The Upstream and Downstream Effects of Government Industrial Policy in the Rare Earth Elements Industry

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Abstract

The Chinese government has found considerable success in stimulating economic modernization through its industrial policy. The development of the rare earths industry, in both upstream and downstream markets, exemplifies this success. Rare earths are a group of metals whose natural properties make them critical for many pieces of modern technology. Upstream, Chinese raw rare earth producers extracted minimal output in 1985; by 2001 they accounted for more than 90 percent of global production. China stimulated this growth beginning in 1990 with implicit and explicit subsidies for rare earth producers, which enabled them to enter the market and produce at lower marginal costs than other world firms. These lower costs enabled Chinese producers to assume a market-leading position, and this paper explains the resulting developments in the upstream rare earth market through the Stackelberg model, which describes sequential quantity competition. In 2006, China introduced an additional policy of export quotas on rare earths, intended to benefit downstream Chinese firms. These firms depend on rare earths as inputs for the final goods (such as batteries and personal electronics) they produce. After the quota announcement, Chinese downstream firms benefitted from continued unrestricted access to rare earths, while non-Chinese downstream firms faced higher costs on the world market for rare earth inputs. This paper uses the Bertrand model, in which firms compete on prices, to examine the subsequent effects on these downstream markets. While Chinese rare earth producers were harmed by the export quotas, the combination of the subsidy and the export quotas enabled China to complete its economic goals: to first gain leverage in the rare earths industry, and to second transition its economy toward higher-value products and services.

JEL classification: L5, L52; F13; L13; L72

Keywords: Industrial Organization, Industrial Policy, International Trade, Mining

Introduction

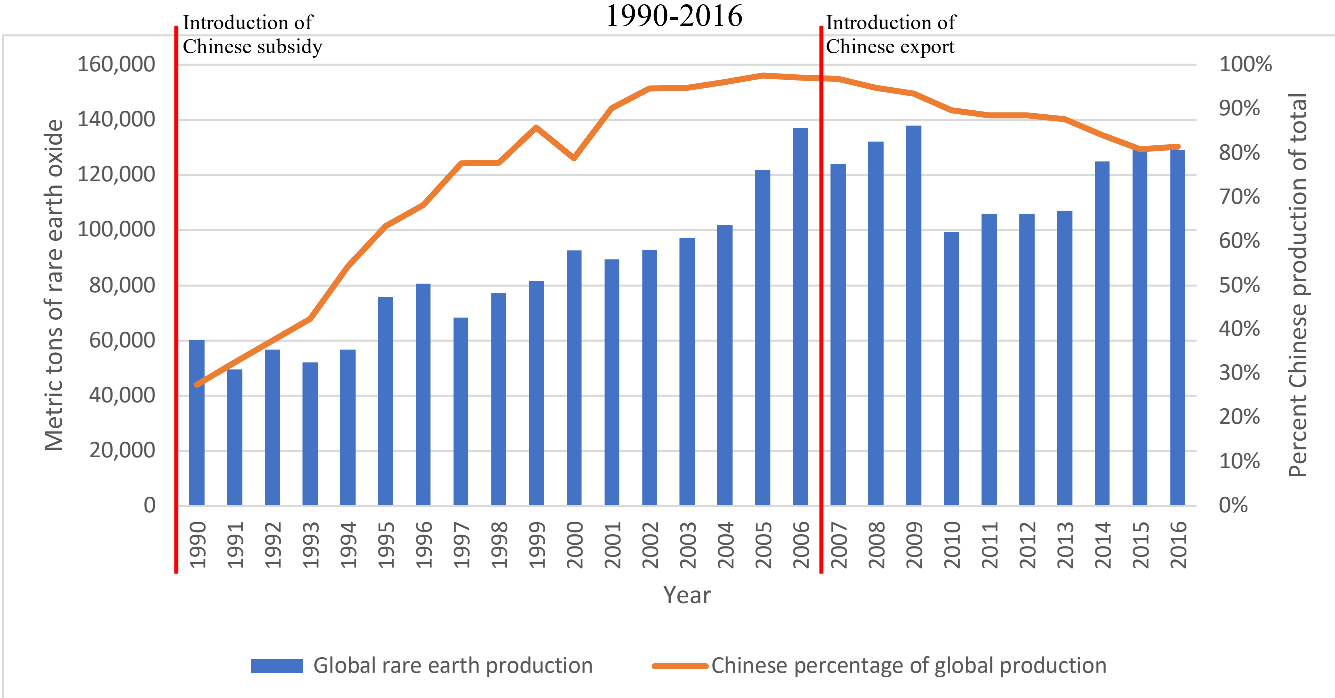
Industrialization and economic modernization are goals which many developing countries seek. Some states have attempted to expediate these goals through industrial policy, by which the state intervenes in a specific sector to aid that sector's growth and to promote the economy as a whole. The success of these interventions has varied widely. Several Latin American countries, for example, employed import substitution industrialization from the 1930s to the 1980s, under which states used tariffs to protect domestic industry. These tariffs, however, failed to prepare Latin American firms for international competition, and many economists attribute the region's slow growth, in part, to such policies (Meller, 2009). China, however, has found success in several of its industrial policies. From subsidizing certain strategic industries to requiring foreign entrants share critical technologies, Chinese policy has enabled its industry to move away from production of cheap, low-quality goods toward higher-value products and services.

One domain which exemplifies China's strategic usage of policy is the rare earths industry. Rare earths are a group of seventeen elements that, due to their unique physical properties, are critical inputs to many technologies, such as computer, phone, and electric vehicle batteries (Goonan, 2011). They are found on every continent except Antarctica. The elements are extracted collectively, and their prices have fluctuated similarly over time; for these reasons, existing research has tended to study these elements in aggregate. Demand for rare earths by technology firms has increased especially with the growth of personal electronics. As their technical importance has grown, they have also grown in strategic importance with the development of military technologies which use the elements as inputs. Their current importance, however, was not obvious as the industry initially developed, and governments took different approaches with respect to supporting the industry's development and limiting the environmental costs of extraction.

Firms that seek profitable entry into the rare earth extraction industry face two major hurdles. First, rather than forming in concentrated deposits, rare earths tend to be dispersed across wide areas (hence, they are "rare"). This dispersion impedes firms' ability to extract high volumes of rare earth material from individual mining sites (Fernandez, 2017). Second, firms tend to face both high start-up costs (when purchasing land and equipment) and high regulatory compliance costs. Most countries regulate rare earth mining, due to the environmentally destructive nature of their extraction. Miners must unearth large swaths of land for mines to be viable, and rare earths tend to be found in conjunction with certain radioactive elements, which creates risk for uncontrolled radioactive waste around the mining sites (Riesgo García et. al., 2017). In fact, rare earths were predominantly mined in California between 1965 and 1985, but a series of radioactive waste spills led policymakers on the state and local levels to pass legislation restricting continued extraction.

Chinese producers had not been major players in the rare earths space before 1985, but they gained market share as the Chinese government left rare earth production environmentally unregulated. This lack of regulation implicitly subsidized Chinese rare earth extraction, as Chinese producers did not face the high regulatory compliance costs faced by firms in other countries. Additionally, as with other strategic industries, the Chinese government facilitated the growth of the rare earths industry through low-cost loans and subsidies (Haley, Haley, 2013). As demand for rare earths grew, Chinese production boomed; its percentage of global production grew from 30 percent in 1990 to 90 percent in 2001. The growth of the industry and of the Chinese market share is shown in Figure 1.

Figure 1. Global Rare Earth Production and Chinese Percentage of Global Production, 1990-2016



Source: United States Geological Survey (1994-2016)

The low-cost loans and lack of environmental regulation effectively subsidized Chinese rare earths firms relative to firms in other countries. With artificially low marginal costs and growing global demand for rare earths, Chinese firms increased their output. By 2001, China accounted for more than 90 percent of worldwide output and has continued to dominate the industry since. Throughout this time period from 1990 to the present, the Chinese government has continued to play an active role in the industry. Within China, the government promotes collusion among the several rare earth firms through strong interventions like its low-cost loans, which force the Chinese rare earth producers to coordinate in the world rare earths market. As a result of this enforcement, the Chinese firms collectively operate like a monopoly and influence market prices in their profit-maximizing production decision. The Chinese government also has instituted policies aimed directly at world markets, such as its series of export quotas on rare earth output that began in 2006.

The Chinese government's policies affect domestic and international firms in both the upstream (raw rare earth) and downstream (final goods dependent on rare earths as inputs) markets. (Mancheri, 2015). The government's subsidy of rare earth extraction enabled Chinese upstream firms to enter the industry and reduced their marginal cost (relative to world competitors) on a per-unit basis. With lower marginal costs and demand for rare earths increasing, Chinese firms increased output and assumed a leading position in the industry. From this position, Chinese firms have used output quantity decisions to influence the entry and exit behavior of other firms, an outcome predicted by the Stackelberg model. In fact, from the mid-1990s through 2006, Chinese producers maintained high output and low per-unit profitability, deterring other firms from entering the market. The government's subsidies benefitted, in turn, downstream firms both within and beyond China, as total production of rare earths was greater (and prices lower) than if there had been no subsidies.

While continuing its subsidies for rare earth extraction, China introduced in 2006 a new policy of an export quota of rare earths, intended to benefit downstream Chinese firms. The quotas, which were maintained until 2014, affected only Chinese exports (not production), and influenced competition in both the upstream and downstream industries. The policy harmed upstream Chinese firms, as it limited their ability to supply the world rare earth market and opened opportunity for other world firms to enter. Chinese downstream firms benefitted as they continued to have unrestricted access to the Chinese rare earths. Non-Chinese downstream firms, however, were harmed, as their access to Chinese rare earths was restricted and prices for rare earth inputs on the world market rose.

The Chinese government made its export quotas increasingly restrictive between 2006 and 2010, and in 2012, the United States, European Union, and Japan filed a complaint to the

World Trade Organization (WTO) asserting the export restrictions were inconsistent with WTO requirements. Upon reviewing the arguments, the WTO rejected China's position that its export quotas were a measure of resource conservation, on the grounds that the quotas did not reduce actual rare earth production. The Chinese government removed its quotas in 2014 to comply with the WTO ruling, but in the years since, it has developed other means to control production and export, such as new monitoring of illegal mining activity (Mancheri et. al, 2019).

My research begins with a literature review of past analysis on the rare earths industry and on strategic trade and industrial policy. Following this review, I model firms in the upstream market as competing on quantities, as in the Cournot and Stackelberg models. I include consideration for the subsidies and then the export quota. I next model firms in downstream markets (markets for final goods dependent on rare earths as inputs) competing on prices, as under the Bertrand model. I consider the subsidies and export quotas, which here function as a form of vertical foreclosure. Last, I offer an approach to evaluate the effects of the policies from the perspective of the Chinese government.

Literature Review

This paper seeks to add to existing literature on the rare earths industry by studying the effects of Chinese industrial policy. While study has been conducted on the key players, countries, and incentives of the rare earths industry, an approach rooted in industrial organization theory has not previously been published. China has strengthened the market positions of both its upstream and downstream rare earths firms though its policies, and lessons for other countries and other firms may be applicable.

Academic study of rare earth elements is a relatively new area of research, spurred by a trade dispute in 2010-2011 which focused international attention on their market. China's dominance of rare earth element production has created concern among policymakers and academics alike of the stability of supply, especially as new technologies develop that require rare earth elements as inputs. The existing research on rare earths can be broadly divided into three focal areas: international trade, environmental sustainability, and financial analysis of production opportunities beyond China. Most of the existing research on rare earths employs qualitative approaches, creating opportunity for model-based and quantitative research to be explored. A large body of industrial organization literature also forms the foundation for my approach, which I review at the end of this section.

Study on the international trade of rare earth elements was prompted by recognition of China's monopoly-like control of the supply chain. Mancheri (2015) outlines the factors, such as expanding domestic consumption, that initially led China to restrict exports. Tracking trade through country-level imports and exports, the research explores factors including industry consolidation in China among six state-owned-enterprises and a changing resource tax system that stand to affect future trade of rare earth elements (Mancheri, 2015, p 267). This direction of research was further developed by Mancheri and his team with a theoretical model exploring the relationships between trade restrictions, the global supply chain, the Chinese supply chain, and rare earth elements prices (Mancheri, Sprecher, Bailey, Ge, Tukker, 2019). Specifically, researchers investigated the effects of changes in taxation, product quality standards, Chinese imports, illegal mining, consolidation of rare earth enterprises, and state-sponsored stockpiling on global supply, international price, and Chinese price for rare earth elements. Barakos, Gutzmer, and Mischo (2016) researched the supply chain with a different approach, analyzing why new entrants who appeared during the 2010-2011 trade conflict were unsuccessful in establishing themselves as permanent competitors to Chinese producers. Using a qualitative framework, the researchers developed an understanding of the importance of China's vertical integration of the rare earths industry, from mining to end product. No other country or region has developed such a degree of integration of the industry, strengthening China's position of market power.

A second direction of research on rare earth elements pertains to their usage, sustainability, and recyclability. This literature focuses especially on environmental externalities of production and on the ways these externalities can be reduced. McLellan, Corder, Golev, and Ali (2014) examine the sustainability of rare earth element extraction from environmental, social, economic, and technical lenses. Their analysis predicts that demand for rare earth elements will outstrip production feasible through existing methods by 2050, so both new extraction methods (such as sub-sea mining) and an increased focus on recyclability will need to be developed. A report by the United States Geological Survey on rare earth element usage and recyclability furthers this analysis, finding that across the many applications of rare earth elements, which include glass, catalysts, metallurgy, ceramics, magnets, and battery alloys, only approximately 1 percent of rare earth elements are recycled (Goonan, 2011).

A third area of research focuses on the opportunity for rare earth element production outside of China. Riesgo García, Krzemień, Manzanedo del Campo, Alvarez, and Gent (2017) analyze the expected production and profitability of five mining projects in Canada, South Africa, the United States, Greenland, and Australia. While the researchers found that these projects could provide for as much as a third of worldwide consumption of rare earth elements, the inability to predict rare earth element prices challenged their analysis of expected profitability from the production. Fernandez (2017) explored with greater depth the pricing trends of rare earth elements, finding no statistically significant correlation between their prices and the prices of commodity indices. Further, the study found that the market capitalization and economic viability of leading rare earth element companies worldwide is driven largely by the production from Chinese production companies, a result that would be expected, given China's dominant market position.

The foundations of this paper rely also upon literature from industrial organization theory. Dixit (1980) examined the results of the Stackelberg model with respect to entry deterrence in an international context. He shows that though the rules of the model are exogenous, firms can change the initial conditions of the game and alter competitive outcomes through making irrevocable investments. Spencer and Brander (1983) then incorporated the role of governments by studying the effects of strategic industrial policies, such as R&D or export subsidies, on domestic welfare. They use government objective functions to represent policy effects from the state's perspective. Their research shows that strategic policy can raise welfare by shifting profits from foreign to domestic firms, but that the noncooperative equilibrium between governments is suboptimal. Eaton and Grossman (1986) continue research into the role of government intervention by studying optimal tax and subsidy policy under a variety of circumstances. They find intervention can raise domestic welfare by reducing marginal cost relative to the costs of competitors. Spencer and Jones (1991) studied the incentives for a foreign upstream firm and foreign country to supply a domestic downstream firm. Their research finds that vertical integration can create significant cost advantages for a firm, and they identify the criteria that support vertical foreclosure when downstream firms compete on quantities (Cournot competition) or on prices (Bertrand competition).

Development of the Rare Earths Industry

As mentioned in the introduction, the rare earths industry can be divided into two distinct markets: the upstream and the downstream. The upstream industry extracts and refines raw rare earth material. The downstream industry purchases these raw rare earths as input for their own final products, such as personal computers and other consumer electronics, which they sell to end users. To simplify the dynamics of the industry, the upstream and downstream firms can each be aggregated into a single Chinese firm and a single non-Chinese (or rest of world) firm.[1] This simplification is supported by actual industry dynamics: under enforcement by the government, the Chinese firms tend to act like a single player, and world firms tend to respond similarly to Chinese policy.

Upstream, Chinese and non-Chinese firms compete in the raw rare earths market, and downstream, Chinese and non-Chinese firms compete in the final goods market. This distinction between Chinese and non-Chinese firms enables exploration into the implications of Chinese government policies, which, between 1990 and 2014, affected both upstream and downstream firms. This section of the paper will model the competitive dynamics between both upstream and downstream firms, examine the predictions of those models, and explore the ways in which Chinese government policies have affected both upstream and downstream outcomes.

Upstream Firm Competition

Upstream rare earths firms compete to provide the raw inputs required by downstream final goods manufacturers. Competition in the industry is oligopolistic. To focus on the sequential nature of competition between Chinese firms and non-Chinese firms, I model the Chinese rare earths producers as being part of an aggregate Chinese rare earth producing firm,

[1] I use non-Chinese, rest-of-world, and world interchangeably through this paper to describe firms outside of China.

and I similarly consider a single representative non-Chinese (rest of the world) firm. This assumption that independent Chinese rare earth producers can reasonably be modeled as a single Chinese firm simplifies my analysis and is supported by market evidence. In particular, the strong interventions of the Chinese government – such as its ability to impose the export quota – force the Chinese rare earth producers to act with a significant level of coordination in the world market for rare earths.

While, non-Chinese rare earth firms may not coordinate, I model the behavior of a single non-Chinese firm to represent the general behavior of a follower firm in a Stackelberg setup. This simplification limits any analysis of competition between follower firms, but it allows me to focus on the ability of the Chinese rare earth producer to impact entry and profitability of non-Chinese follower firms.

Because of the high capital investment required for extraction, the firms compete on the quantities they produce. I initially model this competition with the Cournot model. The Cournot model assumes firms make decisions simultaneously, so in order to capture the sequential nature of the competition between Chinese and non-Chinese firms, I then move to the sequential Cournot, or Stackelberg, model. In this model, the Chinese firm maintains the market leader position and the non-Chinese firm is the market follower. Then, I consider through the model the effects on the upstream industry of the Chinese government's strategic policies. These policies include subsidies for Chinese rare earth producers and export quotas on raw rare earths.

Simultaneous quantity competition in Cournot. The results of the sequential Stackelberg model can be better understood once first having established the fundamentals of the simultaneous Cournot model. In both models, firms compete on the quantities they supply, q_i^s. Through the remainder of these models, quantities and prices for Chinese firms will be denoted with the subscript c and for non-Chinese (rest of world) firms with the subscript w. For simplification, the model will initially assume that marginal costs of production in China and outside of China are equal; $mc_C = mc_w = mc$.

To reach the payoffs that firms receive in the model, the relationship between market prices for rare earths (p) and the quantity of rare earths demanded (q^d) must first be identified. Here, the quantity of rare earths demanded is a function of price. Where a and b are coefficients that indicate the price quantity relationship:

$$q^d(p) = \frac{a-p}{b} \qquad (1)$$

By this equation, an increase in price would lead to a decrease in quantity demanded. By rearranging the equation to solve for price, the inverse demand function then identifies the price for each level of quantity demanded:

$$p(q^d) = a - bq^d \qquad (2)$$

When this market reaches equilibrium, the conditions for which are described below, the quantity demanded q^d is equal to the sum of the quantity supplied by the Chinese firm and the world firm. Price in this market will be determined by this summed supply.

$$q^d = q_C^s + q_w^s \qquad (3)$$

The payoffs to the firms are their profits. The prices the firms receive for rare earths are represented as functions of the total quantity supplied by both the Chinese and the world firm. As mentioned, the marginal costs of the firms are assumed to be equal. These functions, respectively for the Chinese firm and for the world firm:

$$\pi_C(q_C^s, q_w^s) = p(q_C^s + q_w^s)q_C^s - mcq_C^s \qquad (4)$$

$$\pi_w(q_C^s, q_w^s) = p(q_C^s + q_w^s)q_w^s - mcq_w^s \qquad (5)$$

For the model to reach a Cournot equilibrium, two conditions must hold. First, at equilibrium, neither firm is able to increase its profit by changing its output level, given the output level of the other firm. Additionally, the market price clears the market. Specifically,

Given $q_C^s = q_C^*$, q_w^* solves $\max_{q_w} \pi_w(q_C^*, q_w)$

Given $q_w^s = q_w^*$, q_C^* solves $\max_{q_C} \pi_C(q_C, q_w^*)$

$$p^* = a - b(q_C^* + q_w^*) \text{ for } p^*, q_C^*, q_w^* \geq 0 \qquad (6)$$

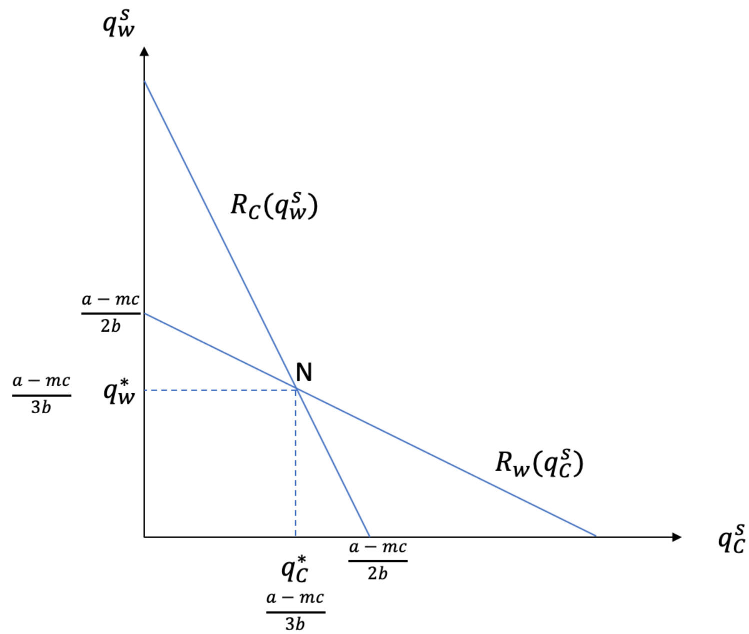
At this equilibrium, we take the first order conditions to maximize (4) and (5) with respect to q_C^* and q_w^*, respectively. The result of this maximization identifies as reaction functions how each firm responds through its own quantity supplied to a change in quantity supply by the other firm. China's reaction function to non-Chinese quantity supplied is denoted $R_C(q_w^s)$; the world firm's reaction function to Chinese quantity supplied is denoted $R_w(q_C^s)$:

$$R_C(q_w^s) = q_C^* = \frac{a-mc}{2b} - \frac{1}{2} q_w^s \qquad (7)$$

$$R_w(q_C^s) = q_w^* = \frac{a-mc}{2b} - \frac{1}{2} q_C^s \qquad (8)$$

In a graphic representation, the reaction functions are downward sloping because the rare earths from each firm are substitutes. In Figure 2 below, the reaction functions are graphed with the quantity supplied by each firm, q_C^s and q_w^s, on the axes and the equilibrium output quantities, q_C^* and q_w^* at the intersection (point N) of the functions.

Figure 2. Reaction functions of Chinese and world firms, at Cournot equilibrium



The Cournot equilibrium output can also be found algebraically, by setting the reaction functions equal to each other. The equilibrium output quantities are:

$$q_C^* = q_w^* = \frac{a-mc}{3b} \tag{9}$$

The equilibrium quantity for the market is the sum of these quantities:

$$q^* = q_C^* + q_w^* = \frac{2a-2mc}{3b} \tag{10}$$

As in (6), the market price at Cournot equilibrium must clear the market:

$$p^* = a - bq^* = \frac{a+2mc}{3} \tag{11}$$

Sequential quantity competition in Stackelberg. The Cournot model assumes that firms make their output decisions simultaneously. Firms in the rare earths industry, however, have competed through sequential responses to one another. In 1990, the Chinese government began to subsidize its rare earth producers, implicitly through lax environmental regulations and explicitly through low-cost loans, which have affected industry development through two separate channels. First, the subsidies gave Chinese firms a first-mover advantage in the industry. If we assume the

Chinese subsidy announcement came before decisions for future production by firms, it credibly signaled to market participants that Chinese firms would commit to increasing investment in extraction technology. In doing so, Chinese firms extract a greater portion of the total industry profit and gain a market-leading position; non-Chinese firms have to respond in turn. From this leading position, Chinese firms were also able to influence the world firms' strategies with their own accommodation and deterrence strategies. Second, the marginal cost of extracting rare earths in China fell below the costs in other countries, due to the government subsidies and lax environmental regulations.

In this section, I first examine how the equilibrium prediction changes in a two-period, sequential Stackelberg model relative to the simultaneous Cournot model, and then I incorporate the divergent marginal costs. Last, I incorporate the effects of the Chinese export quota.

When the Chinese firm moves first, it supplies quantity q_C^s, to which the world firm reacts and produces quantity q_w^s. This world firm response, like in the Cournot model, is according to its reaction function $R_w(q_C^s)$; the firms have the same reaction functions as they did before, in equations (7) and (8). As before, I am still assuming the firms have the same marginal cost and know each other's reaction functions. The Chinese firm chooses an output quantity q_C^s that maximizes its own profit function; to do so, it substitutes the world firm's reaction function $R_w(q_C^s)$ for world quantity q_w^s in its profit function:

$$\max_{q_C^s} \pi_C(q_C^s, R_w(q_C^s)) = p(q_C^s + R_w(q_C^s))q_C^s - mcq_C^s \qquad (12)$$

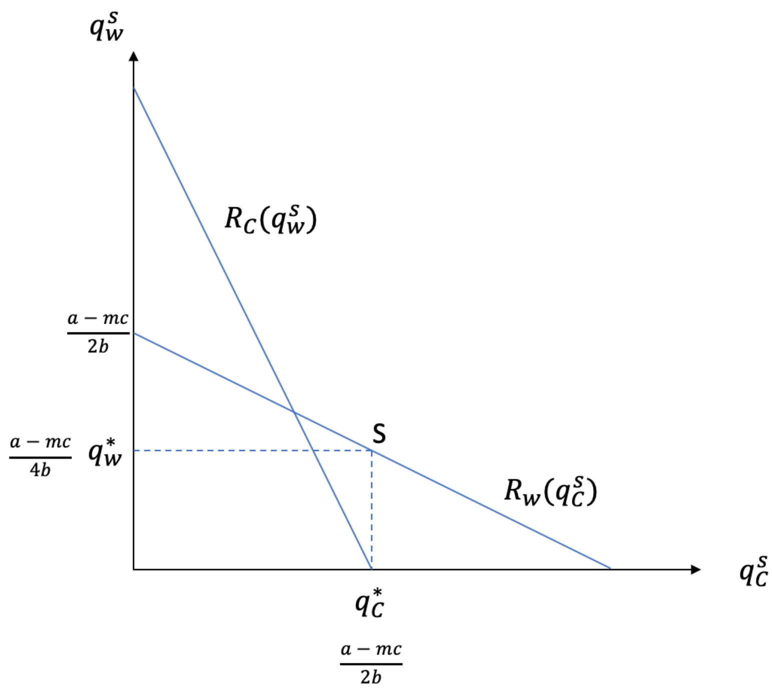
Equilibrium arises under the same conditions outlined in the Cournot game: neither firm can increase its profits with a unilateral change in quantity, and prices clear the market. This equilibrium makes two additional assumptions. First, it is assumed that world firms entering the market in the second period do not face costs of entry in addition to their marginal costs. This assumption eases comparison between the simultaneous game and sequential game results; consideration for possible entry costs will be made later. Second, the Chinese (market-leading) firm is assumed to not reduce its output in the second period. Though the Chinese firm would best respond to the world firm's reaction by reducing its own output, this action would lead to successive output reductions, and the equilibrium would converge on the Cournot equilibrium, with each firm producing the same level of output. The market leader, in the long run, profit maximizes by maintaining the market leading position. When the firms sequentially profit maximize, the following equilibrium quantities in the second period result:

$$q_C^* = \frac{a-mc}{2b} \quad (13)$$

$$q_W^* = \frac{a-mc}{4b} \quad (14)$$

The market quantity q^* is the sum of these quantities. This total output level is higher than the level at Cournot equilibrium; the equilibrium market price p^* is lower in the Stackelberg equilibrium than the Cournot equilibrium. Representing the Stackelberg equilibrium graphically, as in Figure 3 below, the Chinese firm chooses its output level as if the world firm's output q_W^s were zero. The world firm then responds according to its reaction function, $R_W(q_C^s)$. The equilibrium quantities q_C^* and q_W^* are reached at point S.

Figure 3. Reaction functions of Chinese and world firms, at Stackelberg equilibrium



In addition to giving the Chinese firm a first-mover advantage, the subsidy affects the marginal cost of the Chinese firm, reducing it relative to the marginal cost of the world firm. While the world firm's marginal cost is still mc, the Chinese firm's marginal cost is $mc(1-s)$. The payoff function for the world firm's profit remains as equation (5); the Chinese payoff function now includes the per-unit subsidy:

$$\pi_C(q_C^s, q_w^s, s) = p(q_C^s + q_w^s)q_C^s - mc(1-s)q_C^s \quad (15)$$

The equilibrium conditions remain as they were before the subsidy, as does the reaction function of the world firm $R_w(q_C^s)$. The Chinese firm, with knowledge of how the world firm will react, chooses an output quantity q_C^s that maximizes its profit function. Like in (12), it substitutes into its profit function the world firm's reaction function $R_w(q_C^s)$ for world quantity q_w^s:

$$\max_{q_C^s} \pi_C(q_C^s, R_w(q_C^s), s) = p(q_C^s + R_w(q_C^s))q_C^s - mc(1-s)q_C^s \quad (16)$$

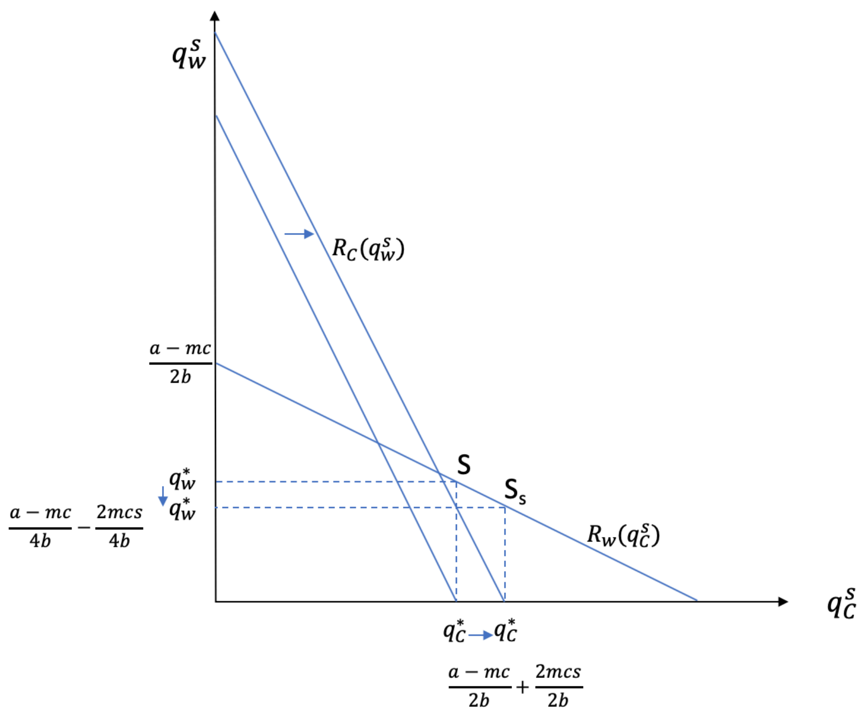
The equilibrium quantities that result from the Chinese profit maximization and the reaction of the world firm account for the Chinese subsidy:

$$q_C^* = \frac{a-mc+2mcs}{2b} \tag{17}$$

$$q_W^* = \frac{a-mc-2mcs}{4b} \tag{18}$$

The Stackelberg equilibrium market quantity q^* is the sum of these quantities. This sum is greater than the non-subsidized Stackelberg equilibrium by $\frac{mcs}{2b}$. In Figure 4, the graphic representation of the reaction functions captures this change in each firm's equilibrium quantities, as the Chinese reaction function $R_C(q_W^s)$ shifts parallel outward. The new equilibrium point is S_s.

Figure 4. Reaction functions of Chinese and world firms, at Stackelberg equilibrium after Chinese subsidy



As a result of the Chinese government's subsidies, the Chinese firm gained a first-mover advantage in the industry, thereby extracting more profits than it would have in the simultaneous case. Additionally, as the subsidy lowers the Chinese firm's marginal cost relative to that of the world producer, the Chinese firm further increases its equilibrium quantity relative to the quantity of the world firm and extracts greater profits.

Consideration for fixed costs. This model, and its resulting equilibrium, assume that world firm entering the market in the second period (market follower) does not face fixed entry costs. In the rare earths industry, however, market followers face fixed entry costs, such as purchases of land and equipment. The Chinese firm already bore these costs, so considers them sunk and does not include them in the production decisions for future periods. The fixed costs faced by a potential new firm affect its expected profitability and market-entry decision. The market leading Chinese firm, by changing its own output levels, can further affect the follower's profitability and induce particular responses. Depending on the follower's expected profitability upon entering the market, the market leader can profit maximize by either deterring or accommodating the follower's entry.

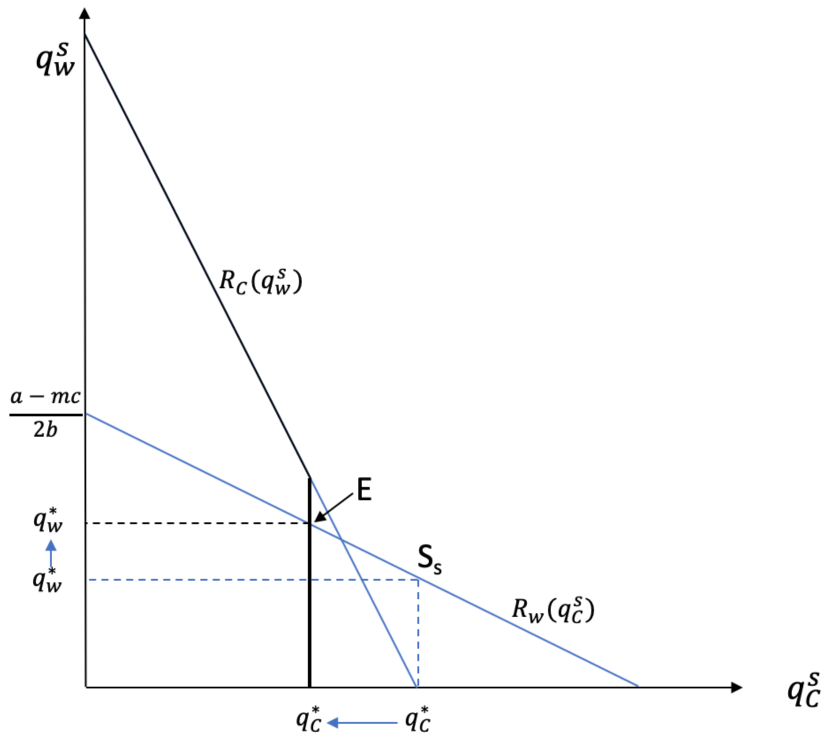
When the follower faces fixed cost of entry, it enters the market as long as expected profitability is positive. If expected profitability is positive but small, the leader can increase its output to reduce per-unit profitability, making expected profitability for the follower negative, thereby deterring its entry. If expected profitability is positive and high, the cost of deterrence to the leader is high, so it accommodates entry. In the rare earths industry, the subsidy to the Chinese firm allowed it to profit maximize at a higher output than if there had not been a subsidy. This high level of output reduced per-unit profitability and deterred other world firms from entering the rare earths industry from 1990 to 2006. The Chinese firm, by its deterrence strategy, came to control even more of the market than the above model (which did not include fixed costs faced by the follower) suggested.

The below analysis on the Chinese export quota proceeds without consideration for the fixed costs faced by non-Chinese firms. The nature of the quota, however, is such that the results hold even if non-Chinese firms did face fixed costs. The export quota prevents the Chinese firm from pursuing the entry deterrence strategies, forcing the Chinese firm to accommodate the entry of the non-Chinese firm. In fact, during the years of the export quota, firms from the United States and Australia entered the market; they had previously been deterred from entry by the high levels of Chinese quantity supplied.

Introduction of Chinese export quota. Beginning in 2006, the Chinese government introduced an export quota on raw rare earths. The quota applied only to exports, not to the production, of rare earths. This policy intended to benefit downstream Chinese firms dependent on rare earths as inputs, but it also affected the profitability of the upstream Chinese rare earth producers. Specifically, in the upstream, the quotas capped the ability of the Chinese firm to respond in the world market to changes in quantity supplied by the world firm. The Chinese export quota became increasingly restrictive between 2006 and 2010, before being removed in 2014.

In Figure 5 below, the export quota is represented graphically as a vertical line; the Chinese firm is unable to supply quantities according to its reaction function $R_C(q_w^s)$ beyond this point. The world firm chooses the level of output at which the Chinese export quota intersects with its reaction function $R_w(q_C^s)$; the market equilibrium is represented at point E.

Figure 5. Reaction functions of Chinese and world firms, at Stackelberg equilibrium after Chinese subsidy and export quota



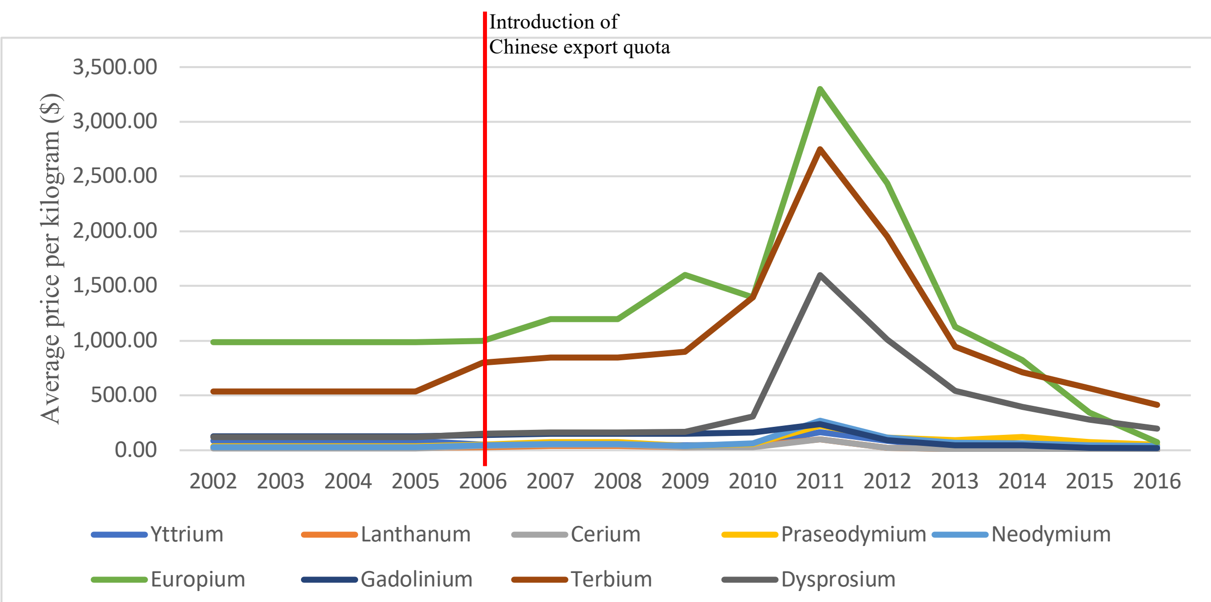
In this world market for rare earths, the Chinese equilibrium quantity has fallen relative to before the quota. The Chinese firm is unable to profit maximize according to its reaction function, so a corner solution is reached at the level of the quota. The world firm responds by increasing its own quantity of supply. Because its reaction function $R_W(q_C^s)$ has a slope of $\frac{-1}{2}$, the world producer will replace half of the Chinese quantity reduction.

The world firm supplies its quantity only to the world market, and its profit function does not change as a result of the export quantity. The export quota does, however, split the Chinese downstream market from the world downstream market, and the Chinese rare earth firm supplies both markets. A final consideration for the Chinese firm's profit function after this market split must be made, to indicate the payoffs it receives for the quantity supplied to the Chinese market.

Whereas before the export quota, when both Chinese and non-Chinese downstream firms bought rare earths on the world market, after the export quota the Chinese firms buy within the Chinese market and the non-Chinese firms on the separate world market. Under the assumption that the quantity of the export quota is binding, in the sense that the quota is lower than the quantity of Chinese rare earth demanded by non-Chinese firms, the quota causes world market demand to exceed supply, and world market prices increase. In the Chinese market, where Chinese downstream firms access the rare earths produced above the quota quantity, a binding export quota causes quantity supplied to exceed quantity demanded, and the market prices fall.

The available pricing data support the binding quota assumption and show an increase in prices for rare earths on the world market. As visible in Figure 6, the prices for most rare earths increased after the Chinese quota was introduced in 2006. Prices peaked in response to the strictest quotas in 2010, and they remained elevated (relative to 2005 levels) until after the quotas were lifted in 2014.

Figure 6. Pricing trends for select rare earth elements, 2002-2016



Source: United States Geological Survey (2002-2016)

With world prices now denoted p', Chinese prices denoted p, the Chinese export quota quantity $q_C^{s\prime}$, and the quantity supplied to the domestic Chinese market q_C^s, the Chinese profit function divides revenues from the Chinese and world markets. The government subsidy of rare earths is still included.

$$\pi_C(q_C^{s\prime}, q_C^s, q_w^s, s) = p'\left(q_C^{s\prime} + q_w^s\right)q_C^{s\prime} + p(q_C^s)q_C^s - mc(1-s)(q_C^{s\prime} + q_C^s) \quad (19)$$

The world firm's profit function remains as in equation (5), except that the quantity of Chinese rare earths on the world market is determined by the Chinese export quota:

$$\pi_w(q_C^{s\prime}, q_w^s) = p'(q_C^{s\prime} + q_w^s)q_w^s - mcq_w^s \quad (20)$$

The same equilibrium conditions hold - neither firm can increase its profits through a unilateral change in quantity, and prices clear the markets. The upstream Chinese firm's profits and position as market leader are challenged by this export quota policy. The quota limits the Chinese firm's exposure to rising prices in the world market, and the world firm captures the market share vacated by the Chinese firm. The world firm benefits from the higher market prices, which increase its profits. As the Chinese prices fall below the initial world market prices, the Chinese upstream profits are harmed.

While the export quota disadvantages Chinese firms by limiting their exposure to the world market, research on vertical foreclosure suggests they could benefit through other channels. Vertical foreclosure is the exclusion that results when a downstream buyer is denied access to an upstream supplier. Stefanadis (1997) finds that upstream firms that capture the business of downstream firms through steps like vertical foreclosure experience higher rates of innovation than firms that are unable to capture downstream business. While the export quotas limited the ability of Chinese rare earth firms to supply world markets, they also captured for the Chinese rare earth firms the downstream Chinese business, a relationship which over time may lead to greater upstream Chinese innovation. As data becomes more available, future research can examine the relative investments in innovation by Chinese and non-Chinese rare earth firms.

Downstream Firm Competition

Unlike the quantity competition between upstream rare earth firms, the downstream competition between firms dependent on rare earths seems best described as price competition. Firms produce a variety of final goods and compete to capture consumer demand by offering the lowest prices (or lowest quality-adjusted price). Like in the upstream market, I simplify the downstream market to two firms, a Chinese and a world firm, in order to capture the effects of Chinese government policy. When the two firms offer the same price, I assume that consumers split their purchases evenly between the firms. I initially assume that the two firms have the same technology, so they have the same marginal cost ($mc_C = mc_w = mc$). I will use the Bertrand model to map the downstream market before and after the Chinese export quota. This quota increases the marginal costs of the non-Chinese firm by raising the price of rare earth inputs used in each final good. The quota can be considered a case of vertical foreclosure, orchestrated by the Chinese government, in favor of downstream Chinese firms and at the expense of downstream firms outside of China.

Bertrand model with equal marginal costs. The quantity of final goods demanded q^d from the Chinese and world downstream firms depend upon the relative prices offered by each firm. In the below equations, a and b are coefficients that indicate the relationship between price and quantity demanded for the final goods (as in equation (1)). Where p_C is the price offered by the Chinese firm and p_w is the price offered by the world firm, quantity demand from the Chinese firm is represented:

$$q_C^d = \begin{cases} 0 \; if \; p_C > p_w \; (or \; if \; p_C > a) \\ \frac{a-p_C}{2b} \; if \; p_C = p_w = p < a \\ \frac{a-p_C}{b} \; if \; p_C < \min(a, p_w) \end{cases} \tag{21}$$

Quantity demanded from the world firm is represented similarly:

$$q_w^d = \begin{cases} 0 \; if \; p_w > p_C \; (or \; if \; p_w > a) \\ \frac{a-p_w}{2b} \; if \; p_C = p_w = p < a \\ \frac{a-p_w}{b} \; if \; p_w < \min(a, p_C) \end{cases} \tag{22}$$

Quantity demanded for the total market is the sum of these quantities demanded, equal to $\frac{a-p}{b}$. As each firm has the ability to set its own price, the profits of each firm are represented as functions of the prices it offers, its marginal cost, and the quantity it supplies:

$$\pi_C(p_C, p_w) = (p_C - mc)q_C^s \tag{23}$$

$$\pi_w(p_C, p_w) = (p_w - mc)q_w^s \tag{24}$$

Market equilibrium is reached under the condition that neither firm can increase its profit by changing its price, given the price set by the other firm. Specifically, $\{p_C, p_w, q_C, q_w\}$ is in Bertrand equilibrium if

Given $p_w = p_w^*$, p_C solves $\max_{p_C} \pi_C(p_C, p_w^*)$

Given $p_C = p_C^*$, p_w solves $\max_{p_w} \pi_w(p_C^*, p_w)$

In this model, given that firms have the same marginal cost, the firms compete by undercutting each other on price, until the price falls to the level of the marginal cost. At equilibrium, firms reach the perfectly competitive outcome where price equals marginal cost and profits are zero.

In the rare earths industry, the Bertrand model predicts this result both before and after the Chinese government's subsidy on the production of upstream rare earths. The subsidy increases the total market quantity of rare earths, as seen in Figure 4 and equations (17) and (18). In doing so, it lowers the input cost for all firms; marginal cost mc falls evenly for all firms.

Bertrand model with unequal marginal costs. Unlike the subsidy, the export quota on raw rare earths does not affect all downstream firms in the same way. Before the export quota, the upstream Chinese rare earth firm had supplied rare earths to all downstream firms. The export quota, however, restricts the downstream world firm's access to the Chinese rare earths, while leaving the Chinese downstream firm's access unrestricted. By this step of vertical foreclosure by the Chinese government, the Chinese downstream firm benefits, and the world downstream firm is harmed.

As before, under the assumption that the export quota is binding, (world demand for Chinese rare earths exceeds the quantity set by the quota) the rare earth prices increase on the world market in response to the quota. As these rare earths are inputs for all downstream firms, the marginal costs for the world firm increase relative to the marginal costs of the Chinese firm. The profit functions account for the different marginal costs, $mc_w > mc_C$.

$$\pi_C(p_C, p_w) = (p_C - mc_C)q_C^s \tag{25}$$

$$\pi_w(p_C, p_w) = (p_w - mc_w)q_w^s \tag{26}$$

Because of the different marginal costs, a perfectly competitive equilibrium no longer results. The Chinese firm, which faces a lower marginal cost, can charge a price just below the marginal cost of the world firm:

$$p_C^* = mc_w - \varepsilon \tag{27}$$

The world firm is unable to match this price and still be profitable. As a result, at equilibrium, the world firm supplies zero quantity and China captures the full market. China supplies equilibrium quantity:

$$q_C^* = \frac{a - mc_w + \varepsilon}{b} \tag{28}$$

This result approximates the downstream competition between Chinese and non-Chinese firms. Loosening the assumption that firms have the same technology and allowing for differentiated end products pulls the original Bertrand equilibrium result away from the perfectly competitive outcome. Additionally, capacity constraints on production may prevent a single firm from capturing an entire market. Despite these considerations, however, the result is clear that the rare earth export quota benefits downstream Chinese firms and harms downstream non-Chinese firms.

Perspective from Chinese Government

The efficacy of the subsidy and export quota policies can be evaluated from the perspective of the Chinese government through an objective function. Here, I apply the approach of Brander and Spencer (1983) to the rare earths industry. The Chinese government considers the economic effects of its policies on domestic firms and the costs of those policies. While the objective function does not focus on all parties potentially affected by a policy, it enables analysis into particularly salient considerations.

For example, when only the subsidy was in place from 1990-2006, the government considers just the effects of its policy on the upstream domestic firm. This analysis includes the relative profits the Chinese firm experiences before the subsidy (represented in equation (4)) and after (represented in equation (15)) and the cost of the subsidy to the government. When the upstream market is at equilibrium, the objective function B_C is represented

$$B_C(s) = \pi_C(q_C^*, q_w^*, s) - \pi_C(q_C^*, q_w^*) - sq_C^* \tag{29}$$

Later, China instituted its export quota on rare earths from 2006 through 2014. With the subsidy and export quota both in place during this time, the Chinese government considers in its objective function the effects on both the domestic upstream rare earth firm and the domestic downstream firm dependent on rare earths as inputs. Here the upstream profits are denoted π_C and the downstream profits π_{D-C}. With the world markets at equilibrium, $q_C'^*$ denotes the quantity of rare earths supplied to the world market (determined by the export quota from 2006 to 2014) and q_C denotes the quantity of rare earths supplied to the domestic Chinese market.

$$B_C(s, q_C^{*'}) = \pi_C(q_C'^*, q_W^*, q_C, s) - \pi_C(q_C^{*'}, q_W^*, s) - sq_C^*$$

$$+\pi_{D-C}(p_C^*, p_W^*, q_C'^*) - \pi_{D-C}(p_C^*, p_W^*) \qquad (30)$$

In the downstream market, the export quota enables the Chinese firm to extract greater industry profits through the higher marginal costs that it imposes on the non-Chinese firm, as described by the Bertrand model.

While these representations of the government objective functions are preliminary, they can lead to further investigation on the optimal level of subsidy and of export quota by the Chinese government in the rare earths industry.

Conclusion

While many governments have been challenged in crafting industrial policy, the Chinese government has found success, as exemplified by the rare earths industry. Where Chinese production accounted for a negligible quantity of global rare earth production before 1985, by 2001 Chinese firms accounted for more than 90 percent of the world's total. The boom in Chinese production was precipitated by forms of subsidies to rare earth producers, introduced in 1990. As explained through the Stackelberg model, the subsidies effectively gave Chinese firms a first-mover advantage in the industry and lowered their marginal costs relative to world firms; as a result, the Chinese firms extracted higher profits than they would have without the subsidy.

From their market-leading position, the Chinese firms were able to deter competitors from entering the market by manipulating their own output levels and per-unit profitability.

China next prioritized development of its downstream industries dependent on rare earth inputs with the introduction of export quotas in 2006. These quotas challenged upstream Chinese rare earth firms: they capped the ability of upstream Chinese firms to respond to changing quantity decisions by world firms. In addition, rare earth prices on the world market rose in response to the export quotas, and as Chinese firms had limited exposure to this price rise, they were disadvantaged relative to world firms. In the downstream markets, however, Chinese firms benefitted relative to non-Chinese firms; the Chinese firms continued to have unrestricted access to Chinese rare earths, but non-Chinese firms' access was limited. As identified through the Bertrand model, the export quotas increased the marginal costs of firms outside of China, and Chinese firms were able to capture greater market share.

Lessons from the rare earths industry can apply to other contexts. As governments consider the efficacy of particular policies, they should use objective functions to identify the benefits and costs of each policy. China's interventions in the rare earth market, as well as its policies to create vertical foreclosure in many key high technology downstream markets, were prioritized over domestic environmental concerns and pursued at the risk of dispute with the WTO, and they resulted in China becoming the dominant player in the market. Together, these interventions demonstrate the Chinese government's interest and willingness to undertake strategic industrial policy to support Chinese industrial development goals.

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