



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

Andrew L. Gulley<sup>a,1</sup>, Nedal T. Nassar<sup>a</sup>, and Sean Xun<sup>a</sup>

<sup>a</sup>National Minerals Information Center, US Geological Survey, Reston, VA 20192

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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.

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<sup>1</sup>To whom correspondence should be addressed. Email: agulley@usgs.gov.

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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 ( $Ga_L$ ) and another in quadrant 3 ( $Ga_H$ ). 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 ( $Ga_L$ ; 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 ( $Ga_H$ ; 99.999+% pure).  $Ga_H$  is subsequently used to produce gallium arsenide (GaAs) and gallium nitride (GaN) substrates, epitaxial wafers, 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  $Ga_L$  and  $Ga_H$  production (36). Between 2010 and 2015, China's share of global  $Ga_L$  production rose from 33 to over 80% (36, 37). As for  $Ga_H$ , China imported over half of the  $Ga_H$  utilized in production of advanced technology components in 2014 but has reportedly expanded  $Ga_H$  capacity such that China now leads the world and is capable of satisfying its  $Ga_H$  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  $Co_m$ ,  $Cu_m$ , and  $Ga_H$ . Chinese SOEs have addressed prominent  $Co_m$  and  $Cu_m$  supply risks through so-called "infrastructure-for-minerals" deals with African governments (42, 43). China's potential vulnerability to  $Ga_H$  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:

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

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,  $\text{NIR}_{i,t}$  simplifies as follows:

$$\text{NIR}_{i,t} = \frac{C_{i,t} - P_{i,t}}{C_{i,t}} \quad [2]$$

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:

$$\text{HHI}_{i,2014} = \sum S_{i,j,2014}^2 \quad [3]$$

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.

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