,t}$) is reported rather than estimated. In such cases, $\mathrm{NIR}_{i,t}$ simplifies as follows:

$$\mathrm{NIR}_{i,t} = \frac{C_{i,t} - P_{i,t}}{C_{i,t}}. \qquad [2]$$

Most production data, for both the United States and China, are obtained from US Geological Survey (USGS) publications. US consumption data are either reported or estimated using trade statistics from the US Census Bureau. Chinese consumption data are primarily reported by industry and government sources. Due to insufficient data on Chinese industry and government stocks, levels are assumed to remain constant. For minerals such as bauxite and mined nickel, this assumption cannot be supported and NIR estimates are not made for these minerals. For most minerals however, stock changes are not expected to substantially impact the results. As discussed, the majority of NIR estimates are for the year 2014, but estimates from other years are used when 2014 estimates are not available. Data sources, details, and calculation assumptions are presented in Dataset S1.

Production concentration is measured using the HHI. HHI is calculated for each mineral for the year 2014 based on the following equation, which sums the square of each country's (j) global production share (S) of mineral i in 2014:

$$\mathrm{HHI}_{i,2014} = \sum S^2_{i,j,2014} \qquad [3]$$

HHI values are obtained from ref. 7. based mainly on production data from USGS publications, with a few minor modifications, which are again detailed in Dataset S1.

It is important to note that data for mineral production, consumption, and trade are difficult to obtain or verify and, in some cases, different sources provide contradictory information. This is especially the case for the minor metals for which little published data are available. In conducting this analysis, we have sought to utilize the best available information and have sought to be as transparent as possible regarding data sources and assumptions.

Geographic Scope. The geographic scope of this analysis focuses on two countries (China and the US) that are not only the largest national economies with significant mineral resource endowments but that are also emblematic of many nations whose material-intensive manufacturing industries depend on imported raw materials. China has perhaps become the most influential mineral producing, mineral consuming, and manufacturing country in the world. While the focus of popular media has been on China's REE export quotas, a more pressing concern may be that China is consuming increasing proportions of its own mineral production. China may thereby become a net importer of minerals that it had previously provided to industries in other countries.

In contrast to China's global mineral dominance stands the United States, whose situation is similar to many developed material-intensive nations. A lack of comparative advantage has dampened domestic mineral production to the point that the United States is now heavily dependent on foreign resources (many of which come from China) for its manufacturing industries (46).

The trade relationship between China and the United States is thus representative of China's relationships with other developed material-intensive countries. We therefore focus on China and the United States because the countries and their relationship provide valuable insight into the global dynamics driving international resource competition potential.

Temporal Scope. The temporal scope of this analysis focuses on the most recent year with sufficient data to estimate the NIR of China and the United States for a wide range of mineral commodities—2014. Although insufficient data preclude more recent analysis, annual changes in mineral production (and consumption) are often muted by long lead times in capacity expansions (5–10+ years). Therefore, although mineral production and consumption have transformed over the last two decades for China (and to a lesser extent the United States), 2014 estimates are broadly representative of the contemporary situation.

System Scope. The system focus of this assessment is the first two (or three) upstream production stages of minerals that are, in turn, utilized by manufacturing and industrial processes. These distinct stages often take place in different countries. For example, cobalt mined in the DRC may be shipped to Zambia for intermediate processing before being traded to China for refinery production. It may then be alloyed with other metals and incorporated into final products that may be used by US consumers for a certain period of time and subsequently recycled elsewhere. In this example, our scope is limited to the first and third production steps, which will provide different results than focusing on the consumption of final products. To address the issue of recycling stocks, we include secondary production from recycling (if any) in each country's production estimate and NIR calculation. Additional discussion of production stages and resulting raw material trade is provided in *Results* where the supply chain of Ga is provided as an example.

ACKNOWLEDGMENTS. We thank the commodity specialists and materials flow analysts at the USGS's National Minerals Information Center for much of the data relied upon in this analysis.

1. National Research Council (2008) *Minerals, Critical Minerals, and the US Economy* (US National Research Council, National Academies Press, Washington, DC).
2. National Research Council (2008) *Managing Materials for a Twenty-First Century Military* (National Academies Press, Washington, DC).
3. Graedel TE, Harper EM, Nassar NT, Reck BK (2015) On the materials basis of modern society. *Proc Natl Acad Sci USA* 112:6295–6300.
4. Greenfield A, Graedel TE (2013) The omnivorous diet of modern technology. *Resour Conserv Recycling* 74:1–7.
5. Erdmann L, Graedel TE (2011) Criticality of non-fuel minerals: A review of major approaches and analyses. *Environ Sci Technol* 45:7620–7630.
6. Graedel TE, Reck BK (2016) Six years of criticality assessments: What have we learned so far? *J Ind Ecol* 20:692–699.
7. McCullough E, Nassar NT (2017) Assessment of critical minerals: Updated application of an early-warning screening methodology. *Miner Econ* 30:257–272.
8. National Science and Technology Council (2016) *Assessment of Critical Minerals: Screening Methodology and Initial Application* (Office of Science and Technology Policy, Washington, DC).
9. Nassar NT, Graedel TE, Harper EM (2015) By-product metals are technologically essential but have problematic supply. *Sci Adv* 1:e1400180.
10. Graedel TE, et al. (2011) What do we know about metal recycling rates? *J Ind Ecol* 15:355–366.
11. Hatch GP (2012) Dynamics in the global market for rare earths. *Elements* 8:341–346.
12. Yager TR, Soto-Viruet Y, Barry JJ (2013) Recent strikes in South Africa's platinum group metal mines: Effects upon world platinum group metals supplies (US Geological Survey, Reston, VA), Open-File Report 2012–1273.

13. Loferski PJ (2016) *Platinum-Group Metals. 2014 Minerals Yearbook* (US Geological Survey, Reston, VA), pp 57.1–57.12.
14. European Commission (2010) Critical raw materials for the EU. Report of the Ad-hoc Working Group on defining critical raw materials (European Commission, Brussels).
15. European Commission (2014) Report on critical raw materials for the EU. Report of the Ad hoc Working Group on defining critical raw materials (European Commission, Brussels).
16. Deloitte Sustainability British Geological Survey, Bureau de Recherches Géologiques et Minières, Netherlands Organisation for Applied Scientific Research (2017) Study on the review of the list of critical raw materials (European Commission, Brussels). Available at https://publications.europa.eu/en/publication-detail/-/publication/08fdab5f-9766-11e7-b92d-01aa75ed71a1/language-en. Accessed September 25, 2017.
17. Graedel TE, et al. (2012) Methodology of metal criticality determination. *Environ Sci Technol* 46:1063–1070.
18. British Geological Survey (2011) Risk list 2011 (National Environmental Research Council, British Geological Survey, Nottingham, UK).
19. British Geological Survey (2012) Risk list 2012 (National Environmental Research Council, British Geological Survey, Nottingham, UK).
20. British Geological Survey (2015) Risk list 2015 (National Environmental Research Council, British Geological Survey, Nottingham, UK).
21. Robinson GRJ, Menzie WD (2012) Economic filters for evaluating porphyry copper deposit resource assessments using grade-tonnage deposit models, with examples from the U.S. Geological Survey global mineral resource assessment (ver. 1.2, March 2014) (US Geological Survey, Reston, VA), Scientific Investigations Report 2010–5090–H.
22. Morley N, Eatherley D (2008) *Material Security: Ensuring Resource Availability for the UK Economy* (Oakedene Hollins, C-Tech Innovation Ltd, Chester, UK).
23. Duclos S, Otto J, Konitzer G (2010) Design in an era of constrained resources. *Mech Eng* 132:36–40.
24. Moss RL, Tzimas E, Kara H, Willis P, Kooroshy J (2011) *Critical Metals in Strategic Energy Technologies—Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Technologies* (Publications Office of the European Union, Luxembourg).
25. Moss RL, Tzimas E, Willis P, Arendorf J, Tercero Espinoza L (2013) *Critical Metals in the Path Towards the Decarbonisation of the EU Energy Sector* (European Commission Joint Research Centre Institute for Energy and Transport, Luxembourg).
26. Bauer D, et al. (2011) *Critical Materials Strategy* (US Department of Energy, Washington, DC).
27. Bauer D, et al. (2010) *Critical Materials Strategy* (US Department of Energy, Washington, DC).
28. Graedel TE, Harper EM, Nassar NT, Nuss P, Reck BK (2015) Criticality of metals and metalloids. *Proc Natl Acad Sci USA* 112:4257–4262.
29. Nassar NT, Du X, Graedel TE (2015) Criticality of the rare earth elements. *J Ind Ecol* 19:1044–1054.
30. Graedel TE, Nassar NT (2013) The criticality of metals. *Ore Deposits in an Evolving Earth Special Publication*, eds Jenkin GRT, et al. (Geological Society, London), pp 291–302.
31. Herfindahl OC (1950) Concentration in the steel industry. Doctoral dissertation (Columbia University, New York).
32. U.S. Geological Survey (2017) *Mineral Commodity Summaries 1996-2017* (US Geological Survey, Reston, VA).
33. Krugman P (October 17, 2010) Rare and foolish. *New York Times*, p A35.
34. Haxel GB, Hedrick JB, Orris GJ (2002) *Rare Earth Elements—Critical Resources for High Technology* (US Geological Survey, Reston, VA).
35. Weng Z, Jowitt SM, Mudd GM, Haque N (2015) A detailed assessment of global rare earth element resources: Opportunities and challenges. *Econ Geol* 110:1925–1952.
36. USGS(2016) *2014 Minerals Yearbook* (US Department of the Interior, US Geological Survey, Reston, VA).
37. Rongguo C, Juan G, Liwen Y, Huy D, Liedtke M (2016) *Supply and Demand of Lithium and Gallium* (Information Center of Ministry of Land and Resources, Federal Institute for Geosciences and Natural Resources, Hannover, Germany).
38. Roskill Information Services Ltd (2017) Niobium continues to attract investment. Available at https://roskill.com/news/niobium-continues-attract-investment/. Accessed April 3, 2017.
39. Reck BK, Chambon M, Hashimoto S, Graedel TE (2010) Global stainless steel cycle exemplifies China's rise to metal dominance. *Environ Sci Technol* 44:3940–3946.
40. Chen Y-J, Zhang C, Wang P, Pirajno F, Li N (2017) The Mo deposits of Northeast China: A powerful indicator of tectonic settings and associated evolutionary trends. *Ore Geol Rev* 81:602–640.
41. Gettleman J (2013) Price of precious. *Natl Geogr Mag*. Available at ngm.nationalgeographic.com/2013/10/conflict-minerals/gettleman-text. Accessed March 16, 2018.
42. BBC (2007) China opens coffers for minerals. *BBC News*. Available at: news.bbc.co.uk/2/hi/africa/7000925.stm. Accessed May 10, 2017.
43. Aaron Ross (2015) China's "infrastructure for minerals" deal gets reality-check in Congo. *Reuters Insight*. Available at: https://www.reuters.com/article/congodemocratic-mining-china/insight-chinas-infrastructure-for-minerals-deal-gets-reality-check-in-congo-idUSL8N0ZN2QZ20150708. Accessed May 10, 2017.
44. Tilton JE (2003) *On Borrowed Time?: Assessing the Threat of Mineral Depletion* (Resources for the Future, Washington, DC).
45. Tilton JE, Guzmán JI (2016) *Mineral Economics and Policy* (Routledge, New York).
46. Fortier SM, DeYoung JHJ, Sangine ES, Schnebele EK (2015) *Comparison of U.S. Net Import Reliance for Nonfuel Mineral Commodities—A 60-year Retrospective (1954–1984–2014)* (US Geological Survey, Reston, VA).