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Effect of Chinese policies on rare earth supply chain resilience

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ABSTRACT

Rare earths elements (REE) are considered as strategic resources because they interact with business and governments' direct policy interventions. Policy interventions can have a major effect on security of rare earth supply (Kooroshy et al., 2015). The purpose of this study is to scrutinize China's REE policies and its impacts on the supply chain resilience. We analyze the supply chain dynamics by specifically targeting a number of Chinese REE policies that have disruptive tendencies. We analyze various policies placing the price at the center as an overarching feedback loop. In other words, we focus on how price responds to various resilience influencing mechanisms such as diversity of supply, regulatory frameworks, and stockpiling. In the process, we investigate Chinese influence on rest of the world (RoW) supply chain and dynamics inside the Chinese supply chain as there are two different layers of supply chain one for China and another one for rest of the world. We show that the supply chain is a complex phenomenon and resilience of a system is not solely dependent on physical disruptions but also on dynamic factors such as societal and geo-political (eg. environmental regulation, speculative market and export ban). We identify links and interdependencies even where data is not readily available and examine how the overall system reacts to various constraints and disruptions.

1. Introduction

Disruptions can have a major effect on security of supply. This is especially true for critical materials. There are many examples of disruptions–ranging from floods to trade disputes to civil wars–and in the past decades severe supply chain disruptions affected a significant number of materials.

Conceptually, disruptions can happen either slow or fast, and on the supply or demand side. This classification gives four types, as seen in Table 1.

The most prominent method of determining and analyzing material criticality, Graedel et al. (2012), primarily takes disruptions into account through mining investment risk indicators which are in turn based on political stability of the host country through the ratio of foreign and domestic supply. This ratio is used to determine the vulnerability to supply disruptions.

An alternative viewpoint to supply chain disruptions is that of trade flows. Trade and trade disruptions can be analyzed in physical terms. For example, Gholz and Daryl, (2010) discussed the possibility of a disruption to global oil trade if Iran would use anti-ship missiles to block the Strait of Hormuz. Olson (2015) speculates that only an interruption of service at a major port would be able to significantly disrupt global trade in aluminum. Mancheri et al. (2018) found that in case of tantalum, physical disruptions did not affect the supply chain seriously as the industry's ability to respond is well characterized by resilience-promoting mechanisms such as diversity of supply, stockpiling, and substitution.

In an attempt to predict which supply chains will be disrupted beyond identifying which materials are critical, resilience is a useful way of thinking about how to deal with inevitable disruptions of all types, especially those of the unexpected kind. To do so, we investigate a number rare earth policies that China introduced in post 2010 crisis and evaluate how these policies affect the REE supply chain, and prices. By applying the resilience framework, we try to generate a wider understanding of legislative and environmental risk and its impact on the global REE supply chain.

We argue that politics – and specifically industrial and trade policies – have a much larger influence on trade flows than physical disruptions. In this paper we aim to address the disruptions in the rare earth supply chain from the perspective of trade flows and policy. We focus on the effect of policy on the rare earth supply chain and use this analysis to update the critical materials resilience framework with a number of trade and policy related parameters.

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Table 1
Types of system disturbances (Sprecher et al., 2015).

	Supply	Demand
Fast	Natural disaster, trade embargo	Disruptive demand change
Slow	Protective trade measures, ore depletion	Societal or technological trends

1.1. Rare earths

Rare earths are used in numerous products such as battery alloys, polishing powders, liquid crystal displays (LCDs), hybrid cars, and light emitting diodes (LEDs). They also have a strategic role in such military applications as guidance and control, targeting and weapon systems, and communication platforms (US. Department of Energy, 2011). China is the world's largest producer, consumer and exporter of rare earths, controlling more than 90 percent of the global supply base with a virtual monopoly. Currently, Chinese REE extraction expertise remains unparalleled, the necessary production capacities, infrastructure and distribution channels all exist with a fairly lax environment, including work place safety regulations and low labor costs.

The two major drivers of demand for REEs are the rate of overall economic growth and the new development in material applications. For example, sustainable technologies which include REE have grown dramatically in the last two decades. The most rapid growth has been in demand for new applications including magnets, phosphors, catalysts and batteries, which now account for over 60 percent of the demand, and will continue to grow, fueled by heavy investments in clean energy.

Table 2 shows typical quantities of REEs used in the different intermediate products. Each intermediate product uses only some of the 17 REEs. Lanthanum and cerium for example are the two REEs used in the catalysts for petroleum refining. In contrast, permanent magnets use Praseodymium, Neodymium, Gadolinium, Dysprosium and Terbium. Magnets dominate REE usage by weight and value. Catalysts claim the second-highest usage, and metal alloys account for the third highest (Kingsnorth, 2018).

China controls the global REE industry and has established a dominant position in the entire value chain. This control extends all the way from mining to the production of key intermediate products such as magnets. Many of these intermediate products are critical inputs for high growth industries. These are also the industries in which China is trying to build scale with the aim of dominating the supply chain (Mancheri et al., 2013).

In 2010 and 2011 when the Chinese export restrictions became more apparent, many of the world's experts predicted a supply deficit of rare earth oxides (REO) in future, as demand expected to exceed the industry's ability to produce. However that situation has changed since 2013. China's increased production quota and removal of export quotas along with new or reopened mines outside China are expected to increase global production, resulting in an overall surplus, shortfalls are expected in certain elements, particularly in neodymium and europium, and the heavy rare earths such as terbium and dysprosium. Demand for rare-earths is likely to increase between 7–8% annually (Kingsnorth, 2016).

Table 2
Estimated Global Rare Earths Demand (by application in 2017).
Source: Based on Table 3, Kingsnorth (2018).

Application	Total (in tons)	Market share (%)
Catalysts	30,000	18
Glass	9,500	6
Polishing	22,000	14
Metal Alloys	31,000	18
Magnets	51,000	30
Phosphors (including pigments)	5000	3
Ceramics	8500	5
Other	10,500	6
Total	167,500	100

China was a small producer and an exporter of low value REE concentrates prior to 1990s. From 2000 onwards China became the world's leading producer and exporter, and quickly achieved near-monopoly control over the REE supply chain. China was able to acquire their position from 2000 to 2015 via operational cost competitiveness. During this period, China has introduced several policies related to REEs that have had profound effects on rare earth supply chain globally. China's introduction of these policies were targeted to the overall development of the REE industry, domestic industrial needs, curtailing over exploitation and illegal mining. In addition, the government also targets domestic companies to add value by making technologically advanced products rather than exporting the raw material. While China restricted the export of minerals, there were no specific restrictions on exports of finished products. The major REE policies that China implemented since 2015 in achieving the above mentioned targets are depicted in the Fig. 1.

An overview of REE industry in China including the performance, problems the industry faces and the targeted policy objectives were described in a document released by the China Ministry of Industry and Information Technology in October 2016 (MIIT, 2016). The document advocates more state intervention to tackle internal problems such as illegal rare earth production, illegal transaction and processing, lack of innovation, overcapacity problems in upstream sectors and poor legal and regulatory systems to address environmental pollution. The REE development objectives of the government is summarized in the Table 3.

The proposed policy targets explained in Table 3 will influence the REE supply chain resilience in different ways. Our analysis in the results are directly linked to the observed indicators in Table 3. Having observed the efficacy of a resilience framework in analyzing supply chain disruptions, we extend the resilience model to include the Chinese REE policies (Sprecher et al., 2015).

1.2. Literature review on REEs and policy

As an important strategic mineral resource, REE has been a hot topic for research in recent years. When focusing on REE resource or industry, some scholars holistically observed its reserve, production, consumption and international trade (Feng, 2007; Tse, 2011; Mancheri, 2012; Massari and Ruberti, 2013; Nieto and Zhang, 2013; Mancheri, 2015; Nguyen and Imholte, 2016; Wang et al., 2016) or only focused on one kind of rare earth, such as ion-adsorption rare earth (Yang et al., 2013) or single elements (Zhang et al., 2017) and applications (Kulekci, 2009; Goonan, 2012; Sprecher and Kleijn, 2014, 2017). The uneven distribution and difficulty to substitute rare earths led to studies on its supply security and trends. Zhang et al. (2017) exclusively dealt with supply security and criticality of Yttrium and found that Yttrium production causes a variety of environmental/sustainability issues, making the supply vulnerable to more stringent environmental politics. Han (2015), Mancheri et al. (2013) and Wübbeke (2015) discussed China's rare earth policy and proposed some policy implications, such as boosting innovation capability and establishment of a strategic resource reserve system. Nevertheless, even though China's rare earth supply has declined, some studies indicated that there is little significant shortage of rare earth supply for the rest of world (Golev et al., 2014; Tukker, 2014; Rollat et al., 2016) because some countermeasures have been adopted by foreign countries (Mancheri and Marukawa, 2016; Sprecher et al., 2015; Dobransky, 2013; Barteková and Kemp, 2016). More experts turned to consider the recycle and waste management of REE because they are new potentially major sources for supply (Bailey et al., 2017; Schulze and Buchert, 2016 and Binnemans et al., 2013; Morf et al., 2013; Rademaker et al., 2013; Habib and Wenzel, 2014;

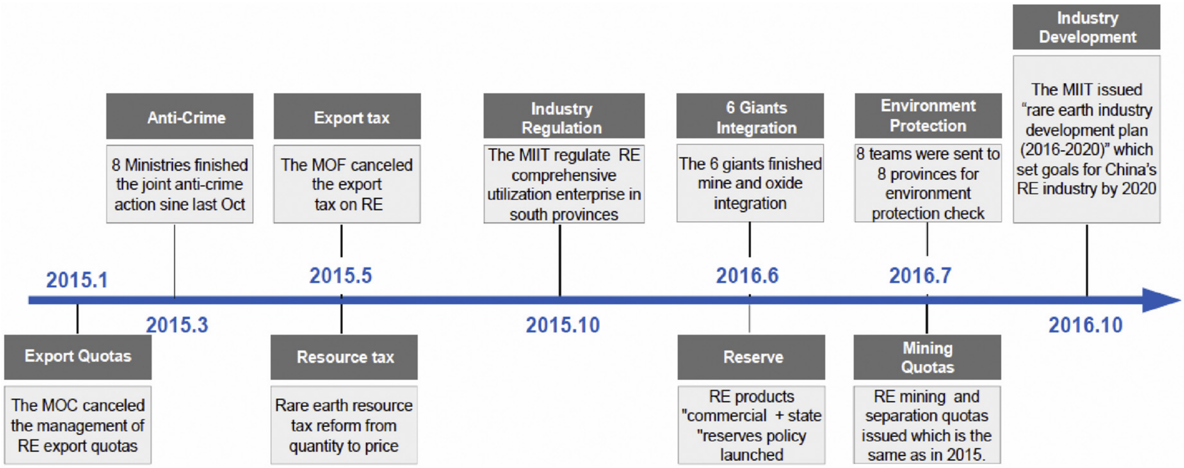

Fig. 1. Various REE policies that China implemented since 2015. Reference: Hu, 2016.

Machacek et al., 2015). Moreover, the recycling and waste management of REE can also contribute to minimizing the negative environmental impacts caused by rare earth production (Wan and Wen, 2015). In addition, there have been studies on replacement of REE as input and its effects on clean energy development (Alonso et al., 2012; Kleijn, 2012; Riddle et al., 2015; Stegen, 2015).

As the largest producer and exporter of rare earths, China's rare earth policies, especially the export restrictions have been of considerable interest in recent years. Several studies demonstrated that the motivations of China's rare earth policy were the domestic concerns, such as environmental protection and resources conservation (Gu, 2011; Hayes-Labruto et al., 2013; Wübbeke, 2013; Barteková and Kemp, 2016), the development of competitive downstream industries (Wübbeke, 2015), and the relocation of rare earth intensive industries (Pothen and Fink, 2015). However, some studies found that the restrictions did not fulfill the objective of environmental protection (Korinek and Kim, 2010; Gavin, 2013; Mancheri, 2015) and violated international trade law (Hu, 2012; WTO, 2014). Rare earths are cheaper to make in China because of less strict environmental standards. Perhaps, the western countries could pay a subsidy to compensate the environmental pollution but this again would violate trade law. This presents an even greater challenge because it is difficult to quantify the cost differences due to different environmental regulations (U.S. Office of Technology Assessment, 1992)

China's rare earth policies have impacted both domestic and foreign rare earth industry. Lackner and McEwen-Fial (2011) and Zhang et al. (2015) indicated that China's rare earth policies exerted significant effects on the market power and price sensitivity of China's rare earth in the international market. Especially, the export restrictions would raise the world price, threat the stable supply (Zachmann, 2010; Wübbeke, 2015; Mancheri, 2015), and hamper global transition to low-carbon energy and mobility systems (Tukker, 2014). On the contrary, some other studies considered that there was a limited influence of China's rare earth policies on the international markets (Müller et al., 2012). Nevertheless, almost all studies concluded that China's rare earth export restrictions would lower the supply of rare earths to the rest of the world. Therefore, there are emerging studies focusing on the sources of rare earth both in China and other countries. For example, Wang et al. (2015) and Ge et al. (2016) made a supply forecast of China's rare earth while some other papers focused on the supply outside China (Christmann, 2014; Machacek and Fold, 2014; Golev et al., 2014).

As the Chinese policies have begun to impact the supply chain, more and more researchers have turned the focus to the domestic policies of China. For example, pollution tax (Wan and wen, 2015), resources tax (Han et al., 2015), industry integration (Cui and Zhao, 2015; Han et al., 2016; Rao, 2016) and industry upgrade (Mancheri and Marukawa,

Table 3
The development of the rare earth industry main target during the "13th Five-Year Plan".

Indicators	Actual in 2015	Targets by 2020	Cumulative percentage change during "13th five-year"
Economic Indicators			
Average annual growth rate of industrial added value(%)	12.5	16.5	—
Industry profit margins(%)	5.8	12	[6.2]
R & D expenditure of key enterprises accounted for the proportion of the main income(%)	3	5	[2]
2. Production Indicators			
Smelting separation capacity (Million tons)	30	20	[-10]
Production of rare earth smelting and separation products (Million tons)	10	< 14	[< 4]
Recovery rate of mineral processing of light rare earth ore(%)	75	80	[5]
Comprehensive recovery rate of recovery of ion type rare earth ore(%)	75	85	[10]
Light rare earth smelting separation recovery rate(%)	90	92	[2]
Ion type rare earth smelting separation recovery rate(%)	94	96	[2]
The integration of the two standards of Enterprise Accounting(%)	30	90	[60]
3. Green Development Indicators			
Reduction of major pollutants emission intensity in the whole industry (Containing sulfur dioxide, ammonia nitrogen, waste water, etc., %)	—	—	[20]
Proportion of enterprise achieving energy consumption standard(%)	40	90	[50]
4. Application Industry Development Indicators			
Market share of high-end rare earth functional materials and devices(%)	25	50	[25]
Proportion of primary raw materials for export products(%)	57	30	[-27]

Inside the brackets [] are cumulative numbers for five years. Source: MIIT, 2016, Rare Earth Industry Development Plan (2016–2020) (translated from Chinese).

2016) are treated as good options for the Chinese government to improve the development of rare earth industry.

The previous literature has looked at Chinese policy in the REE arena, but none have been evaluated through the lens of the resilience framework. In this work we use the resilience framework for critical materials, as introduced in Sprecher et al. (2015). We assert this particular framework is particularly powerful because it evaluates all 4 primary mechanisms: diversity of supply, stock piling, recycling and substitution. Examining the resilience of REE materials in China is becoming as critical as the rare earths themselves. With this evaluation we hope to predict the survival (and resilience?) of the REE supply chain. We extend this framework to include the Chinese REE policies as resilience influencing (either positive or negative) mechanisms. The identified resilience influencing mechanisms are in no particular order: quotas, taxes, international trade laws, China's import of REEs, investment abroad, standardization, stockpiling, environmental regulations, consolidation of the industry, and exchange and speculation market.

2. Method and data

Application of resilience theory for the supply chains of raw materials offers an effective theoretical framework for studying how systems responds to disruptions (short term disturbances) and constraints (long-term disturbances). For the supply chains of raw materials, resilience is defined as 'the capacity to supply enough of a given material to satisfy the demands of society, and to provide suitable alternatives if insufficient supply is available'. In Sprecher et al. (2017), the framework is explained to 'consist of four primary mechanisms that promote resilience. On the supply side, 1) diversity of supply (e.g. primary production in different countries and recycling) is a crucial mechanism to prevent disruptions, while 2) stockpiling of materials, which can buffer against the impact of temporary supply disruptions. On the demand side, the producers have the option of 3) improving the properties to reduce material demand. Finally, 4) substitution can play a significant role in dampening the effects of a supply disruption.

For example, in the case of neodymium-iron-boron- magnet (NdFeB) supply chain, Fig. 2 shows each of these four mechanisms are connected to specific actors in the REE supply chain. The mechanisms influence each other primarily via the neodymium price feedback loop.

One notable feature of the resilience framework is that it is based on a material flow analysis (MFA) approach to supply chains. The framework puts materials front and center and the discussion of threats to security of supply and the solutions to those threats are also framed as material solutions (e.g. The problem of reduced ore grades can be alleviated by increased recycling).

We extend this basic framework to include China's rare earth policies and analyze how the REE supply chain responds to various policies. These policies are introduced in the framework as resilience influencing mechanisms. Three main variables and a sub set of factors under them are identified and analyzed through the lens of resilience framework.

The identified factors are:

1) Restrictions on trade between China and RoW
 a quotas b) taxes and c) international trade laws
2) Chinese influence on RoW supply chain
 a China's import of REEs b) investment abroad c) standardization
3) Dynamics inside the Chinese supply chain
 a stockpiling, b) environmental regulations c) consolidation of the industry d) exchange and speculation market.

This is a qualitative attempt to analyze the Chinese rare earth policies and its impact on supply and should not be viewed through the prism of quantitative methodologies used in literature to investigate the material system dynamics and supply disruptions.

Insights in Chinese policy are based on literature research and interviews with key actors. Data are collected from both primary and secondary sources. The primary source involves interaction with stakeholders, subject experts and documents from government agencies. Descriptive statistics in the analysis are based on the time-series export and import data found in UNCOMTRADE data base. VENSIM software was used to construct the system dynamics figures.

3. Results

In this work we focused specifically on the effects that Chinese policy has on the REE supply chain. Fig. 3 shows the system dynamics of the supply chain as investigated. An essential feature of the REE supply chain is the distinction between the Chinese supply chain and the RoW supply chain. The two are connected via global trade flows and these flows are influenced by policy.

Fig. 3 shows the dynamics of REE supply chain. Here we charted all the supply disruptions, highlighted in red in Fig. 3. For each of the disruptions we will first describe what happened and then indicate how this influences the overall system. Increased demand causes an increase in price, while increased supply influences the price negatively. The price acts as an overarching loop influenced by all factors identified by

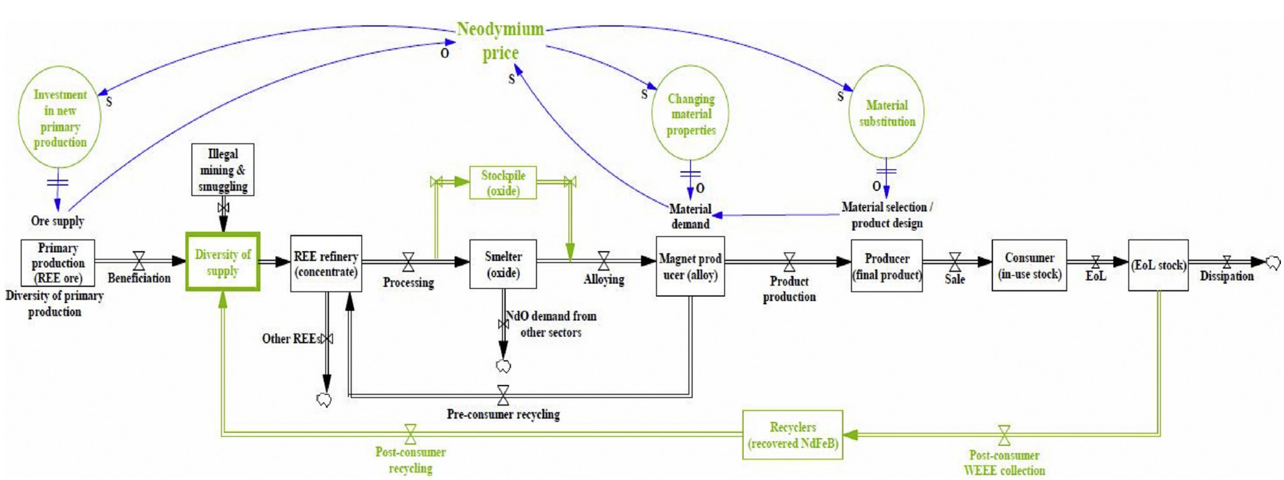

Fig. 2. The conceptual model of the NdFeB supply chain (black) and the associated resilience mechanisms (green). The blue arrows indicate the direction of influence: S = same, O = opposing. < ref Sprecher 2017. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

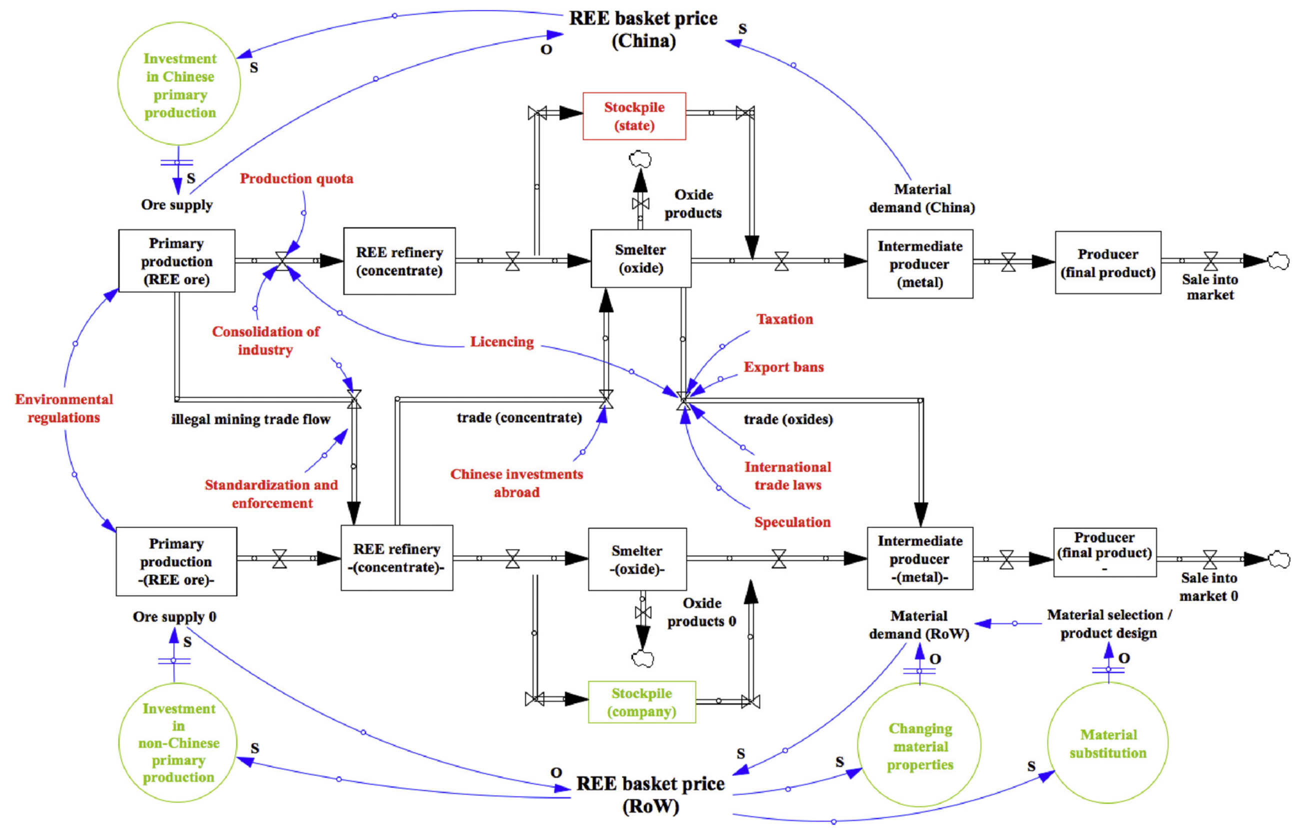

Fig. 3. Shows where the various types of policy influence the overall supply chain, and the direction of the influence. Compared to Fig. 2, this figure introduces blue arrows with dots– indicating a significant delay in the feedback – as red parameters, indicating the different types of disruptions discussed here. Green represents resilience promoting mechanisms as discussed widely in Sprecher et al., 2017 and Mancheri et al., 2018. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

red and green in Fig. 3. Pricing is highly obscure in REE sector and prices are very often affected by Chinese domestic policies as the country controls more than 90 percent of global supply. For example, the tightening supply policies of China caused the sharpest increase in REE prices between 2009-11. The heavier rare earths (e.g., dysprosium, terbium and europium) are more expensive, and historically prices have risen steadily for these elements due to China's rising domestic demand and escalating export controls.

3.1. Restrictions on trade between China and RoW

3.1.1. Quotas

Several objectives motivate implementing quotas on raw material production and export. Generally, the rationale behind imposing the quota is to ensure supply to domestic downstream industries or as means to influence the prices of specified commodities. In some cases, imposing quota is justified as a response to market imperfections or on the ground of protecting environment and resources.

The most restrictive measures that China imposed on REEs were quotas on production, export and other restrictions on mining and separation companies (Hatch, 2010). China's Ministry of Commerce (MOFCOM) used to allot quotas to companies. The export quota has declined almost 50 percent from 2008, until it abolished in 2014. The production quota has remained same from 2014 to 2017 and there is a modest increase in 2018, which is set at 120,000 tons (Table 4). During the quota regime, China didn't distinguish between the individual rare earth oxides, but divided the total tonnage of exports as light rare earth and medium-and-heavy rare earth. This has led to Chinese companies preferring to export as much as possible the high value heavy rare earths like dysprosium, instead of low-value light rare earths like cerium (communication with Chinese companies).

Table 4
China's production quota and export quota (in tons).
Source: Kingsnorth, 2016 and Asian Metal, 2018

Year	Production quota	Export quota
2010	89,200	30,258
2011	93,800	30,246
2012	93,800	30,996
2013	93,800	30,999
2014	105,000	30,610
2015	105,000	–
2016	105,000	–
2017	105,000	–
2018	120,000	

As depicted in Fig. 3, China's restriction of production through quotas is a supply chain constraint (long-term disturbances) rather than an abrupt disruption, which influences domestic and international prices positively (Brown and Eggert, 2017). However, a quota on export volume directly disrupts the global supply, positively influences international price and demotes the resilience of the system. The positive influence of China's export curbs on international price prompts investment in non-Chinese primary production. For example, 2010-11 price spike had created opportunities to open mines or revive production in US, Australia and Canada (Machacek and Fold, 2014). However, none of these projects could emerge as an alternative to Chinese supply. Chinese removal of export quota and export tariff on rare earths, along with a considerable amount of illegal material entering global market had led to decline in long term average price of REEs since mid-2012. The low prices are attractive for consumers but place an impossible burden on new ROW projects to be financially viable; thereby denying customers the diversity of supply needed for a resilient system.

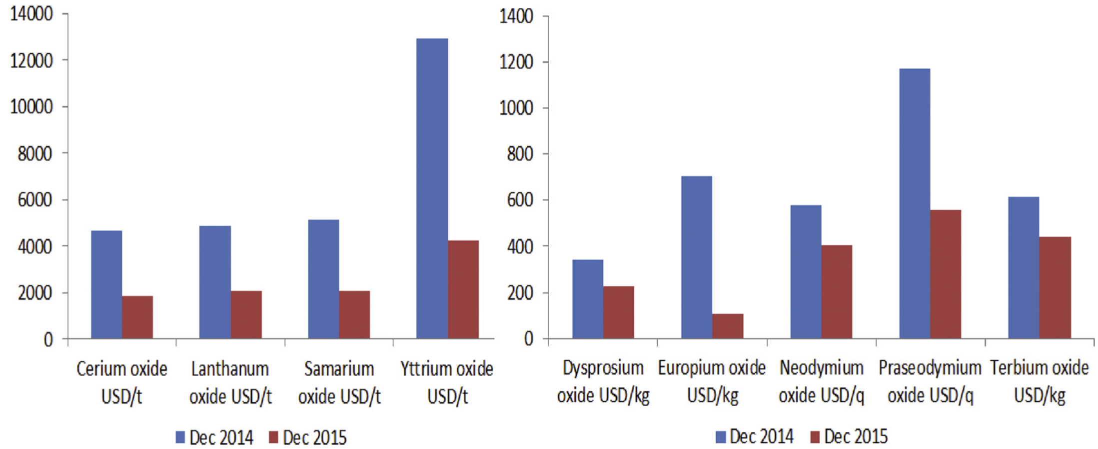

Fig. 4. Chinese rare earth oxide prices December 2014- December 2015- (FOB), Source: Argus metal page, 2016.

Eliminating existing quotas strengthen the global supply and promote the REE resilience. This can have rebound effects on decreasing black market trade of rare earths.

3.1.2. Export taxes

Export taxes as high as 27 percent were applied to many of the rare earths in China and 41 REE products have been listed as prohibited trade goods. REE exporters, including foreign companies face stricter supervision on their business activities. Starting in May 2015, the Chinese government removed export taxes on REEs and introduced a new resource tax based on value rather than on volume. The more critical heavy rare earth concentrates are taxed at a blanket 27 percent across all regions, and light rare earth concentrates are taxed at 11.5 percent in Inner Mongolia, 9.5 percent in Sichuan province, and 7.5 percent in Shandong province (Argus, 2015).

Fig. 4 shows an abrupt decline in the REE-FOB prices between December 2014-December 2015, particularly after the removal of export tariffs in May 2015. There could be other factors that too contributed to falling prices during this period. However, in the long term, the new ad valorem tax introduced was expected to increase the price of REEs particularly that of HREEs as the tax rate is applied differently to LREs and HREs in concentrate form. The imposition of tax on production was expected to influence the domestic as well as international price. Higher taxes may reduce the official Chinese supply. However, a higher tax and consequent price increase will likely both induce illegal production in China and increase demand for projects abroad, thus positively influencing diversity of supply and improving supply chain resilience in long- term.

3.1.3. Countering trade restrictions: WTO lawsuits

Chinese supply restrictions of raw materials came to the forefront when the US and the European Union (EU) (later joined by Mexico, India, Brazil, Japan and Korea as third parties) lodged a complaint against China to the World Trade Organization (WTO) in June 2009, claiming that export restrictions (including quotas and export taxes) imposed by China violate WTO rules. March 2012 the US, the EU and Japan again filed a coordinated complaint against China to the WTO over China's export restrictions on rare earths and non-rare earth metals such as tungsten and molybdenum. The countries challenged China's allocation and administration of export quotas, export licenses, minimum export prices and non-publication of certain measures. They further contended that the Chinese measures were aimed to satisfy domestic demand and to control the international price of minerals (Mancheri, 2015).

Although WTO rules aim to reduce protectionism on the import side, the rules concerning export restrictions are ambiguous (Korinek and Kim, 2010). China had argued that its export restriction policy is reasonable under WTO law, more precisely the general exception clause of Article 20 of the GATT, for reasons of natural resource conservation and on environmental ground. In August 2014, ruling in favor of US, the EU and Japan, the WTO asked China to remove export tariffs and quotas. The reasoning was that China can't justify export restrictions on the ground of environment, since the country continue to extract the resources for domestic use (WTO, 2014). In January 2015, in response to unfavorable ruling, China abolished the quota system and instead implemented a more stringent licensing system for exporters (Mancheri and Marukawa, 2016).

Chinese supply restrictions had distorted REE prices and had major disruptions in international REE supply chain. The WTO led counter measures against China on its REE policies impacted prices negatively and a consequent increase in Chinese export quantities in later years eased the global supply chain. This shows that the WTO and international rules helped to strengthen the supply, reduce prices both in China and globally and strengthen the resilience. The WTO plays an important role as an arbitrator in maintaining a resilient supply chain system, albeit with a significant time-lag.

3.2. Chinese influence on RoW supply chain

3.2.1. International standards

Accepting a proposal from China, the International Organization for Standardization (ISO) has formed a technical committee (ISO/TC 298) in September 2015 to explore the possibility of international standardization of rare earth products. The Standardization Administration of China (SAC) has been appointed as the secretariat. Currently, national standard bureaus of nine countries such as Australia (SA), Brazil (ABNT), Canada (SCC), India (BIS), Japan (JISC), Korea (KATS), Russian Federation (GOSTR), United States (ANSI) are participating members of the TC and there are twenty-two observing members (ISO, 2017).

The initial scope is defined as "standardization in the field of rare earth ores, concentrates, metals, alloys, compounds, materials including the reuse and recycling of waste rare earth products". China led technical committee considers unregulated and /or illegal production of REEs as a core issue. The committee expects the introduction of standards should aid in ensuring all rare earths entering the supply chain are sourced from legal miners, who abide by best environmental practices.

Through the globally accepted standardization, China intends to shut down the illegal flow of rare earths (Investor Intel, 2015; Packey and Kingsnorth, 2016). Once the countries agree on standards, the onus will be on purchasing companies to buy the standardized rare earths products from legal suppliers. Standardization will therefore most probably result in tighter Chinese government control on REE resources.

Standardization could also provide China more power in deciding the price while not guaranteeing a reduced price difference between domestic and international customers. Standardization will also cause additional transaction costs and complexity to REE trade, consequently influencing the price positively. From resilience perspective, the implementation of standards could cause a slow disruption (see Table 1) in global supply chain. If such a policy causes excessive administrative costs and restrictions on trade, standardization will weaken the resilience and may lead (ironically) to an increase in illegal mining and exports.

3.2.2. Chinese imports of REEs

Although China is the largest producer of REEs, its import of rare earth compounds has steadily increased since started in 2013. The country imported 3668 tons of REEs in 2013, which increased to 34,339 tons in 2017. Some of these minerals have been imported from the Molycorp plant in California for further purification in China. Molycorp used to exports its neodymium-praseodymium (Nd-Pr) oxide mixes to China for separation and producing metals. (Interview with Molycorp staff). A major portion of Lynas' output is also being exported to China (Lynas, 2017) (Fig. 5).

China's import marks a reverse transformation in global REE supply chain in the upstream sector. China's import of REE concentrates is expected to increase further due to new policies (see Table 3) targeting industrial upgradation of domestic mineral sector from a mere producer and exporter of REE composites to more sophisticated metals and products. As the domestic mining get restricted increasingly on the grounds of environment or legality, Chinese smelters would be compelled to import the concentrates to fully utilize their processing capacity and to fulfill the demand from downstream industry.

An increase in Chinese imports will reduce the availability of material to non-Chinese companies, consequently reducing the resilience of the global REE supply chain. Interestingly, an increase in Chinese imports would affect the domestic price negatively and international price of REEs positively. The impact would be less disruptive since there are very few smelters and intermediate producers outside China, especially who produce REE oxides and metals. However, European and Japanese companies, including their subsidiaries in Southeast Asia, may face supply risk in case of an unexpected demand surge in China.

3.2.3. Chinese investments in REE projects abroad

Chinese companies have started to invest in rare earth projects outside China. The examples include, the purchase of Molycorp by a consortium comprised of Shanghai-based Shenghe Resources in June 2017 (Roskill, 2017). Shenghe is also a majority shareholder of Australia listed Greenland minerals, which owns the Kvanefjeld REE project in Greenland (Greenland Minerals, 2017). Another example is Huatai mining, which is a major stakeholder in Northern Minerals' Browns Range project in Western Australia. Huatai is a subsidiary of Shandong Taizhong Energy, one of the largest coal companies in China (Northern minerals, 2016a).

The mine, beneficiation and hydrometallurgical processing plant at Browns Range is also being built by a Chinese company, Sinosteel MECC, a subsidiary of Sinosteel, a state owned enterprise (SOE) in China (Northern minerals, 2016b). Northern minerals has signed an offtake agreement with a subsidiary of the Guandong Rare Earths Group, one of the six state owned REE conglomerates.

Acquiring foreign REE assets is a long-term strategy for addressing China's security of supply. This also serves to protect Chinese industry from domestic resource depletion, declining ore grades and increasing cost of domestic mining under strict environmental regulations. There are also efforts by the big six REE SOEs to shut down unprofitable and environmentally polluting mining operations, which serves as a motivation to invest in foreign countries.

Chinese investment in foreign REE mines can impact the supply chain in two ways: 1) the company processes the concentrate in the host country and cater to the global demand 2) or the company can import the concentrate to China to cater to the demand from domestic smelters. China's domestic demand account for more than 80 percent of total global consumption. This is attributed to the ever-increasing domestic production REE contained final products such as wind turbines, electric vehicles and electronic commodities (Kingsnorth, 2016).

From a resilience perspective, one could assume that China's involvement in developing REE projects abroad is a resilience promoting mechanism as this helps diversification of supply, a core component of a resilient system. Especially, the investors in western countries are reluctant to invest when the prices are low and Chinese investments should be seen as a positive step during such situations.

3.3. Dynamics inside the Chinese supply chain

3.3.1. Illegal mining, environmental regulations and consolidation

The current state of the global REE market characterized by oversupply from China and a low price owes much to the significant volume of illegal materials being produced each year in China, particularly in the southern provinces. The exact volume of illegal mining and export is difficult to trace and vary in estimates by different agencies and scholars. One way to trace the illegal trade is by estimating the quantity differences in export and import statistics (Fig. 6). Mancheri and Marukawa (2016) has explored extensively the differences in REE export of China and import of its partners. The most recent and frequently quoted estimates are around 40,000 tons (Packey and Kingsnorth, 2016). According to Kingsnorth, 40–50% of rare earth production in China is grey/illegal and the Chinese REE magnet industry's demand for neodymium/praseodymium exceeds the production quota significantly,

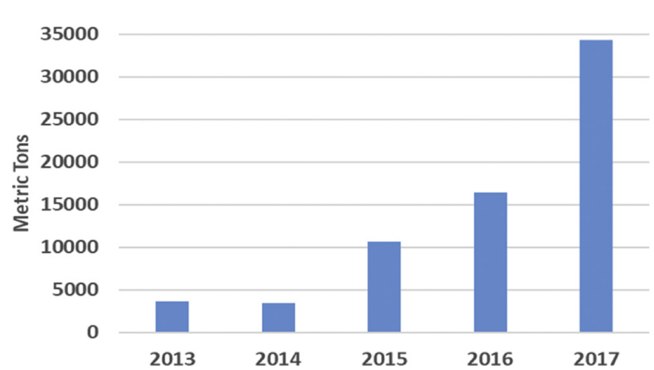

Fig. 5. Chinese import of REE compounds and concentrates, Source: UNComtrade data base 2018.

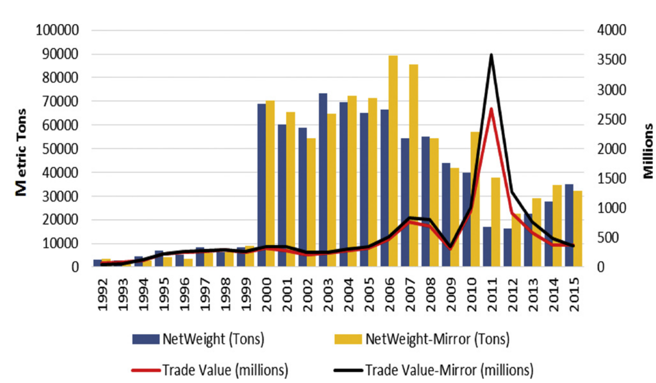

Fig. 6. China's Exports of Rare earth Elements. Yellow bar in the figure shows the import statistics of the same product of China's trade partners. Source: Author's calculations using UNCOMTRADE database, 2016 (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

effectively condoning illegal mining and processing (Kingsnorth, 2016).

Fig. 6 shows that since 2008, exports from China have been declining gradually along with an increase in the average price, which peaked at USD 158.21 per kg in 2011, due to an immediate halt of China's REE export to Japan. Prices have steadily decreased since then, almost reaching to 2009 levels. Fig. 6 also shows (yellow bar in the figure) that the export constraints put in place by China gave rise to significant illegal mining and exports that eventually contributed up to 40 percent of total world production, which is captured from the trade statistics of China's trade partners. The figure also reveals the correlation between Chinese export restrictions and illegal trade. Introduction of trade restricting measures clearly lead to an increasing quantity of illegal trade. For example, in 2011, China's reported export of REEs were equal to 16,860 tons while trade partners reported a total import of 37,615 tons from China. Due to the unfavorable WTO ruling and market reasons since 2013, China has relaxed the export restrictions and the figure shows less differences between export and import quantity in following years.

The campaign to clamp down on illegal production in China is likely to be a gradual process but it will provide officials more control to restrict supply. The price will go up for both domestic and foreign industries in the downstream sector if the government takes strict measures against the illegal mining without addressing the consequent supply constraints. Contrary to popular belief, illegal mining and smuggling help to increase the resilience of the REEs supply chain as it allows an alternative method of obtaining raw materials when official production is constrained. This was evident during the 2010 REE crisis (Sprecher et al., 2015).

The BBC reported in 2015, "it could be argued that China's dominance of the rare earth market is less about geology and far more about the country's willingness to take an environmental hit that other nations shy away from" (Maughan, 2015). Countries like China which exercise lower levels of environmental and legislative control, can produce more readily and at a lower cost in the absence of any government-specific controls. In the pursuit of industrial catch up, China accepted significant environmental degradation caused by the REE industry. For example, to produce one ton of rare earth oxide from ionic-adsorbed clays, 2000 tons of tailings and 1000 tons of wastewater containing heavy metals are generated (Packey and Kingsnorth, 2016). Refining one ton of RE oxide can potentially produce 1.4 tons of radioactive waste (Jiabao and Jie, 2009). The sulfur emissions for 1 ton of REE ore is 9600 to 12,000 cubic meters, containing a mixture of hydrofluoric acid, sulfur dioxide, and sulfuric acid (Hurst, 2010). The environmental problems get worse as only 87 rare earth enterprises are recognized as environmental law abiding and the rest are operating illegally or don't adhere to environmental regulations (Chen, 2015).

China has enacted new laws to deal with environmental problems related to REEs. For instance, ammonium nitrate in waste water is now limited to 25 mg per liter instead of previous limits reported between 300–5000 mg per liter (Gunn, 2014). Reducing the ammonium nitrate content in the waters surrounding the mining facilities in China will be quite difficult if according to life cycle inventory data from REE mines in China (Lee and Wen, 2016).

A rigorous environment protection law has been passed in January 2015, with severe penalties including cancellation of licenses in violation of the rules. China is also stepping up efforts to restrict illegal mining and export of rare earths by setting up a system of certification to trace the origin of material. The government is enforcing measures such as pollution discharge standards, which set limits for CO2 emissions, radioactive waste and particulates that emerge in REE mines and related industries (MIIT, 2016). For example, the Ministry of Environmental Protection in China limits sulfur emissions to 50 ppm for the diesel industry (Dieselnet, 2015).

The liberal environment policy enabled China to supply REE minerals in the international market with low prices forcing others to close down (Fernandez, 2017). No doubt that the REE production in China will become more expensive due to strict environmental regulations. The cost for producers to implement some of the environmental protection efforts would be $161 million with an additional annual environmental protection costs of about $41 million to an annual production of 150 tons of rare earth elements in China (Hurst, 2010). The administrative burden, in addition to the expense of incorporating more advanced technology and infrastructure may increase the price of REEs. There are also doubts the state will not enforce because many of these REE processing facilities are state-owned. The official production will be affected negatively if China implements strict environmental regulations including penalties for violations. Reduced supply may lead to increase in prices of all REOs prompting others to start businesses or increase output in projects like Mount Weld, thus by affecting the resilience positively.

In order tackle the illegal production and pollution, China took a different route by consolidating all rare earth enterprises into six big state-owned enterprises (SOEs). The consolidation process intensified in 2014 particularly after China's debacle in WTO. The process allowed six large SOEs led by China Minmetals, Chinalco, Baotou Steel, Xiamen Tungsten, Ganzhou Rare Earths and Guangdong Guangsheng Rare Earths to bring all rare earth mining and separation companies under their control. The government supported them with legislation and financing, and these large firms are permitted to merge and acquire small operations and illegal mines. As a policy support, over 90 per cent of production quotas are now allocated to these groups (Fig. 7). As of June 2016 these six groups have integrated 22 out of 23 mines, and 54 of 59 smelting separation plants (Hu, 2016).

Consolidation of the industry along with curtailing of illegal mining would enable China to effectively control the supply, prices and keep the annual production of rare earths within 140 thousand tons by 2020, a stated objective of Chinese government (MIIT, 2016). China achieved its objective of controlling the entire REE supply chain from mining to end products through the consolidation and government's hold on the REE industry has become stronger. Consolidation is seen as a resilience demoting mechanism as it centralizes the production and limits the consumer choices. Consolidation and the supply side actions taken by China have led to a steady increase in the price of rare earths in later part of 2017. A sustained increase in prices would prompts further development of new mines outside China, however, the monopoly position of Chinese companies gives them the power to manipulate pricing, which dissuades investments in non-Chinese primary production.

3.3.2. State sponsored stockpiling

Stockpiling of REEs in China has gained momentum since 2012. Under the direction of the Ministry of Land and Resources (MLR), at least 10 storage facilities are being built and managed by the world's largest producer of rare-earth metals; government-controlled Baotou Steel Rare-Earth Group. The Chinese State Reserve Bureau (SRB) began a rare earth stockpiling program and in late-2014 and the government had built storage for more than 40 thousand tons of REOs. The SRB may purchase up to 100 thousand tons, primarily focusing on medium to heavy rare earths (Brown and Eggert, 2017).

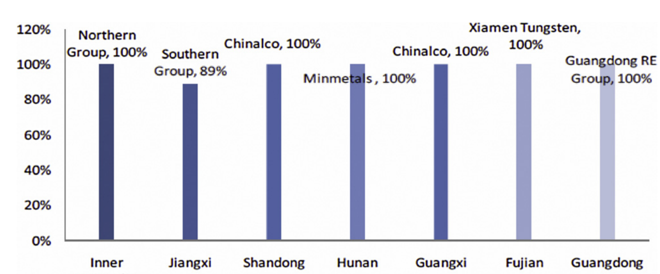

Fig. 7. RE oxide plants market share of six SOEs in major provinces. Source: Hu, 2016.

Table 5
Chinese state and commercial stockpile of REEs in tons (2012–2016).
Source: Hu, 2016

Year	Subject	Total	Light REEs	%	Heavy REEs	%
2012	State	19750	16500	83.54	3250	16.46
2014	State	10900	5000	45.87	5090	46.70
2016	Commercial	5400	2590	47.96	2810	52.04

China also started stockpiling of REEs as a commercial reserve in March 2016. The first commercial reserve after the completion of consolidation and the reserves are collected from the six group's warehouses. The mining companies also stockpile certain grades of ore for future processing.

Zhang and Kleit, 2016 established a theoretical model to drive the value of such stockpile by mining companies and found that kpiling option can significantly boost a mine's profit.

In the first commercial reserve, neodymium and praseodymium are stockpiled as a mixture as well as individual oxides, which constitute the largest share of about 2590 tons (Table 5). Stockpiled heavy REEs are dysprosium (830 tons), terbium (260 tons), yttrium (700 tons), erbium (500 tons), europium (270 tons) and lutetium (50 tons). Stockpiling can have tremendous impact on the REE market as the volume of stockpiled material as a fraction of yearly production is very high. For example, the annual global production of lutetium is 10 tons, terbium 650 tons and erbium 900 tons, which are mostly produced in China (Kingsnorth, 2016). China's continuation of stockpiling, especially the more critical heavy rare earths (HREE) can severely impact the prices (Fig. 8). Consequently, China is in a strong position to manipulate supply and hence rare earth prices by increasing or releasing its strategic reserves.

As illustrated in Fig. 8, building up a significant stockpile can cause a surge in demand and hence increase prices. Release of an existing stockpile creates supply and consequently influences price negatively (Mancheri et al., 2018 and Sprecher et al., 2017). Stockpiling is inherently a disruptive mechanism and has shown demoting effects on supply chain resilience in the following way. Urgent stockpiling during a supply crisis can drive up the price significantly, fueling the perceived threat of supply disruption (Sprecher et al., 2015). The perceived supply threat consequently leads to emergency stockpiling by manufacturers and speculators further pushing the price up. Brown and Eggert (2017) showed that stockpiling increases the price of the stockpiled REO and increases legal Chinese ore production. A significant complication is that an increase in production of all REOs may lead to the balance problem in REEs (Binnemans et al., 2013) and a decrease in prices of non-stockpiled REOs.

3.3.3. Exchange markets and speculation

In 2011, China had set up the Fanya Metal Exchange for trading technology metals in Kunming, the capital of Yunnan province. This exchange had a powerful impact on the minor metals and had been widely successful in attracting investors between 2011 and 2015. In just three years of its operation, starting with Indium trading, it has amassed around four times the amount of indium the world consumes a year. Fanya turned China, the world's largest supplier of indium, from a net indium exporter into an importer. Subsequently the exchange added around 14 minor metals to its trading portfolio like, ammonium paratungstate (APT), germanium, bismuth, antimony and gallium, cobalt, rhodium, vanadium pentoxide, silver, dysprosium oxide and terbium oxide (Abraham 2015).

The exchange reportedly held 19,228 tons of bismuth, more than twice as much as total annual global consumption in 2012, 3629 tons of indium, equaling around ten years of China's domestic production and gallium stocks of around 197 tons (Metal Bulletin, 2017). The exact quantity of REEs in the inventory is unknown. In 2015 the exchange bankrupted due to corruption and financial irregularities.

The Fanya Metal Exchange highlights how stockpiling of metals by investors or speculators waiting for higher prices has the potential to disrupt supply – similar to the mechanism behind state-sponsored stockpiling. But uncertainty about the release of vast inventories from the collapsed exchange continues to weigh heavily on China's minor metals market. The Chinese government intervention on the bankrupted exchange market and consequent release of existing metals stocks to the market was expected to ease the supply and suppress the prices. The price may go up marginally if the inventory is added to the existing commercial stocks.

4. Discussion and implications

Rare earths are considered as strategic resources because of the business, technological applications and governments' direct policy interventions in the sector. This study, on scrutinizing these policy interventions and its impact on business contribute to the wider understanding of the sector. Resilience is a useful framework to follow the consequences of policy through the system. By adopting a resilience framework, we can see how policies works like ecological theory—-when one part of the system is disrupted then it has a trickle-down effect.

This study highlighted how the policies affect supply chain differently in China and in the rest of the world. We analyzed various policies such as: restrictions on trade between China and RoW, Chinese influence on RoW supply chain, and the dynamics inside the Chinese supply chain. We focused on how price responds to various resilience influencing mechanisms such as diversity of supply, legal and regulatory

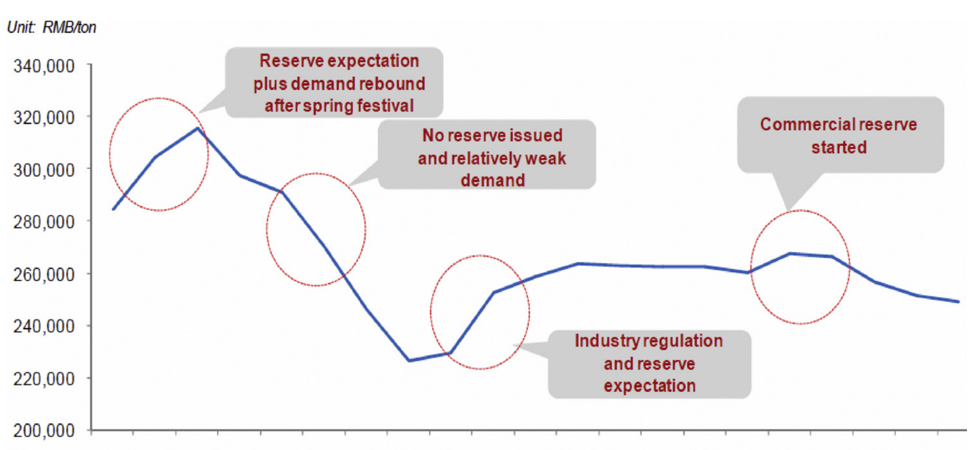

Fig. 8. Impact of stockpiling on neodymium/praseodymium oxide price in 2015-16.

Table 6
Effect of policies on REE supply resilience.

Restrictions on trade between China and RoW				
Policy	Global supply	International price	Chinese price	Resilience
Imposition of quotas	Weaken	Increase (positive effect)	Increase (positive effect)	Demote/weaken
Taxes	Weaken	Increase (positive effect)	Increase (positive effect)	Demote/weaken
WTO and international regulations	Increase	Decrease (negative effect)	Decrease (negative effect)	Improve/strengthen
Chinese influence on RoW supply chain				
Policy	Global supply	International price	Chinese price	Resilience
International standards	Weaken	Increase (positive effect)	Increase (positive effect)	Demote/weaken
Chinese import of REEs	Weaken	Increase (positive effect)	Decrease (negative effect)	Demote/weaken
Chinese investments in REE projects abroad	Increase	Decrease (negative effect)	Decrease (negative effect)	Improve/strengthen
Dynamics inside the Chinese supply chain				
Policy	Global supply	International price	Chinese price	Resilience
Illegal mining and export	Increase	Decrease (negative effect)	Decrease (negative effect)	Improve/strengthen
Chinese environmental regulations	Weaken	Increase (positive effect)	Increase (positive effect)	Demote/weaken
Consolidation of rare earth enterprises	Weaken	Increase (positive effect)	Increase (positive effect)	Demote/weaken
State sponsored stockpiling	Weaken	Increase (positive effect)	Increase (positive effect)	Demote/weaken
Exchange markets and speculation	Weaken	Increase (positive effect)	Increase (positive effect)	Demote/weaken

frameworks and, stockpiling. Ultimately, we show that supply chain is a complex phenomenon and resilience of a system is not solely dependent on physical disruptions but also on dynamic factors such as societal and geo-political.

Based on our analysis we determine that the international policies generally tend to serve supply chain resilience better than national policies. In terms of the restrictions on trade between China and RoW, Table 6 shows that through the various policies made on the national levels, resilience is weakened, but strengthened by policies made on the global level. Regarding the Chinese influence on RoW supply chain, the policies such as: international standards and Chinese import of REEs– serve to weaken resilience whereas Chinese investments abroad serve to increase it. Finally, the dynamics inside the Chinese supply chain serve ultimately to demote supply chain resilience. This type of analysis though is based on dynamic, ever changing factors so needs to be updated every few years.

The Table 6 summarizes the results analyzed in previous sections. The table is not based on any quantitative assessment and doesn't demonstrate the resilience model quantitatively. The rankings in the table are without a scale as it is very difficult to quantify the policies and their impact.

The Chinese production quota, the region-based tax system, stockpiling strategies and consolidation of the industry will probably continue to tighten the supply of rare earths keeping the prices high for particularly the heavy elements. REE prices are largely dependent and volatile on Chinese actions as we explored in this paper. Price uncertainty is considered as a characteristics of a less resilient market. Price uncertainty makes investors vulnerable to short term risks, prevents new investment and diversification of supply.

Consolidation of the industry, restricting the export of primary raw materials and policies to increase market share of high-end rare earth products suggest that China intents industrial upgradation and divert more supply for domestic use. However, the liberal REE policies of the early years of China's industrialization, which led to overcapacity, blind competition and significant environmental damages may not work again in achieving such targets. The new policies like strict environmental standards, closing of illegal mines and comparatively high cost concentrate imported from abroad reduce Chinese advantages of low cost production and low price REEs for domestic downstream industry. The new environmental standards will certainly affect capex and opex of the Chinese downstream industry in the long-term.

A limitation of this study is that it is often difficult to quantify the public policy issues and its impacts, particularly due to the lack of data. For future research, a detailed quantitative analysis of Chinese REE policies and its impact on supply chain can provide knowledge about the dynamics of global REE flows. It will also help to fully quantify the resilient supply chain framework parameters. Our findings doesn't imply that the price fluctuations are only due to changes in Chinese policies. However, price volatility is also related to prevailing global market conditions, affecting the entire mineral sector. In this context, it would be very interesting to see future research applying this framework to the supply chains of major metals like steel, aluminum or copper.

Since this study is based on an inductive reasoning, by its nature, is more exploratory of each identified factors, we believe this study will enable other researchers to build on the resilience approach and analyze more thoroughly the bottlenecks and disruptions in a supply chain of critical materials.

By applying our framework, one can explain that a supply chain has no fixed amount of resilience, so the question is, how it become more resilient? We resolve that resilience is like a muscle, it can be built-up. Policies are never perfect, and they don't always go according plan, and sometimes even have opposite effects. This study is to designed to help the RE industry, policy makers, and stakeholders make some sense out of it.

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References

Alonso, E., Sherman, A.M., Wallington, T.J., Everson, M.P., Field, F.R., Roth, R., Kirchainet, E.R., 2012. Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. Environ. Sci. Technol. 46 (6), 3406–3414.
Argus, 2015. Argus Rare Earth Monthly Outlook. Argus Media, London.
Asian Metal, 2018. MNR And MIIT Release Rare Earth Ore and Tungsten Ore Mining Quota in 2018, July 31, 2018. http://www.asianmetal.com/news/data/1436371/.
Bailey, G., Mancheri, N., Acker, Van, 2017. Sustainability of permanent rare earth magnet motors in (H)EV industry sustainability of permanent rare Earth magnet motors in (H)EV industry. J. Sustain. Metall 3 (3), 611–626.
Barteková, E., Kemp, R., 2016. National strategies for securing a stable supply of rare earths in different world regions. Resour. Policy 49, 153–164.
Binnemans, P.T., Jones, K., Van Acker, B., Blanpain, B., Apelian, Mishra D., 2013. Rare-earth economics: the balance problem. Jom 65 (7), 846–848. https://doi.org/10.1007/s11837-013-0639-7.
Brown and Eggert, 2017. Simulating producer responses to selected Chinese rare earth policies. Resour. Policy 6 (November). https://doi.org/10.1016/j.resourpol.2017.10.013.
Chen, 2015. Rare earth Market Over view in 2014 and Market Prospect for 2015. Proceedings of the China Rare Earth Market Conference 2015.
Christmann, P., 2014. A forward look into rare earth supply and demand: a role for sedimentary phosphate deposits? Procedia Eng. 83, 19–26.
Cui, Y., Zhao, Y., 2015. Mergers and acquisitions of China rare earth industry: a review and outlook. Proceedings of 2014 1st International Conference on Industrial Economics and Industrial Security 143–148.
Dieselnet, 2015. The National Sulfur Implementation Schedule for Fuels in China. https://www.dieselnet.com/standards/cn/fuel.php.
Dobransky, S., 2013. Rare Earth Elements and U.S. Foreign Policy: the Critical Ascension of REEs in Global Politics and U.S. National Security. American Diplomacy.
DOE, 2011. Critical Materials Strategy. United States Department of Energy Report. From http://energy.gov/node/349057 (Accessed 21 December 2016.).
Feng, H., 2007. Rare earth: production, trade and demand. J. Iron Steel Res. Int. 13 (1), 33–38.
Fernandez, V., 2017. Rare-earth elements market: a historical and financial perspective. Resour. Policy 53 (September), 26–45. https://doi.org/10.1016/j.resourpol.2017.05.010.
Gavin, B., 2013. China's growing conflict with the WTO. Intereconomics 48 (4), 254–261.
Ge, J., Lei, Y., Zhao, L., 2016. China's rare earths supply forecast in 2025: a dynamic computable general equilibrium analysis. Minerals 6 (3), 95.
Gholz, E., Daryl, G., 2010. 'Protecting "The Prize": Oil and the U.S. National Interest'. Secur. Stud. 19 (3), 453–485. https://doi.org/10.1080/09636412.2010.505865.
Golev, A., Scott, M., Erskine, P.D., Ali, S.H., Ballantyne, G.R., 2014. Rare earths supply chains: current status, constraints and opportunities. Resour. Policy 41, 52–59.
Goonan, T.G., 2012. Rare Earth Elements-end Use and Recyclability. U.S. Geological Survey.
Graedel, T.E., Barr, R., Chandler, C., Chase, T., Choi, J., Christoffersen, L., Friedlander, E., Henly, C., Jun, C., Nassar, N.T., 2012. Methodology of metal criticality determination. Environ. Sci. Technol. 46 (2), 1063–1070.
Greenland Minerals, 2017. Kvanefjeld Project Update, Company Announcement, September 14, 2017. http://www.ggg.gl/docs/ASX-announcements/Kvanefjeld-Project-2017-Field-Season-Complete.pdf.
Gu, B., 2011. Mineral export restraints and sustainable development-are rare earths testing the WTO's loopholes? J. Int. Econ. Law 14 (4), 765–805.
Gunn, G., 2014. Critical Metals Hand Book. Wiley, London.
Habib, K., Wenzel, H., 2014. Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling. J. Clean. Prod. 84, 348–359.
Han, A., Ge, J., Lei, Y., 2015. An adjustment in regulation policies and its effects on market supply: game analysis for China's rare earths. Resour. Policy 46, 30–42.
Han, A., Ge, J., Lei, Y., 2016. Vertical vs. Horizontal integration: game analysis for the rare earth industrial integration in China. Resour. Policy 50, 149–159.
Han, G., 2015. Analysis of China's rare earth industry security and countermeasures. Proceedings of 2014 1st International Conference on Industrial Economics and Industrial Security. Springer, Berlin Heidelberg.
Hatch G. 2010. China's Rare Earths Game Plan: Part1 – The Effects of Reduced Export Quotas, Technology Metals Research, V1. 1 July 2010 〈http://www.techmetalsresearch.com/2010/07/chinas-rare-earths-game-plan-part-1-the-effects-of-reduced-export-quotas/〉.
Hayes-Labruto, L., Schillebeeckx, S.J.D., Workman, M., Shah, N., 2013. Contrasting perspectives on China's rare earths policies: reframing the debate through a stakeholder lens. Energy Policy 63, 55–68.
Hu, 2016. China's Rare Earth Policy What Has Changed and The Trend, Metals Events, Hong Kong November 2016.
Hu, D., 2012. China's governance of exhaustible natural resources under the WTO era: taking its REE governance as a case. Energy Procedia 16 (PartA), 656–660.
Hurst, C., 2010. China's Rare Earth Elements Industry: What Can the West Learn? Institute for the Analysis of Global Security (IAGS), Washington DC, March. http://www.iags.org/rareearth0310hurst.pdf.
Investor Intel, 2015. China Still Distorting the Rare Earth Market. https://investorintel.com/sectors/technology-metals/technology-metals-intel/china-still-distorting-the-rare-earth-market/.
ISO, 2017. Strategic Business Plan ISO/TC298. International Standard Organization. https://isotc.iso.org/livelink/livelink/fetch/2000/2122/687806/ISO_TC_298_Rare_earth_.pdf?nodeid=18833229&vernum=-2.
Jiabao, Jie, Liu, 2009. Rare Earth Industry Adjusts to Slow Market. China Daily. 09 July. http://www.chinadaily.com.cn/bw/2009-09/07/content_8660849.htm.
Kingsnorth, D., 2018. The Rare Earth Market in 2018, Driven by e-Mobility. March, IMCOA and Curtin University, Perth.
Kingsnorth, D., 2016. Rare earths- the China conundrum. The 12th International Rare Earths Conference Hong Kong, 8th–10th.
Korinek and Kim, 2010. Restrictions on Strategic Raw Materials and Their Impact on Trade 2010 OECD Trade Policy Working Papers 95, OECD Publishing, Paris. https://doi.org/10.1787/5kmh8pk441g8-en.
Kleijn, R., 2012. Materials and Energy: a Story of Linkages. Ph.D. Thesis. Leiden University, the Netherlands.
Kooroshy, J., Tiess, G., Tukker, A., Walton, A., 2015. Strengthening the European Rare Earths Supply Chain: Challenges and Policy Options. The European Rare Earths

Competency Network (ERECON) Report.
Kulekci, M.K., 2009. Magnesium and its alloys applications in automotive industry. Int. J. Adv. Manuf. Technol. 39 (9), 851–865.
Lackner, D., McEwen-Fial, S., 2011. From Resource Advantage to Economic Superiority: Development and Implications of China's Rare Earth Policy. Univ.-Bibliothek Frankfurt am Main.
Lee, J.C.K., Wen, Zongguo, 2016. Rare earths from mines to metals: comparing environmental impacts from China's main production pathways. J. Ind. Ecol. 21 (5 October), 1277–1290. https://doi.org/10.1111/jiec.12491.
Lynas, 2017. Annual Report, Lynas Corporation. . https://www.lynascorp.com/Shared%20Documents/Investors%20and%20media/Reporting%20Centre/Annual%20reports/2017/171003%20Annual%20Report%20and%20Appendix%204G%201721565.PDF.
Machacek, E., Fold, N., 2014. Alternative value chains for rare earths: the Anglo-deposit developers. Resour. Policy 42, 53–64.
Machacek, E., Richter, J.L., Habib, K., Klossek, P., 2015. Recycling of rare earths from fluorescent lamps: value analysis of closing-the-loop under demand and supply uncertainties. Resour. Conserv. Recycl. 104, 76–93.
Mancheri, N., 2012. Chinese monopoly in rare earth elements: supply–demand and industrial applications. China Rep. 48 (4), 449–468.
Mancheri, N., Lalitha, S., Chandrasekar, S., 2013. Dominating the World: China and the Rare Earth Industry, R-19. National Institute of Advanced Studies, Bangalore. http://isssp.in/wp-content/uploads/2013/09/R19-2013_Rare-earth-strategyin-China_Finalcompressed.pdf.
Mancheri, N., 2015. World trade in rare earths, Chinese export restrictions and implications. Resour. Policy 46, 262–271.
Mancheri, N., Marukawa, 2016. Rare Earth Elements: China and Japan in Industry. Trade and Value Chain ISS CCRS No.17.. http://web.iss.u-tokyo.ac.jp/kyoten/research/issccs/no17.html.
Mancheri, N., Sprecher, Benjamin, Deetman, Sebastiaan, Young, Steven, Dong, Liang, Bleischwitz, Raimund, Kleijn, Rene, Tukker, Arnold, 2018. Resilience in the tantalum supply chain, resources. Conserv. Recycl. 129 (February 2018), 56–69. https://doi.org/10.1016/j.resconrec.2017.10.018.
Massari, S., Ruberti, M., 2013. Rare earth elements as critical raw materials: focus on international markets and future strategies. Resour. Policy 38 (1), 36–43.
Metal Bulletin, 2017. Unresolved Fanya Stocks Cast Shadow Over China's Minor Metals Market, 2017 Review. https://www.metalbulletin.com/Article/3649780/2017-PREVIEW-Unresolved-Fanya-stocks-cast-shadow-over-Chinas-minor-metals-market.html.
MIIT, 2016. Rare Earth Development Plan, 2016–2020 (In Chinese). Ministry of Industry and Information Technology, China. www.miit.gov.cn/n1146295/n1652858/n1652930/./5287774.doc.
Morf, L.S., Gloor, R., Haag, O., Haupt, M., Skutan, S., Lorenzo, F.D., Böni, D., 2013. Precious metals and rare earth elements in municipal solid waste – sources and fate in a swiss incineration plant. Waste Manage. 33 (3), 634–644.
Müller, M.A., Schweizer, D., Seiler, V., 2012. Wealth effects of rare earth prices and China's rare earth elements policy. J. Bus. Ethics 1–22.
Nieto, A., Zhang, K.Y., 2013. Cutoff grade economic strategy for byproduct mineral commodity operation: rare earth case study. Min. Technol. 122 (3), 166–171.
Nguyen, R.T., Imholte, D.D., 2016. China's rare earth supply chain: illegal production, and response to new cerium demand. Jom J. Miner. Metals Mater. Soc. 68 (7), 1948–1956.
Northern minerals, 2016a. Northern Minerals Enters Into $30 Million Equity Funding Agreement ASX Announcement 02 August 2016. http://northernminerals.com.au/wp-content/uploads/2016/02/ASX-Announcement-30M-funding-partner-secured-updated-final-MT-Clean.pdf.
Northern minerals, 2016b. Sinosteel MECC Selected As EPC Contractor for Browns Range Pilot Plant ASX ANNOUNCEMENT, 23 November 2016. http://member.afraccess.com/media?id=CMN://6A800400&filename=20161123/NTU_01804860.pdf.
Olson, D.L., 2015. Systems perspective of the primary aluminum supply chain: unintended consequences of participant policies. HSM 34 (4), 237–248.
Packey, Daniel J., Kingsnorth, P., 2016. The Impact of Unregulated Ionic Clay Rare Earth Mining in China 48. Resources Policy, Elsevier, pp. 112–116.
Pothen, F., Fink, K., 2015. A Political Economy of China's Export Restrictions on Rare Earth Elements. ZEW-Centre for European Economic Research Discussion Paper, pp. 15–025.
Rademaker, J.H., Kleijn, R., Yang, Y., 2013. Recycling as a strategy against rare earth element criticality: a systemic evaluation of the potential yield of NdFeB magnet recycling. Environ. Sci. Technol. 47 (18), 10129–10136.
Rao, Z., 2016. Consolidating policies on Chinese rare earth resources. Miner. Econ. 29 (1), 23–28.
Riddle, M., Macal, C.M., Conzelmann, G., Combs, T.E., Bauer, D., Fields, F., 2015. Global critical materials markets: an agent-based modeling approach. Resour. Policy 45, 307–321.
Rollat, A., Guyonnet, D., Planchon, M., Tuduri, J., 2016. Prospective analysis of the flows of certain rare earths in Europe at the 2020 horizon. Waste Manage. 49, 427–436.
Roskill, 2017. Rare Earths: Mountain Pass Sold to Chinese-led Consortium. Posted on 21st June 2017 in Roskill Weekly Round-up. https://roskill.com/news/rare-earths-mountain-pass-sold-chinese-led-consortium/.
Schulze and Buchert, 2016. Estimates of global REE recycling potentials from NdFeB magnet material. Res. Conserv. Recycl 113, 12–27. https://doi.org/10.1016/j.resconrec.2016.05.004.
Sprecher, B., Kleijn, Kramer., 2014. Recycling potential of neodymium: the case of computer hard disk drives. Environ. Sci. Technol. 48, 9506–9513. https://doi.org/10.1021/es501572z.
Sprecher, B., Daigo, Murakami, Kramer, Kleijn Vos, 2015. Framework for resilience in material supply chains, with a case study from the 2010 rare earth crisis. Environ. Sci. Technol. 49, 6740–6750. https://doi.org/10.1021/acs.est.5b00206.
Sprecher, B., Daigo, I., Spekkink, W., Vos, M., Kleijn, R., Murakami, S., Kramer, G.J., 2017. Novel indicators for the quantification of resilience in critical material supply chains, with a 2010 rare earth crisis case study. Environ. Sci. Technol. 51 (7), 3860–3870.
Stegen, K.S., 2015. Heavy rare earths, permanent magnets, and renewable energies: an imminent crisis. Energy Policy 79, 1–8.
Tse, P. 2011. China's rare-earth industry: U.S. Geological survey open-file report 2011-1042. Available at: 〈http://pubs.usgs.gov/of/2011/1042/〉.
Tukker, A., 2014. Rare earth elements supply restrictions: market failures, not scarcity, hamper their current use in high-tech applications. Environ. Sci. Technol. 48, 9973–9974.
U.S. Office of Technology Assessment, 1992. Trade and the Environment: Conflicts and Opportunities. Assessment, 1992 #727, Report no. OTA-BP-ITE-94, Washington, D.C.
Wan, R., Wen, J., 2015. The Environmental Conundrum of Rare Earth Elements. Environ. Resour. Econ. (Dordr) 1–24.
Wang, X., Ge, J., Wei, W., Li, H., Wu, C., Zhu, G., 2016. Spatial dynamics of the communities and the role of major countries in the international rare earths trade: a complex network analysis. PLoS One 11 (5).
Wang, X., Lei, Y., Ge, J., Wu, S., 2015. Production forecast of China's rare earths based on the Generalized Weng model and policy recommendations. Resour. Policy 43, 11–18.
WTO, 2014. China-Measures Related to the Exportation of Rare Earths, Tungsten, and Molybdenum, Reports of the Panel, WT/DS431/R, WT/DS432/R, WT/DS433/R, 26, March, Geneva. . https://www.wto.org/english/tratop_e/dispu_e/431_432_433r_e.pdf.
Wübbeke, J., 2013. Rare earth elements in China: policies and narratives of reinventing an industry. Resour. Policy 38 (3), 384–394.
Wübbeke, J., 2015. China's Rare Earth Industry and End-Use: Supply Security and Innovation. The Political Economy of Rare Earth Elements. Palgrave Macmillan, UK, pp. 20–42.
Yang, X.J., Lin, A., Li, X.L., Wu, Y., Zhou, W., Chen, Z., 2013. China's ion-adsorption rare earth resources, mining consequences and preservation. Environ. Dev. 8 (1), 131–136.
Zachmann, G., 2010. Rareearth–no Case for Government Intervention. Bruegel. Available at. http://www.bruegel.org/nc/blog/detail/article/38-rare-earth-no-case-for-government-intervention.
Zhang, K., Kleit, A.N., Nieto, A., 2017. An economics strategy for criticality-application to rare earth element Yttrium in new lighting technology and its sustainable availability. Renew. Sustain. Energy Rev. 77, 899–915.
Zhang, K., Kleit, A.N., 2016. Mining rate optimization considering the stockpiling: a theoretical economics and real option model. Resour. Policy 47, 87–94.
Zhang, L., Guo, Q., Zhang, J.B., Huang, Y., Xiong, T., 2015. Did China's rare earth export policies work?-Empirical evidence from USA and Japan. Resour. Policy 43, 82–90.