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Innovative Applications of O.R.

Competition for limited critical resources and the adoption of environmentally sustainable strategies

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Highlights

- Game-theoretical methodology that incorporates competition for limited resources.
- Competition stimulates firms to switch from unsustainable to sustainable strategies.
- Empirical evidence that competition leads to sustainable strategies.
- Competitive pressure promotes environmental sustainability.

Abstract

We develop a game-theoretical methodology that incorporates competition for limited resources to explicitly model a firm's valuation and, hence, its decision whether to adopt environmentally sustainable strategies (e.g., recycling programs to replace limited natural resources, alternative technologies). Even if switching to environmentally sustainable alternatives proves too expensive for individual firms, or resource costs are expected to remain low, we show that competition for resources would still push firms to incur switching costs as they become more environmentally sustainable. Using a sample of firm-level data from the KLD database which includes firms' sustainability policies, we find empirical support that competition for resources is positively correlated with a firm's adoption of environmental strategies. Tests that use the Chinese government's 2010 rare-earth supply suspension as an exogenous shock to competition for limited resources suggest a causal interpretation for our finding.

Previous Next

Keywords

Decision analysis; Environmentally sustainable strategy; Game theory; Input competition

1. Introduction

Sustainability points to the capacity to endure and the potential for long-term maintenance, which in turn depends on the wellbeing of the natural world and the responsible use of natural resources (Laszlo, 2008). In this paper, we focus on the environment sustainability and its drivers that can lead to firm's economic sustainability. Daly (1990) defined environmental sustainability as "*the rates of renewable resource harvest, pollution creation, and non-renewable resource depletion that can be continued indefinitely.*" Traditional drivers of firms' environmental sustainability policies include new legislation, pollution concerns, global political security issues, and general consumer concerns (Laszlo, 2008). Profit maximization can be another driver, for stakeholder theorists suggest that firms can strategically deploy their sustainability strategies to achieve superior financial performance (e.g., returns on assets, returns on equity, returns on sales) (Hull and Rothenberg, 2008, McWilliams and Siegel, 2000, Waddock and Graves, 1997) or market value (Konar & Cohen, 2001). We propose that competition for raw materials can also serve as a driver of sustainability, and we employ both a game-theoretical and an empirical model to help explain why firms adopt environmentally sustainable strategies. One can argue that the reason why little attention has been given to competition for scarcer resources as a driver to environmental sustainability is that the market supply of these resources has always matched or exceeded the demand for them. In the case of shortage, firms that depend on those resources need to find alternative resources or implement recycling policies to eliminate future supply chain risk and guarantee their economic sustainability, therefore fostering environmental sustainability.

Currently, firms are increasingly competing for raw materials that are becoming scarcer or more costly to extract, or are protected as security assets by some countries (Folger, 2011, Walsh, 2011). As a result, firms that depend on those materials are forced to find alternative resources or implement more aggressive recycling policies (e.g., Gray, 2010, Raz and Schlosser, 2010). However, researchers have given little attention to the effect of competition for resources on firms' ability to implement environmentally sustainable strategies and obtain competitive advantages with these strategies (Stanford, 2011). To date, environmental sustainability research has focused mostly on production of environmentally friendly products (Bloemhof-Ruwaard et al., 1995, Hill, 1997), emissions reduction (Cholette & Venkat, 2009), and closed-loop supply chains as in recycling (Nagurney and Toyasaki, 2005, Wakolbinger et al., 2014) and remanufacturing (Bhattacharjee and Cruz, 2015, Guide and Wassenhove, 2009, Guide et al., 2003). A complete review of the green and sustainable supply chain management literature can be found in Brandenburg, Govindan, Sarkis, and Seuring (2014) and Varsei, Soosay, Fahimnia, and Sarkis (2014).

One notable example in our analysis is the supply of rare-earth (RE) metals. These elements are crucial to the production of many developing technologies, such as batteries for hybrid vehicles (lanthanum, neodymium), smart phones (neodymium, europium, terbium), and wind turbine rotors (neodymium), as well as more traditional mass consumption products, such as baseball bats (scandium) and cigarette lighters (cerium), among others (Aldersey-Williams, 2011). Norman, Zou, and Barnett (2014) note that end-market products and technologies use RE materials to generate over $259 billion in revenue, and argue that RE materials support more than $298 billion in revenue from downstream economic activity. In September 2010, in reaction to a border incident with Japan, China suspended its RE supply to Japan, the U.S., and Europe for five weeks (Grushkin, 2011). In the past five years, China has reduced export quotas of these elements by half, while imposing a tariff of 25% on the four most expensive ones and a 15% tariff on the rest (Bradsher, 2011, Grushkin, 2011). Since China holds 36% of the world's 110 million tons of recoverable RE ores and produces as much as 97% of the world's RE oxides, it was not unexpected that a surge in prices—up to a ten-fold increase by July 2011, in some cases —for RE elements unfolded (see Table 1). Even though prices eventually decreased by October 2011, they only decreased between 20% and 35% with respect to July's prices (Grushkin, 2011).

Table 1. Price/kilograms of critical rare earths.*

Element	September 2, 2010	July 19, 2011	October 18, 2011
Yttrium	$36	$185	$145
Neodymium	$57	$340	$265
Dysprosium	$298	$2850	$2250
Terbium	$605	$4520	$3020
Europium	$595	$5880	$3800

*

Bloomberg Business Week.

Under these circumstances, firms must carefully consider strategic ways to either use new technologies that replace such limited materials or increase their recycling of such materials (e.g., Burrows & Hesseldahl, 2009). For example, Toyota announced in January 2011 the development of a new type of RE-free propulsion technology (induction motor) to be used in electric and hybrid vehicles (Aldersey-Williams, 2011). In 2012, Honda began recycling RE metals from old nickel-metal-hydride batteries in the motors of its new hybrid cars (Muri, 2012). Today, Nissan Leaf vehicles sold in Japan use an electric motor that includes 40% less of the RE element dysprosium; this is a result of the change in technology, in which the implementation of new magnets shaves the use of the heat-resistant dysprosium by 40% (Rousseau, 2012). Hitachi announced the design of a new eleven-kilowatt motor that does not require the magnetic properties that RE metals provide (Robertson, 2011). Firms in the electronic industry also face the same pressure. In particular, the growing electronic industries are expected to augment the demand for magnets in new products, which in turn is expected to drive further the market demand for RE elements. Many companies have begun to research the steps and processes necessary to turn recycled RE materials back into high-purity REs that can be reused. For example, Hitachi has developed a machine to harvest RE metals from discarded hard-disk drives and compressors (Clenfield & Shiraki, 2010). Walton and Williams (2011) indicate that computer hard disk drives are the most important source of RE scraps; therefore, increasing the rate at which consumers recycle these key-end products will be essential.

To capture the essence of the competition for a limited resource (CLR), we observe current practices and develop a game-theoretical model that considers two strategies: continuing to purchase the limited resource (denoted as an ``unsustainable strategy''), or investing in new technology to replace the limited resource, such as by recycling or developing alternative resources (denoted as an ``environmentally sustainable strategy''). We study the effects of cost changes in the resource for a single firm's adoption of environmentally sustainable strategies (Section 3.1) and for multiple firms competing for the same resource (Section 3.2). The comparison of the two (Section 3.3) indicates that firms can switch from unsustainable to sustainable policies because of competition for the inputs.

We note that there are many reasons why a firm may switch production strategies and inputs. Classical economics models for exhaustible resources (Hotelling, 1931) indicate that a higher demand for inputs could lead to higher input prices, which may lead firms to look for alternative inputs. However, higher competition (i.e., more firms competing in the input market) does not necessarily imply higher demand (i.e., higher input consumptions); for example, the entire industry's demand for the input could remain the same or even increase, while the firms' individual market shares decrease as more firms join (i.e., as the saying goes, "the pie does not change; it is just cut into thinner slices"). In addition, higher input prices by themselves are not necessarily the main driver for a firm to switch to other technologies; we find that in some cases, firms still choose to use a limited resource, despite a rise in the input price, whereas in other cases, firms choose to develop sustainable strategies despite having a stable low input price. In our paper we show that the "competition effect" offers some explanations (see Sections 3 and 4). In particular, the Hotelling Eq. (2) and inequality (5) indicate that even if the price of the limited resource remains stable, as more firms compete for the same resource, the industry consumption as a whole will push for higher extraction costs in the future, making the switch more attractive for individual firms (despite the high cost of the switch). This is an aggregate effect from the industry. The same analysis shows the opposite effect, even if the input price is rising, firms might decide not to switch because the industry consumption as a whole is low and/or the cost of the switch is too high. The literature offers other explanations. For instance, Hartwick (2001) argues that the amount of "backstop" technology supply, that is, the supply of a substitute resource for the resource being depleted might have a passive or active role in the switching of firms to the substitute resource. He also mentions that there can be uncertainty effects in the cost of extraction and/or the output price, in some cases observing the paradoxical behaviour in which a firm would make more profits when there is more uncertainty on those parameters. There are strategic explanations in terms of improving the firm's public image, new legislation, political issues, etc., as we discussed before (Table 2).

Table 2. Summary of notation.

p	**unit price of the output good**
D_n	demand for output good when using the "do nothing" strategy
D_r	demand for output good when using the "alternative" or "recycling" strategy
D_n^T	total industry consumption of the limited resource
$c_n^{(t)}$	supplier's selling price of the limited resource in stage t
λ	increase factor of the rate of return in Hotelling's model
R	fixed-cost from switching technology
π	firm's profit in the single-firm model
w_j	firm's profit in the two-firm model

In Section 4, we statistically test the hypothesis that a firm's adoption of environmentally sustainable strategies is positively correlated with competition for resources; we do so by using accounting data from the Compustat dataset (Standard & Poor's, 2012) and social performance data from the Kinder, Lydenberg, and Domini (KLD) dataset (Kinder, Lydenberg, & Domini, 2010). In keeping with the RE metals examples we cited earlier, we only focus on industries that use RE materials in their production. Our analysis shows that this hypothesis holds, even after we control for a firm's size, risk ratio, innovation intensity, advertising intensity, and other factors. To help interpret the direction of causality, we consider the Chinese government's 2010 suspension of RE metal supplies as an exogenous shock to firms' adoption of environmentally sustainable strategies. This suspension was largely unexpected, and significantly tightened up the RE supply, hence intensifying the competition for this resource. That said, this competition was unlikely to affect directly a firm's environmental strategy other than CLR. We find that firms' adoption of environmentally sustainable strategies increased following this shock. This result points to a causal interpretation of CLR's impact on firms' environmental strategies, because the intermediary role of China's suspension was unrelated to other financing and economic factors in firms' environmentally sustainable strategies, but only intensified CLR.

Finally, our research also has public policy consequences, as we show that raising the cost of a limited resource encourages firms to adopt environmentally sustainable strategies. Hence, a policy-maker's price-control strategies could have the intended (or unintended) consequence of promoting sustainability, as was the case with China's political posturing regarding RE metals. Moreover, our analysis shows that the higher the competition for a limited resource, the more likely firms will be to adopt environmentally sustainable strategies; hence, instead of controlling the cost of the resource, a policy-maker can promote sustainability by facilitating more competition for the resource in the input market.

2. Literature review and theoretical background

There are several research streams related to our study. One of them deals with the drivers of sustainable environmental strategies, linking supply chain sustainability to the choice of materials and substitutes for non-renewable inputs. While Kleindorfer, Singhal, and Van Wassenhove (2005) provide an extensive survey of previous literature; this literature lacks a rigorous economic approach that integrates common factors driving sustainable environmental decisions across firms. Hence, we incorporate those common factors in our mathematical model. Our work also differs in that we study the effects of competition for limited resources as a driver of environmental strategy adoption.

A second research stream related to our study is resource-based competition. Lippman and Rumelt (2003) use cooperative game theory to analyse business management and strategy concerns with respect to the creation, evaluation, manipulation, administration, and deployment of unpriced, specialized scarce resource combinations. MacDonald and Ryall (2004) argue that competition among economic actors determines the value of resources that each is able to appropriate. Further, Adner and Zemsky (2006) address the evolution of substitution threats, resource rents, and competitive positions, using a model of competition with differentiated products that incorporates production technologies that improve over time. Finally, Pacheco-de-Almeida and Zemsky (2007) develop a model of the timing of competing firms' development as a function of the imitation of competitive advantages. We contribute to this second research stream by establishing how sustainable environmental strategies are affected by firms' interaction with each other, as well as by changes in the cost of resources. In our models, instead of the dynamics of emerging imitators, we consider the dynamics of established firms as they react to external changes in resource availability.

Our study is also closely linked to the strategic factor market (SFM) literature. As game-theoretical models have been widely adopted in this literature stream to explain firms' strategic choices (e.g., Adegbesan, 2009, Lippman and Rumelt, 2003, Liu et al., 2012, Makadok and Barney, 2001), we also adopt a game-theoretical model to simulate the interaction among firms competing for the same resource. However, our study differs from those in the existing SFM literature in that we directly model the costs and valuation of the two strategies (unsustainable and sustainable ones), and show how firms make their decisions simultaneously. Our empirical model also fits with this SFM literature stream; each firm has its own valuation and cost, and we approximate such heterogeneity by using a firm-fixed effect. Only when the valuation is higher than the potential cost associated with it (which is affected by the industry-wide consumption) can a firm switch from an unsustainable to a sustainable strategy.

One major difference with our work is in the application of game theory concepts to the field of sustainable strategies for firms. Concretely, we show that the decision process faced by competing firms whose production depends on a resource being depleted can be modelled as a two-period simultaneous game, that is, a game where each player chooses his action without knowledge of the actions chosen by other players. This leads to a normal form representation of the game as provided in Table 3. Further, we provide conditions (Proposition 2) that make the status-quo a unique Nash equilibrium for this game and then, validate this theoretical result by our empirical study of the rare-earth metals industry (Section 4). As far as we know, no other research in this field has used (1) a similar methodology combining a theoretical and empirical analysis of a game in this context, (2) used game theory to explain the competition effect in explaining firms' switching to alternative sustainable technologies, and (3) incorporated Hotelling's model of exhaustible resources in a switching technology game as we have proposed in our paper.

Table 3. Payoff matrix.

	Firm 2		
Firm 1	**(*n*, *n*)**	**(*n*, *r*)**	**(*r*, *r*)**
(*n*, *n*)	$[w_1, w_1]$	$[w_1, w_3]$	$[w_2, w_4]$
(*n*, *r*)	$[w_3, w_1]$	$[w_3, w_3]$	$[w_3, w_4]$
(*r*, *r*)	$[w_4, w_2]$	$[w_4, w_3]$	$[w_4, w_4]$

Another contribution is that we validate our model by using the panel data from the Kinder, Lydenberg, and Domini (KLD) dataset (Kinder et al., 2010), which provides firms' social performance indicators, and by using the Compustat dataset (Standard & Poor's, 2012), which provides firms' accounting data. Researchers have used the KLD dataset in prior studies and, in particular, have used its indicators as a proxy for corporate social responsibility (CSR) analysis (e.g., Berman et al., 1999, Graves and Waddock, 1994, Waddock and Graves, 1997, Hull and Rothenberg, 2008, McWilliams and Siegel, 2000, McWilliams and Siegel, 2001, Ruf et al., 1998, Siegel and Vitaliano, 2007). Such research, however, has focused on the relationships between corporate social performance and corporate financial performance (CFP). Other non-KLD empirical studies on sustainability have focused on the relationship between operational practices and firm performance (Zhu & Sarkis, 2004), green product design (Baumann, Boons, & Bragd, 2002), the use of environmental management systems (Darnall, Jolley, & Handfield, 2008), and how sustainability issues might be integrated into supply-chain management (Vachon & Klassen, 2006), among others. We follow the literature using the KLD dataset, and study the role of CLR on firms' environmentally sustainable strategy adoption, instead of studying the link between CSR and CFP.

3. Mathematical model

Motivated by the RE examples and firms' strategic reactions, we propose a game-theoretical model to capture the dynamics of firms' decisions in response to limited resources' rising costs and other factors, such as consumption competition. We consider a perfect competition market for a certain output good. The per-unit selling price of the good is denoted by p (exogenous and fixed)[1]. Current production of this good requires the use of a limited raw-material input factor. Because of the limitation on the input factor, firms participating in this market consider investing in either a resource-recycling program or an alternative resource to replace their current use of the limited resource. For the recycling option, we assume that every unit of output can be manufactured using a 100% (or close to 100%) recycled limited material, and that in the market there is always enough recycled limited materials to satisfy demand for the output[2]. To model the dynamics of a firm's decision process, we use a simple two-stage model. In the first stage, a firm chooses one of the following strategies: (1) do not change (denoted as index n), or (2) invest in technologies to replace the limited resource (denoted as index r). The latter strategy can include, but is not limited to, recycling (e.g., reverse supply chain) or developing an alternative resource. If a firm decides not to change in the first stage, then the same two alternatives will be available to the firm in the second stage. However, if the firm decides to replace the input factor in the first stage, then the firm will continue with the replacement strategy during the second stage. Hence, if we represent the two sequential decisions using an ordered pair, there are three possible courses of action: (n, n), (n, r), or (r, r).

The stage output-good demand faced by a firm, given strategy k, is denoted by D_k, $k = n, r$. Without loss of generality, we assume that every unit of output demand requires exactly one unit of the input factor (i.e., one unit of the raw or recycled limited material or one unit of the replacing material), so that a firm's demand for the input factor is the same as the output-good demand faced by the firm.[3] The supplier of the input factor is monopolistic (e.g., China's RE industry: see Els, 2014 or Schüler, Buchert, Liu, Dittrich, & Merz, 2011). We assume that the unit cost of the limited input factor (selling price set by the supplier) increases proportionally to the amount of materials used from one stage to the next:

$$c_n^{(2)} = \left(1 + \lambda\left(\frac{D_n^T}{D_n}\right)\right) c_n^{(1)} \tag{1}$$

for which $c_n^{(t)}$ denotes the supplier's selling unit price of the resource in stage t, $t = 1, 2$, D_n^T is the total industry consumption of the limited resource in stage 1, and λ is a positive constant. The unit cost of a replaced input is denoted by c_r and is considered constant across both stages. If the firm chooses strategy r, then it will incur a one-time fixed cost $R>0$.

Expression (1) is consistent with the classical Hotelling's model of exhaustible resources (see, for instance, Gaudet, 2007, Hartwick, 2001, Hotelling, 1931). In particular, notice that (1) can be expressed as:

$$\frac{c_n^{(2)}-c_n^{(1)}}{c_n^{(1)}} = \frac{D_n^T}{D_n}\lambda, \tag{2}$$

which corresponds to Hotelling's rule with a small marginal extraction cost relative to the selling price. The low marginal extraction cost is common in many limited resource industries and, in particular, consistent with the RE metal industry (Brumme, 2014). The term $(D_n^T/D_n)\lambda$ corresponds to the equilibrium discount rate or rate of return from the supplier investing the proceeds from sales elsewhere (e.g., bonds). For example, if there are m firms in the industry using the limited input factor in stage 1 and all the firms have the same demand D_n, then $D_n^T = mD_n$ and the discount rate is $m\lambda$, indicating that the supplier has to discount at a higher rate (proportional to the size of the industry) as the demand for the factor is also higher. In light of Eq. (2), the parameter λ can also be thought of as a measure of the price stability as time progresses.

3.1. Single firm decision

First, we consider the case with only one firm in the industry acquiring the limited resource. Let $\pi(k_1, k_2)$ denote the total profit for choosing strategy k_1 in the first stage and strategy k_2 in the second stage. To simplify our notation, we simply write $c_n$for$c_n^{(1)}$. Using Eq. (1), we get $D_n^T = D_n$, and the corresponding profit functions across the two stages are:

$$\begin{aligned}\pi(n,n) &= (p-c_n)D_n + (p-(1+\lambda)c_n)D_n,\\ \pi(n,r) &= (p-c_n)D_n + (p-c_r)D_r - R,\ \textit{and}\\ \pi(r,r) &= 2(p-c_r)D_r - R.\end{aligned}$$

Using simple algebra, we can prove Proposition 1.

Proposition 1

Strategy (n, n) is weakly optimal if and only if

$$\begin{aligned}&(D_r - D_n)p + c_nD_n\lambda \le c_rD_r - c_nD_n + R, \text{and}\\ &2(D_r - D_n)p + c_nD_n\lambda \le 2(c_rD_r - c_nD_n) + R.\end{aligned} \tag{3}$$

If any of Inequalities (3) is not satisfied, then (n, r) is weakly optimal if and only if

$$(D_r - D_n)p \le c_rD_r - c_nD_n. \tag{4}$$

If any of Inequalities (3) is not satisfied and Inequality (4) is not satisfied, then (r, r) is weakly optimal.

The relevance of Proposition 1 is that it provides a set of linear conditions for p and λ to compare the profits for the three strategies. For example, if $D_r \neq D_n$, Inequalities (3) indicate that as long as p and λ are very small (output price is low and input price remains stable) or R is very large (large capital investment to replace input factor), then it is optimal for the firm to not do anything and continue consuming the limited input resource. Also notice that Inequality (4) is independent of λ; that is, if the (n, n) strategy is not optimal (so that it is better to switch technologies), then deciding when the switch should take place (first or second stage) might depend on how high the price of the output is, but not on the stability of the price of the input factor. In particular, if output price p is very low and the firm has decided to switch, then it is better to delay the switch. When $D_n = D_r$, Inequalities (3) indicate that the firm's decision of not doing anything will be independent of the output price, and will solely depend on the stability of the input factor price.

3.2. Multiple firms decision

We extend the single firm model to multiple firms consuming the same limited input factor to investigate the effects of competition. Consider m firms facing the same strategic options as those of the single firm in the previous section. Our goal is to determine conditions under which the “do nothing” strategy for all firms is a unique Nash equilibrium.[4] As before, these m firms face perfect competition markets for their outputs respectively, so that the unit prices of their outputs are constant and denoted by p_i, for firm i.[5] We also relax the assumption that the demand is the same for all firms and assume that firm i faces an initial output demand of $D_n^{(i)}$ if it chooses n, and faces a demand of $D_r^{(i)}$ if it chooses r, for $i = 1, \ldots, m$. In this case, $D_n^T = \sum_{i=1}^{m} D_n^{(i)}$. The cost of strategy r is $c_r^{(i)}$ with a one-time fixed cost, R_i.

It is not difficult to show that strategy (n, n) for all firms is a unique Nash equilibrium as long as, for all firms, the profit for choosing (n, n)—given that others choose (n, n)—is higher than the profit from choosing either of the two switching strategies. After completing a simple algebraic manipulation to extend the result from Proposition 1, we obtain a condition for which all firms choosing (n, n) is a unique Nash equilibrium:

$$\lambda \leq \frac{D_n^{(i)}}{c_n D_n^T} \left(R_i + s_i B_i \right), \forall i, \tag{5}$$

in which $B_i := \left(c_r^{(i)} - p_i \right) D_r^{(i)} - \left(c_n - p_i \right) D_n^{(i)}$, and $s_i = 1$ if $B_i \geq 0$, $s_i = 2$ if $B_i \leq 0$.

In particular, if we simplify the model by letting $D_n^{(i)} = D_n$, $D_r^{(i)} = D_r$, $c_r^{(i)} = c_r$, $R_i = R$, and $p_i = p$, for all i, (i.e., the output markets have identical characteristics and firms have identical costs and market structures), then the threshold condition on λ can be simplified to the inequality $\lambda \leq (R + sB) / (mc_n)$, for which $B = (c_r - p) D_r - (c_n - p) D_n$, and $s = 1$ $(B \geq 0)$ or 2 $(B \leq 0)$. This inequality explains the competition effect: in a single-firm market with very high costs of implementing an environmental strategy (R is large), the do-nothing strategy will still be optimal. However, under the same circumstances (R is large) in a multiple-firm market, the inequality $\lambda \leq (R + sB) / (mc_n)$, indicates that the bound on λ quickly decreases as the number of firms m increases, thus making the do-nothing strategy less attractive, even for small values of λ (i.e., the input factor price would have to be very stable to ensure that λ will be small and the firms will not switch). Furthermore, even if m is small, according to Inequality (5), it is still possible for the bound on λ to be small when the total consumption of the limited resource is high.

3.3. Effect of competition

To illustrate this situation, consider two firms competing for a limited resource; for simplicity's sake, we only consider the symmetric case, in which the parameters are the same for both firms. We introduce the following notation:

$$w_1 := 2(p - c_n) D_n - 2c_n D_n \lambda,$$
$$w_2 := 2(p - c_n) D_n - c_n D_n \lambda,$$
$$w_3 := (p - c_n) D_n + (p - c_r) D_r - R,$$
$$w_4 := 2(p - c_r) D_r - R.$$

The corresponding payoff table is shown in Table 3.

In particular, the unit cost for the limited resource in the second stage becomes $(1 + 2\lambda) c_n$ if both firms choose strategy *n* in the first stage, leading to a consumption of $2D_n$, whereas the second-stage unit cost becomes $(1 + \lambda) c_n$ if one firm chooses *n* and the other firm chooses *r* in the first stage, leading to a consumption of D_n. Using a simple algebraic manipulation, we can prove Proposition 2.

Proposition 2

Choosing strategy (n, n) for both firms is a unique Nash equilibrium point if and only if

$$(D_r - D_n) p + 2c_n D_n \lambda \leq c_r D_r - c_n D_n + R,$$
$$2(D_r - D_n) p + 2c_n D_n \lambda \leq 2(c_r D_r - c_n D_n) + R.$$

Using Propositions 1 and 2, we find that, with respect to competition for resources, the area in (λ, p)-parameter-space in which two competing firms maintain the status quo (i.e., always play strategy *n* in each stage) was reduced by half when compared to the area in which a single firm maintains the status quo. Fig. 1 illustrates this point for a particular choice of parameters.

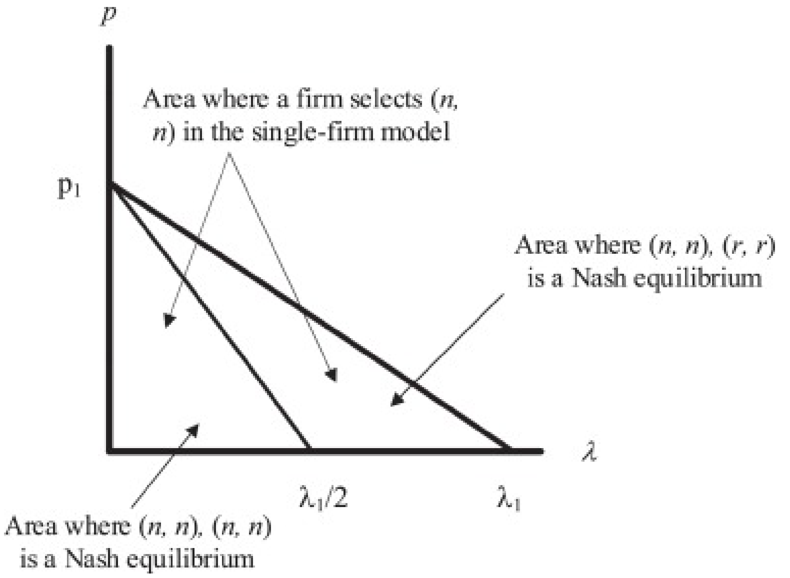

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Fig. 1. Comparing strategies.

Finally, notice that, under other conditions, it is possible to obtain asymmetric equilibrium points in the game. For instance, the strategies (*n*, *n*) for Firm 1 and (*r*, *r*) for Firm 2 (i.e., one firm does nothing while the other firm switches) is a Nash equilibrium when $w_2 \geq w_4$ and $w_4 \geq w_1, w_3$.

These conditions lead to another similar set of inequalities in terms of λ and p as in Proposition 2. Fig. 1 also illustrates the area for which this asymmetric solution is an equilibrium point in (λ, p)-space for a particular set of parameters.

3.4. Baseline hypothesis

We rewrite Inequality (5) as

$$\lambda D_n^T \leq \frac{D_n^{(i)}}{c_n}(R_i + s_i B_i). \tag{6}$$

Inequality (6) relates the effect of a potential cost increment, represented by λ, and the total consumption D_n^T. The inequality implies that, if the competition for the limited resource is more severe (i.e., higher λD_n^T), then it is easier for firms to embrace the environmentally sustainable strategy. Thus, we propose the following hypothesis:

Hypothesis: *A firm's degree of adopting environmentally sustainable strategies is positively correlated with the industry competition for the limited resource.*

4. Empirical methods

4.1. Data

Since the consumption of RE metals fits our model, we focus on firms in industries that use RE metals so we may study the influence of competition on these firms' adoption of environmentally sustainable strategies. We used several reports to identify a sample of industries that use rare earths (Folger, 2011, Haxel et al., 2002, Morrison and Tang, 2012, Royal Society of Chemistry 2012, Schüler et al., 2011; Walsh, 2011), and matched these industries with SIC codes provided by the U.S. Securities and Exchange Commission (www.sec.gov/info/edgar/siccodes.htm). We linked our data with the KLD dataset (Kinder et al., 2010), which provides a firm's social performance indicators, and the Compustat dataset (Standard & Poor's, 2012), which gives a firm's accounting data. The KLD dataset categorizes a firm's policies into positive strengths and negative concerns with respect to the environment, community, diversity, human rights, governance, products, and employees; for our research, we only focus on the environmental area.

Our time window for this study is from 2003 to 2011 because of data availability and because, after 2003, the KLD dataset expanded its collection from the 1000 to the 3000 largest U.S. companies. Although the KLD dataset includes several binary indicators of strengths and concerns in the environmental area, these indicators may not be enough to assess sustainability. For instance, a firm may just focus on one or two indicators because of the nature of its business. Thus, we measure firm *i*'s status of adopting environmentally sustainable strategies at year *t*, S_{it}, by the sum of the positive strength indicators minus the sum of the negative concern indicators (Fernández-Kranz and Santaló, 2010, Siegel and Vitaliano, 2007).[6] For example, although Firm A has been identified for the negative impact of its products and services in 2010, it has addressed pollution prevention, used clean energy, and engaged in "other" positive aspects categorized in the KLD dataset. As a result, its S_{it} is equal to 3–1 = 2. Note that in Section 4.4, we replace S_{it} with a binary indicator that only accounts for recycling and hazardous materials reduction, and we obtain similar results.

Following Inequality (6), the main explanatory variable to assess the competition for limited resource (CLR) is defined as:

$$\mathrm{CLR}_t = \lambda D_n^T.$$

We use the ratio of current RE metal prices to the previous year's prices to approximate λ.[7] We collect the prices of the RE metals (bastnäsite concentrates) from the U.S. Geological Survey (USGS), and denote them as pRE_t. [8] We then approximate D_n^T using the cost of goods sold in the industry s, $cogs_t = \sum_{i \ in \ s} cogs_{it}$. Keeping all else constant, the industry consumption of RE metals should be positively correlated with the cost of goods sold in the industry that uses the limited resource. In particular, we adopt the 48-industry classification proposed by Fama and French (1997) which reorganizes all four-digit standard industry classification (SIC) codes, to test our hypothesis.[9] We include other industry-specific controls (e.g., input market competition) as well as time-specific controls (e.g., yearly-fixed effect) to mitigate the assumption that all else remains unchanged in the main regression and robustness tests. The right-hand side of Inequality (6) shows that the firm's cost and efficiency of implementing environmentally sustainable strategies affect the threshold of λ, which is a firm-specific variable; hence, we control for a firm's heterogeneity by using firm-fixed effects. In Section 4.4, we add market share and input market competition to control for market changes and further check the robustness of our results. Additionally, we use the following control variables from the management literature (e.g., McWilliams and Siegel, 2001, Waddock and Graves, 1997; Hull & Rothenberg, 2008): firm size ($size_{it}$), approximated by the logarithm of firm i's assets at year t; firm risk ($risk_{it}$), approximated by firm i's debt-to-asset ratio; innovation intensity ($innov_{it}$), approximated by firm i's research and development (R&D) expenses to sales; and advertising intensity ($market_{it}$), approximated by firm i's advertising expenses to its sales.

Table 4 provides the summary statistics of the sample data.[10] The sample includes 3359 observations with non-missing S_{it}. In particular, we exclude firms with fewer than five years of history in the KLD dataset, so we may implement the firm-fixed effects. First, from the summary statistics table, we see that, on average, firms tend to have slightly more positive strengths (i.e., they are more environmentally sustainable) than negative concerns.

Table 4. Sample descriptive statistics.

Variable	# of samples	Mean	Standard deviation	Percentile				
				p1	p25	p50	p75	p99
S_{it} (sustainability level)	3359	0.040	0.777	–2	0	0	0	3

Variable	# of samples	Mean	Standard deviation	Percentile				
				p1	p25	p50	p75	p99
ΔS_{it} (changes in sustainability level)	2863	0.058	0.470	−1	0	0	0	2
Asset ($ in millions)	3359	5459	21,622	58	332	885	2576	113,331
Sales ($ in millions)	3359	5498	24,488	19	270	781	2297	118,719
Employees (in thousands)	3332	10.75	26.54	0.12	0.88	2.74	8.70	136.50
$cogs_{it}$ ($ in millions)	3359	3975	19,289	10	136	450	1440	95,836
CLR_{it} (in trillions)	2995	0.43	0.53	0.01	0.09	0.32	0.49	2.49
$size_{it}$	3359	6.96	1.58	4.06	5.80	6.79	7.85	11.64
$risk_{it}$	3351	0.162	0.173	0.000	0.000	0.125	0.259	0.707
$innov_{it}$	3359	0.115	0.296	0.000	0.018	0.059	0.145	0.777
$market_{it}$	3359	0.005	0.016	0.000	0.000	0.000	0.003	0.079

Note: S_{it} represents firm *i*'s sustainability level, which is measured by the sum of the positive strength indicators minus the sum of the negative concern indicators from the KLD dataset. ΔS_{it} measures firm *i*'s change in the sustainability level from year *t*-1 to year *t* by calculating $S_{it} - S_{i,t\text{-}1}$. CLR_{it} approximates the competition for limited resources at year *t*. Finally, $size_{it}$ approximated firm size, which is the logarithm of firm *i*'s assets at year *t;* $risk_{it}$ approximated firm risk, which is firm *i*'s debt-to-asset ratio; $innov_{it}$ approximated innovation intensity, which is firm *i*'s research and development (R&D) expenses to sales; and $market_{it}$ approximated advertising intensity, which is firm *i*'s advertising expenses to its sales.

In particular, among the 3359 observations, we have 452 observations with positive S_{it} and 351 observations with negative S_{it}. This measure, S_{it}, is fairly balanced in both tails and fits well with the normal distribution assumption. From the game-theoretical model, we observe that firms are more likely to switch to be environmentally sustainable when the competition for limited resources is more intense. Therefore, instead of focusing on the value of S_{it}, we also define its interval change:

$$\Delta S_{it} = S_{it} - S_{i,t\text{-}1}.$$

The mean value of ΔS_{it} shows that the firms in our dataset, on average, improve their status of adopting environmentally sustainable strategies. Our goal, then, is to investigate whether the competition for the limited resources (CLR) contributes to such a trend, after controlling for common factors. Second, the sample includes a wide range of sizes (in terms of assets, sales, the number of employees, or cost of goods sold). Finally, the explanatory and control variables are shown in the last five rows. We follow Lev, Petrovits, and Radhakrishnan (2010) and treat the R&D and advertising expenses that are missing in Compustat as zero.

Table 5 shows the correlations between the major variables. In particular, instead of examining the CLR in the current period, we consider a delayed effect from CLR. We do so since the KLD dataset collects the actions of firms that have appeared in various channels (e.g., quarterly/annual reports) and, hence, the observed action could be a decision made some time ago. To assess for proper time lags, we consider one-, two-, and three-year lags. The correlation reveals that CLR one year ago and the change in environmentally sustainable strategies are negatively correlated, whereas CLR two and three years ago and the respective change on environmentally sustainable strategies are positively correlated. As we will show in our empirical results, the negative correlation between ΔS_{it} and $CLR_{i,\, t\text{-}1}$ disappears after we control for other variables, whereas the positive correlation between ΔS_{it} and $CLR_{i,\, t\text{-}2}$ still remains significant.

Table 5. Correlation among the major variables.

	ΔS_{it}	$CLR_{i,\, t\text{-}1}$	$CLR_{i,\, t\text{-}2}$	$CLR_{i,\, t\text{-}3}$	$size_{it}$	$risk_{it}$	$innov_{it}$	$market_{it}$
ΔS_{it}	1							
$CLR_{i,\, t\text{-}1}$	−0.0568***	1						
$CLR_{i,\, t\text{-}2}$	0.1150***	0.8441***	1					
$CLR_{i,\, t\text{-}3}$	0.0443**	0.9075***	0.8764***	1				
$size_{it}$	0.1520***	0.2244***	0.2136***	0.2174***	1			
$risk_{it}$	0.0313*	0.0745***	0.0783***	0.0792***	0.2411***	1		
$innov_{it}$	−0.0136	−0.0189	−0.0191	−0.0758***	−0.0455***	−0.0006	1	
$market_{it}$	0.0004	−0.0285*	−0.0275	−0.0780***	−0.0553***	0.0033	0.2316***	1

Note: ΔS_{it} measures firm *i*'s change in the sustainability level from year *t*-1 to year *t*. CLR_{it} approximates the competition for limited resources at year *t*. Finally, $size_{it}$ approximated firm size, which is the logarithm of firm *i*'s assets at year *t;* $risk_{it}$ approximated firm risk, which is firm *i*'s debt-to-asset ratio; $innov_{it}$ approximated innovation intensity, which is firm *i*'s research and development (R&D) expenses to sales; and $market_{it}$ approximated advertising intensity, which is firm *i*'s advertising expenses to its sales.

*, **, *** Statistically significant $p<10\%$, $p<5\%$, and $p<1\%$, respectively, for two-tailed tests.

4.2. Baseline model and results

Inequality (6) shows that, as λ and/or D_n^T increase, firms are more likely to pass a threshold and become environmentally sustainable. By measuring CLR with λD_n^T, we consider two model specifications:

$$\Delta S_{it} = a^1 CLR_{i,t\text{-}j} + \mathrm{a}^2 X_{it} + F_i + T_t + \varepsilon_{it}, \text{ and} \tag{7}$$

$$S_{it} = b^0 S_{i,t\text{-}1} + b^1 CLR_{i,t\text{-}j} + b^2 X_{it} + F_i + T_t + \varepsilon_{it}, \quad (8)$$

for $j = 1, 2, 3$. The game-theoretical model suggests that CLR triggers a switch to adopting environmentally sustainable strategies. Thus, we consider the change of S_{it} in Eq. (7) to simulate the switch. However, Table 4 also shows a concern for using ΔS_{it} as the dependent variable. From the data, only 11% of the firm-year observations have non-zero changes of S_{it}, which could cause estimation bias.[11] Therefore, we also propose Eq. (8), in which we control $S_{i,\ t\text{-}1}$ to gauge the effect of CLR on the policy changes. X_{it} represents the control variables, including firm size, risk, innovation, and marketing intensity. We consider the fixed-effect model to represent the threshold of λ in Inequality (6); the fixed-effect model (confirmed by the Hausman test) controls for the heterogeneity across firms by including the firm-specific fixed effect F_i. To allow for sufficient time points, we only include firms with more than five years of KLD data in our regression model. Recognizing that improvements in environmental sustainability can be affected by macroeconomic factors (e.g., economic conditions), we include the time-specific fixed effect, T_t, to control for time-varying heterogeneity. Moreover, our statistical inferences are based on standard errors corrected for heteroscedasticity (confirmed by the modified Wald test) and autocorrelation (confirmed by the Wooldridge test for autocorrelation). Finally, to test if there is multicollinearity, we compute the variance inflation factors (VIFs) for both models, and the VIFs are less than eight. Thus, multicollinearity is not significant among the independent variables.

Table 6 shows the coefficient estimates for Eqs. (7) and (8). Columns (a) to (c) show the results for $CLR_{i,\ t\text{-}j}$, for $j = 1, 2$, and 3, respectively, and column (d) includes all three estimates in one regression for Eq. (7). Similarly, columns (e) to (g) show the results with only one CLR measure, whereas column (h) includes all three estimates in Eq. (8). With respect to our findings, we can first see that, from the significance levels for $CLR_{i,\ t\text{-}1}$, $CLR_{i,\ t\text{-}2}$, and $CLR_{i,\ t\text{-}3}$ in column (d), there is indeed a two- to three-year gap between the pressure from CLR and the observable action in firms' adopting environmentally sustainable strategies. Although column (a) shows that there is a negative effect of $CLR_{i,\ t\text{-}1}$ on ΔS_{it}, it becomes insignificant (or is significantly weakened) after we include $CLR_{i,\ t\text{-}2}$ and $CLR_{i,\ t\text{-}3}$ in the same regression (column d). We observe a similar pattern in the coefficient estimates for Eq. (8) in Columns (e)–(h).

Table 6. Coefficient estimates for change in the sustainability level (Eq. (7)) and the sustainability level (Eq. (8)).

	Dependent Variable: Change in sustainability level (ΔS_{it})				**Dependent variable: Sustainability level (S_{it})**			
	(a)	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**	**(h)**
$CLR_{i,\ t\text{-}1}$	−0.221**			−0.157	−0.226***			−0.187*
	(−2.49)			(−1.63)	(−2.75)			(−1.92)
$CLR_{i,\ t\text{-}2}$		0.483***		0.505***		0.328***		0.353***

	Dependent Variable: Change in sustainability level (ΔS_{it})				Dependent variable: Sustainability level (S_{it})			
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
		(4.04)		(4.23)		(3.20)		(3.58)
$CLR_{i,\ t\text{-}3}$			0.299***	0.386***			0.382***	0.461***
			(3.40)	(4.57)			(4.77)	(5.08)
$S_{i,\ t\text{-}1}$					0.572***	0.593***	0.531***	0.549***
					(18.21)	(20.17)	(15.76)	(17.80)
$size_{it}$	−0.015	−0.011	−0.002	0.009	0.003	0.004	0.031	0.040
	(−0.56)	(−0.42)	(−0.06)	(0.30)	(0.09)	(0.16)	(0.95)	(1.23)
$risk_{it}$	0.040	0.036	0.023	0.002	0.099	0.094	0.080	0.063
	(0.49)	(0.46)	(0.25)	(0.03)	(1.10)	(1.07)	(0.78)	(0.64)
$innov_{it}$	0.069**	0.066*	0.061*	0.053	0.079**	0.076**	0.066**	0.059*
	(1.98)	(1.91)	(1.70)	(1.52)	(2.31)	(2.25)	(1.98)	(1.81)
$market_{it}$	−0.793	−0.700	−1.114	−0.579	−0.815	−0.802	−1.119	−0.704
	(−0.79)	(−0.76)	(−1.05)	(−0.58)	(−0.73)	(−0.75)	(−0.94)	(−0.60)
# of samples	2856	2854	2538	2538	2856	2854	2538	2538
# of firms	430	430	430	430	430	430	430	430
***R*-squared within**	13.8%	16.0%	14.3%	18.0%	39.4%	40.0%	38.5%	40.5%

Note: S_{it} represents firm *i*'s sustainability level, which is measured by the sum of the positive strength indicators minus the sum of the negative concern indicators from the KLD dataset. ΔS_{it} measures firm *i*'s change in the sustainability level from year *t*-1 to year *t* by calculating $S_{it} - S_{i,t\text{-}1}$. CLR_{it} approximates the competition for limited resources at year *t*. Finally, $size_{it}$ approximated firm size, which is the logarithm of firm *i*'s assets at year *t*; $risk_{it}$ approximated firm risk, which is firm *i*'s debt-to-asset ratio; $innov_{it}$ approximated innovation intensity, which is firm *i*'s research and development (R&D) expenses to sales; and $market_{it}$ approximated advertising intensity, which is firm *i*'s advertising expenses to its sales. The numbers in the parentheses are the *t*-values of the variables that control for heteroscedasticity and autocorrelation. We include firm-fixed and yearly-fixed effects in the regressions, but due to space limitations, we do not report the coefficients for these fixed effects. Because we use a fixed-effect panel regression model, the *R*-squared values are separated into three categories: the *R*-squared value within the firm (time series), the *R*-squared value between the firms (across firms in the panel), and the overall *R*-squared value. We only report the *R*-squared value within the firm (time series) to conserve space, as our paper focuses on how the firm makes its decision across time.

*, **, *** Statistically significant p<10%, p<5%, and p<1%, respectively, for two-tailed tests.

Second, focusing on $CLR_{i,\ t\text{-}2}$, the results confirm our hypothesis, as $CLR_{i,\ t\text{-}2}$ is positively correlated with the changes of the sustainability level and with the sustainability level at the 1% significance level, respectively, in columns (d) and (h). The coefficient estimate for $CLR_{i,\ t\text{-}2}$ in column (d) is 0.505, whereas it is 0.353 in column (h). According to the coefficients in (d), if the competition for the limited resources, $CLR_{i,\ t\text{-}2}$, is increased by 1 unit, then the firm will increase its sustainability level by 0.505 units, indicating a high economic significance of CLR. Similarly, according to (h), if the competition for the limited resources, $CLR_{i,\ t\text{-}2}$, is increased by 1 unit, then the firm will increase its sustainability level by 0.353 units, whereas when the firm's previous year's status of adopting environmentally sustainable strategies (i.e., $S_{i,\ t\text{-}1}$) is increased by 1 unit, then the firm will increase its current status by 0.549 units. The comparison again shows that the economic significance of $CLR_{i,\ t\text{-}2}$ is sufficiently high even when we compare it with the firm's adoption status in the previous year. Consider that the price of RE metals can increase tenfold in one year. Assuming that the industry consumption of RE metal remains the same (the same consumer demand to produce the same output), a ten-fold increment in price of the metals would result in an average firm facing 10 times higher CLR (i.e., from the mean, 0.43, to 4.3), and hence, our model predicts an average firm would have to increase its sustainability level by 1.37 points. Even for a firm that has not engaged in any environmental sustainable strategies ($S_{i,\ t\text{-}1}$=0), such a sudden rise on the RE price will force it to engage at least one strategy toward environmental sustainability. As a result, it is not surprising that firms such as Toyota, Hitachi, and Honda have become more environmentally sustainable.

Finally, because we use a fixed-effect panel regression model, the R-squared values are separated into three categories: the R-squared value within the firm (including time series effects), the R-squared value between the firms (across firms in the panel excluding the time series effects), and the overall R-squared value (which can be seen as a weighted average of the within and between R-squared values).[12] As our paper focuses on how the firm makes its decision over time, we only report (and focus on) the R-squared value within firms. When we use change in sustainability level (ΔS_{it}) as the dependent variable, column (d) shows that the model can explain 18% of firms' decision *changes* in their sustainability level, whereas when we use sustainability level (S_{it}) as the dependent variable, column (h) shows that the model can explain 40.5% of the firms' decision on their sustainability level. The difference in the explanation power is reasonable, as changes are more difficult to be captured in regression models.

For the remainder of this paper, we will only show the results with $CLR_{i,\ t\text{-}2}$. $CLR_{i,\ t\text{-}1}$ is insignificant (or weakly significant at only the 10% significance level), and hence we ignore this measure as our explanatory variable. Although $CLR_{i,\ t\text{-}3}$ is significant in Table 6, we acknowledge that the high correlation between $CLR_{i,\ t\text{-}3}$ and $CLR_{i,\ t\text{-}2}$ (87% in Table 5) could cause multicollinearity issues in some model specifications. Therefore, we will only focus on $CLR_{i,\ t\text{-}2}$ and show the exogenous shock test in Section 4.3, and the robustness tests in Section 4.4.

4.3. Exogenous shock test for the baseline model

Although our model implies a causal relationship between CLR and firms' adoption of environmentally sustainable strategies, we do not completely rule out reverse causality. Some omitted variables (e.g., time-variate business/economy conditions) may exist that influence both CLR and firms' adoption of environmentally sustainable strategies. To mitigate for the time-variate concerns, we include the year-fixed effects in all our regression analyses. We also use lead-lag regression models to avoid reverse causality. However, firm-level omitted variables could prove more challenging, although we have considered including firm-fixed effects, other control variables, and lead-lag regression models.

To address further this issue, we use China's suspension of its supply of RE metals as an exogenous shock to CLR. In September 2010, China suspended its RE supply for five weeks. The key assumption underpinning this test is that China's actions did not affect firms' adoption of environmentally sustainable strategies for reasons other than the intensified CLR. We believe this assumption is likely satisfied. First of all, China's suspension of RE elements lasted for almost two months for Japan, but only lasted for 10 days (October 18 to 28, 2010) for RE buyers in the United States and Europe (Bradsher, 2010). More importantly, Bradsher (2010) stated, "the United States in particular mostly buys processed rare earth materials from China and Japan, and was little affected." As a result, the shock did not pose an immediate and long-term suspension of the RE supply to U.S. buyers that would otherwise have driven them to adopt environmentally sustainable strategies because of a comprehensive input-materials shortage. Nonetheless, U.S. buyers (who are the focus of our paper) suffered from intensified competition for RE metals. The overall supply did not change (Chinese suppliers could still produce as much as they used to), but, given the anticipation of export quotas and potential suspensions, the competition for RE materials intensified as λ increased (see Table 1 for example) and the supply pool for non-Chinese buyers (including buyers in all countries) was reduced. Hence, we focus on an event widow that spans from 2008 to 2011 and assign 2008–2009 and 2010–2011 as pre- and post-event periods, respectively. We consider regression models similar to Eqs. (7) and (8), but include the shock dummy and the interaction term of the shock dummy and the demeaned $CLR_{i,\,t\text{-}2}$ (to avoid multicollinearity). Note that, as this shock dummy results from the event time (i.e., before and after 2010), we do not further control the time-fixed effects in the regression models for the short panel. Finally, we note that although we focus our discussion on $CLR_{i,\,t\text{-}2}$, we perform a robustness test based on $CLR_{i,\,t\text{-}2}$ as well as $CLR_{i,\,t\text{-}3}$ with the event-time window changed from 2005 to 2011 to include the three-year lagged value; the results are approximately consistent, and hence are not reported due to space limit.

Table 7 shows the coefficient estimates. Columns (a), (b), and (c), (d) represent the estimation results for Eqs. (7) and (8), respectively. During and after 2010, firms improved their status of adopting environmentally sustainable strategies by 0.267 (column a) and 0.358 (column c), respectively, for the two models, and the increment is statistically significant at the 1% level. As we mentioned previously, the exogenous shock intensifies the competition for RE elements after the suspension, but it should not have a direct impact on firms' adoption of environmentally sustainable strategies, as it only lasted for 10 days for U.S. buyers, who were little affected (Bradsher, 2010), *unless* the adoption decisions were influenced by intensified CLR. As a result, the positive and significant coefficients of the shock dummy support our hypothesis and point to a causal interpretation of the link between CLR and the adoption of environmentally sustainable strategies.

Table 7. Coefficient estimates with the exogenous shock.

	Dependent variable: Change in sustainability level (ΔS_{it})		Dependent variable: Sustainability level (S_{it})	
	(a)	(b)	(c)	(d)
$shock_t$	0.267***	0.246***	0.358***	0.327***
	(8.01)	(8.04)	(8.48)	(8.54)
$shock_t \times (CLR_{i,t\text{-}2} - \overline{CLR}_{i,t\text{-}2})$		0.518***		0.236***
		(8.15)		(3.55)
$CLR_{i,\,t\text{-}2}$		0.194***		0.231***
		(2.72)		(2.69)
$S_{i,\,t\text{-}1}$			0.504***	0.564***
			(21.23)	(25.53)
$size_{it}$	−0.206***	−0.057	−0.034	0.051
	(−3.61)	(−0.99)	(−0.50)	(0.76)
$risk_{it}$	0.335**	0.276*	0.371**	0.339**
	(2.10)	(1.91)	(2.29)	(2.24)
$innov_{it}$	0.101*	0.081	0.120**	0.101
	(1.85)	(1.43)	(2.02)	(1.55)
$market_{it}$	0.209	0.479	0.238	0.399
	(0.16)	(0.35)	(0.13)	(0.23)
Time fixed effects	No	No	No	No
# of samples	1520	1520	1520	1520
# of firms	418	418	418	418
***R*-squared within**	6.3%	18.0%	37.9%	42.7%

Note: S_{it} represents firm *i*'s sustainability level, which is measured by the sum of the positive strength indicators minus the sum of the negative concern indicators from the KLD dataset. ΔS_{it} measures firm *i*'s change in the sustainability level from year *t*-1 to year *t* by calculating $S_{it} - S_{i,t\text{-}1}$. CLR_{it} approximates the competition for limited resources at year *t*, and $\overline{CLR}_{it}$ is the mean across all observations. $shock_t$ represents the exogenous event dummy due to China's suspension of its supply of rare earth metals, and is 1 if the fiscal year of the observation is 2010 and 2011, is zero if the fiscal year is 2008 and 2009, and is missing otherwise.

Finally, $size_{it}$ approximated firm size, which is the logarithm of firm *i*'s assets at year *t*; $risk_{it}$ approximated firm risk, which is firm *i*'s debt-to-asset ratio; $innov_{it}$ approximated innovation intensity, which is firm *i*'s research and development (R&D) expenses to sales; and $market_{it}$ approximated advertising intensity, which is firm *i*'s advertising expenses to its sales.

The numbers in the parentheses are *t*-values of variables that control for heteroscedasticity and autocorrelation. We include firms' fixed effects in the regressions, but due to space limitations, we do not report the coefficients for these fixed effects. We do not include time-fixed effects, as the exogenous shock itself serves as a time-related dummy. Because we use a fixed-effect panel regression model, the *R*-squared values are separated into three categories: the *R*-squared value within the firm (time series), the *R*-squared value between the firms (across firms in the panel), and the overall *R*-squared value. We only report the *R*-squared value within the firm (time series) to conserve space, as our paper focuses on how a firm makes its decision across time.

*, **, *** Statistically significant $p<10\%$, $p<5\%$, and $p<1\%$, respectively, for two-tailed tests.

Interestingly, the coefficients on the interaction term of CLR and the shock (shown in columns (b) and (d) for the two models, respectively) show that the shock positively moderates the CLR influence. The exogenous shock itself is still positively significant at the 1% level, and its coefficient is very close to those without the additional CLR terms. $CLR_{i,\ t\text{-}2}$ retains its positive significant sign as well, although some of its explanatory power is absorbed by the exogenous shock. The two explanatory variables, the shock dummy and the CLR term, still strongly support our hypothesis. Moreover, the interaction term of the demeaned CLR and the shock also shows a very significant and positive sign for both ΔS_{it} and S_{it} in Eqs. (7) and (8); the coefficients of the interaction term are 0.518 and 0.236 with *t*-statistics of 8.15 and 3.55, respectively. In particular, we calculate the pure effect of $CLR_{i,\ t\text{-}2}$ at the mean and at the mean plus one standard deviation. The mean and standard deviation of $CLR_{i,\ t\text{-}2}$ are 0.403 and 0.500, respectively. As a result, for a firm facing high CLR pressure (i.e., measured at one standard deviation above the mean) before the shock, the pure effect is 0.175, whereas after the shock, the effect is 0.680; the difference is 0.505. For a firm facing average CLR pressure (i.e., measured at the mean), the pure effect is 0.078 before the shock, and the effect is 0.324 after the shock; the difference is 0.246. The comparisons imply that the effect of intensified CLR due to the suspension of supply is significantly higher for a firm subjected to a high CLR than a firm subjected to a moderate CLR. This shock strengthens the CLR effect, thereby offering further support to the causal direction.

4.4. Robustness tests for the baseline model

In this section, we perform robustness tests to support further our hypothesis. First, we adopt the Fama-French 48 industry classification (Fama & French, 1997) to compute the industry-level cost of goods sold. As a robustness check, we test Eqs. (7) and (8) with $CLR_{i,\ t\text{-}2}$ using industries grouped by the first two digits and the first three digits of the firms' SIC codes, respectively. Moreover, to echo the findings in Chatterji, Levine, and Toffel (2009), we separate the KLD ratings into strengths and concerns and perform additional robustness tests. When we use the strengths as the dependent variable, the coefficients of $CLR_{i,\ t\text{-}2}$ and $CLR_{i,\ t\text{-}3}$ are again positive and significant, whereas when we use the concerns, the coefficients become negative and significant. The results thus support Hypothesis 1, as higher CLR leads to higher strengths (or lower concerns). Thus, our empirical inferences are robust with respect to the methods of industry classification and the definition of measuring the KLD ratings.

Second, we recognize that a firm's market share and/or gross margin can affect how that firm makes its decisions, for adopting environmentally sustainable strategies can serve as a signalling tool to gain more market share or charge higher premiums. Therefore, we include MS_{it} as the market share of firm i in year t, which is computed by dividing the sales of firm i by the total sales of all firms in industry s, and we also include GM_{it} as the gross margin, which is computed by dividing the annual sales less the cost of goods sold by the annual sales. We also try other financial measures, such as ROE or ROA, and obtain similar results not reported in this paper. Finally, we also test to see if competition intensity in the input market affects a firm's adoption of environmentally sustainable strategies. To do so, we use the traditional Herfindahl–Hirschman index for each industry to assess input-market competition intensity[13] (i.e., we denote the Herfindahl–Hirschman index by $HHI_t = \sum_{\text{i in s}} CS_{it}^2$, in which CS_{it} is computed by dividing the cost of goods sold of firm i by the total cost of goods sold of all firms in industry s). Since it is more competitive to have a large number of small firms in an industry competing for an input in contrast to a few dominant firms, the higher the index is, the less competitive the industry. Finally, we also calculate the Herfindahl–Hirschman index based on market share to control for competition intensity in the output market, and in so doing, we obtain results that are consistent in the unreported tables.

Panel A of Table 8 shows the coefficient estimates for the regression models that include ΔS_{it} and S_{it} with the three additional control variables. Columns (a) and (b) represent the regression coefficients with MS_{it}, GM_{it}, HHI_t and with $MS_{i,\, t\text{-}2}$, $GM_{i,\, t\text{-}2}$, $HHI_{t\text{-}2}$, respectively. For Column (a), the inclusion of the three variables in the current period helps us to control for heterogeneity among firms. $CLR_{i,\, t\text{-}2}$ maintains its explanatory power with almost the same coefficients as in Table 6, and both are significant at the 1% significance level. Column (b) tests one step further; in this additional step, we test to determine if a firm's present-year adoption decision is correlated with the three control variables from two years ago (using the same time lag as $CLR_{i,\, t\text{-}2}$). Again, $CLR_{i,\, t\text{-}2}$ is still significant at the 1% significance level. Moreover, the statistical insignificance of the coefficient of $HHI_{t\text{-}2}$ implies that, even though the competition for resources pushes firms to be more environmentally sustainable, the input-market competition intensity measured by simply the Herfindahl–Hirschman index at that time does not. Hence, competition intensity in the input market does not help improve firms' adoption of environmentally sustainable strategies, and policy makers should therefore think about the right type and mix of incentive/tools to motivate firms to adopt environmentally sustainable strategies. In this case, they might offer taxation or other incentives to stimulate the competition for resources to motivate sustainability, rather than simply lowering entry barriers and introducing more firms to a given industry. On the other hand, the current-period input-market competition intensity may have a short-lasting correlation with firms' adoption of environmentally sustainable strategies; as our results indicate, the coefficient of HHI_t is negative and significant at the 5% level. This result supports the results from Fernández-Kranz and Santaló (2010), which provide evidence that various market concentration proxies are negatively correlated with CSR measures (including not only environmental measures but also other related measures on corporate social responsibility). Similar results are shown in columns (c) and (d) for the model with S_{it} and its lagged term.

Table 8. Coefficient estimates for the change in the sustainability level (Eq. (7)) and the sustainability level (Eq. (8)).

	Panel A					Panel B			Panel C
	Change in sustainability level (ΔS_{it})		Sustainability level (S_{it})			Change in sustainability level (ΔS_{it})	sustainability level (S_{it})		Enviro dummy
	$j=0$	$j=2$	$j=0$	$j=2$					
	(a)	(b)	(c)	(d)		(e)	(f)		(g)
$CLR_{i, t\text{-}2}$	0.477***	0.483***	0.322***	0.328***	$CLR^{alt}_{i,t\text{-}2}$	0.122***	0.099**	$CLR_{i, t\text{-}2}$	0.991**
	(4.00)	(4.05)	(3.15)	(3.19)		(2.90)	(2.25)		(2.94)
$S_{i, t\text{-}1}$			0.594***	0.593***	$S_{i, t\text{-}1}$		0.574***	$env_{i, t\text{-}1}$	3.265**
			(20.25)	(20.30)			(18.89)		(21.01)
$size_{it}$	–0.019	–0.016	–0.005	0.002	$size_{it}$	–0.020	–0.001	$size_{it}$	0.186**
	(–0.72)	(–0.63)	(–0.18)	(0.06)		(–0.73)	(–0.04)		(3.68)
$risk_{it}$	0.044	0.039	0.102	0.094	$risk_{it}$	0.044	0.102	$risk_{it}$	–0.275
	(0.55)	(0.50)	(1.14)	(1.07)		(0.54)	(1.14)		(–0.58)
$innov_{it}$	0.133***	0.135**	0.132***	0.144***	$innov_{it}$	0.072**	0.082**	$innov_{it}$	0.009
	(2.82)	(2.08)	(3.20)	(2.68)		(2.09)	(2.41)		(0.03)
$market_{it}$	–0.816	–0.740	–0.886	–0.850	$market_{it}$	–0.544	–0.644	$market_{it}$	9.234*
	(–0.91)	(–0.81)	(–0.83)	(–0.81)		(–0.56)	(–0.58)		(1.76)
$MS_{i, t\text{-}j}$	–0.542	2.012	0.116	1.603					
	(–0.44)	(1.06)	(0.07)	(1.07)					
$GM_{i, t\text{-}j}$	0.245**	–0.055	0.202*	–0.056					
	(2.03)	(–1.03)	(1.80)	(–1.09)					
$HHI_{t\text{-}j}$	–1.251**	–1.173	–1.233**	–0.042					
	(–2.57)	(–1.15)	(–2.31)	(–0.04)					

	Panel A				Panel B		Panel C
	Change in sustainability level (ΔS_{it})		Sustainability level (S_{it})		Change in sustainability level (ΔS_{it})	sustainability level (S_{it})	Environ dummy
	$j=0$	$j=2$	$j=0$	$j=2$			
	(a)	(b)	(c)	(d)	(e)	(f)	(g)
Time-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry-fixed effects	No	No	No	No	No	No	Yes
# of samples	2854	2850	2854	2850	2856	2856	2460
# of firms	430	430	430	430	430	430	367
R-squared within	16%	16.1%	40.2%	40.1%	13.4%	39.0%	N/A

Note: The numbers in the parentheses are the t-values of the variables that control for heteroscedasticity and autocorrelation. For Panels A and B, we use the fixed-effect panel regression with firm-fixed and yearly-fixed effects in the regressions, and we control for heteroscedasticity and autocorrelation. For Panels C and D, we use the random-effect probit model, as the unconditional fixed-effect model is biased. Moreover, there is no R-squared value available under the probit model.

*, **, *** Statistically significant $p<10\%$, $p<5\%$, and $p<1\%$, respectively, for two-tailed tests.

Third, although $CLR_{i,\ t\text{-}2}$ is directly constructed from Inequality (6) to test for robustness, we can explain Inequality (6) from a different perspective: if the price of the limited resource is more expensive *and* if the competition for the input is more intense, then the firm's status of adopting environmentally sustainable strategies would be higher. Therefore, instead of taking the product of the cost increment and the total consumption, we replace this with the product of the resource price pRE_t and the competition in the input market, and test if the results can be carried over. Therefore, we propose to test the alternative models that replace $CLR_{i,\ t\text{-}2}$ in Eqs. (7) and (8) with $CLR^{alt}_{i,t\text{-}2}$, in which $CLR^{alt}_{i,t\text{-}2}$ is defined as:

$$CLR^{alt}_{i,t\text{-}2} = pRE_t \times \ (1 - HHI_t)\,.$$

Following the definition of HHI_t, a higher concentration measure means a less competitive market. For our purposes, we take the upper bound, 1, to subtract the measure, so that a higher interaction term means that the resources are more expensive and the competition is more intense. Panel B of Table 8 shows the coefficient estimates. Columns (e) and (f) show the estimates for Eqs. (7) and (8), respectively, with $CLR_{i,\,t\text{-}2}$ being replaced by $CLR^{alt}_{i,t\text{-}2}$. Following this new definition of the independent variable, the delayed time effect still exists, and the results still support our hypothesis. Therefore, our empirical inferences are robust to the construct of the CLR variable.

Fourth, we select two indicators from the KLD dataset to replace the dependent variable, S_{it}. Although S_{it} represents the aggregate measure of a firm's status of adopting environmentally sustainable strategies, it might contain other indicators that may not fit well with our model. Therefore, we choose *env_str_a* and *env_str_c* as proxies for a firm's adoption of recycling or new technology to eliminate the use of limited resources. Since we have excluded the service firm, the indicator *env_str_a* measures the positive environmental impact of a firm's products in reducing consumption of energy, hazardous chemicals, and other resources, whereas the indicator *env_str_c* measures a firm's use of recycled materials in its products. We denote env_{it} as 1 if either indicator is 1, and as 0 otherwise. We then run a random-effect, panel-regression probit model, as the unconditional fixed-effect estimates are biased. In addition, to account for industry differences, we include industry-fixed effects (defined by the Fama and French 48 industries). Panel C of Table 7 shows supporting evidence for our hypothesis, as $CLR_{i,\,t\text{-}2}$ is significant at the 1% significance level in column (g). We do not construct the equivalent difference measure for env_{it}, as we did for Eq. (6). The changes for env_{it} are persistent throughout time, thereby leading to a regression model highly influenced by process noise. Thus, we only estimate the model with env_{it}, but control for the lagged measure, $env_{i,\,t\text{-}1}$.

Finally, instead of using the KLD dataset, we identify a firm's use of recycling and alternative resources via the GRI (Global Reporting Initiatives) platform. Founded in 1997, GRI is an international independent organization with an aim to provide a platform for firms to report their CSR efforts. To date, 92% of the world's largest 250 corporations report on their sustainability performance via GRI. Using the GRI platform, we first collected sustainability reports made by U.S. firms from 2000 to 2015. Then we manually linked the company names with the Compustat dataset to obtain their financial information and their industries (i.e., SIC codes). Next, we only keep firms that were previously identified as users of rare earths (by SIC codes identified in Section 4.1); after this step, 81 firms remain. Finally, we read all 283 reports for these 81 firms to identify their use of recycling or alternative technologies to replace rare earth materials. After the process of data collection, we conducted a probit regression with yearly fixed effects and other control variables[14]. The results are shown in Panel D of Table 8. Similar to the results shown in Panel C, $CLR_{i,\,t\text{-}2}$ is again significant at the 1% significance level in column (h) with a similar magnitude as what has been shown in column (g).

5. Conclusions

In this paper, we investigate how competition for limited resources (CLR) influences firms' adoption of environmentally sustainable strategies. By applying a game-theoretical framework to model firms' simultaneous decisions under the intensified CLR, we provide evidence that the intensified competition for input resources stimulates firms to switch from environmentally unsustainable to sustainable strategies. Such switching behavior is not completely driven by potential benefits with respect to consumer demands; even without such benefits, firms can still become environmentally sustainable, as long as the competition in the input market becomes fiercer. The empirical models we develop reinforce this implication, for there is a positive and significant correlation between firms' adoption of environmentally sustainable strategies and competition for limited resources. Moreover, using the empirical models, we can quantify the contributions of input market competition and benefit to the switching behavior. Using our motivating example in the introduction that the price of RE metals can increase tenfold in one year, such an increment in metal price would result in an average firm to increase its sustainability level by 1.37 points, even when there is no benefit from consumer demands. No wonder that in practice we observe firms—including Hitachi, Toyota, and Honda—responding to the intensified competition for RE metals by adopting new technologies to replace their use of RE metals.

Our research has public policy implications, as we show that raising the cost of a limited resource can trigger firms to make decisions that affect their environmental strategies. Hence, a policy-maker's price control strategy could have the intended (or unintended) consequence of promoting sustainability (e.g., China's RE political posturing). Alternatively, instead of controlling the cost of the resource, a policy maker can promote sustainability by facilitating more competition for the resource. In sum, there is a benefit to using such competitive pressure to promote environmental sustainability.

This study contributes to the extant literature on environment sustainability. While prior studies examine environment sustainability from the perspective of consumer pressure (e.g., the stakeholder theory) or from an individual firm's profit maximizing perspective (e.g., better financial performance), we instead investigate another driving force: competition, in particular in the input market, and apply the strategic factor market view to explicitly model firms' valuation of two strategies, a sustainable one and an unsustainable one. Using an empirical model design, we provide supporting evidence to demonstrate that competition for a limited resource can motivate firms' adoption of environmentally sustainable strategies.

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Appendix. Proofs of main results

Proof of Proposition 1: Strategy (n,n) is weakly optimal if and only if $\pi(n,n) \geq \pi(n,r)$ and $\pi(n,n) \geq \pi(r,r)$. From the first inequality and rearranging terms, we obtain

$$(p-c_n)\,D_n + (p-(1+\lambda)\,c_n)\,D_n \geq (p-c_n)\,D_n + (p-c_r)\,D_r - R,$$
$$c_r D_r - c_n D_n + R \geq (D_r - D_n)\,p + c_n D_n \lambda.$$

From the second inequality and rearranging terms, we obtain

$$(p-c_n)\,D_n+(p-(1+\lambda)\,c_n)\,D_n\geq 2\,(p-c_r)\,D_r-R,$$
$$2\,(c_rD_r-c_nD_n)+R\geq 2\,(D_r-D_n)\,p+c_nD_n\lambda.$$

Thus, we obtain the inequalities (3) from the proposition. If any of the inequalities (3) is not satisfied, then we have $\pi(n,n)\leq max\{\pi(n,r),\pi(r,r)\}$. In this case, (n,r) is weakly optimal if and only if $\pi(n,r)\geq\pi(r,r)$, which leads to

$$(p-c_n)\,D_n+(p-(1+\lambda)\,c_n)\,D_n\geq 2\,(p-c_r)\,D_r-R,$$
$$2\,(c_rD_r-c_nD_n)+R\geq 2\,(D_r-D_n)\,p+c_nD_n\lambda.$$

Therefore, we obtain inequality (4). □

Proof of Proposition 2: Choosing strategy (n,n) for both players entails a payoff of w_1 to each of the firms. Hence, the strategy is a Nash equilibrium point if and only if w_1 dominates the other payoffs a firm can obtain by unilaterally deviating in strategy from this point. In other words, the strategy is a Nash point if and only if $w_1\geq w_3$ and $w_1\geq w_4$. After re-arranging terms, the inequality $w_1\geq w_3$ yields

$$2\,(p-c_n)\,D_n-2c_nD_n\lambda\geq(p-c_n)\,D_n+(p-c_r)\,D_r-R,$$
$$c_rD_r-c_nD_n+R\geq(D_r-D_n)\,p+2c_nD_n\lambda.$$

Similarly, $w_1\geq w_4$ yields

$$2\,(p-c_n)\,D_n-2c_nD_n\lambda\geq 2\,(p-c_r)\,D_r-R,$$
$$2\,(c_rD_r-c_nD_n)+R\geq 2\,(D_r-D_n)\,p+2c_nD_n\lambda.$$

Since $c_nD_n\lambda$ is positive, it follows that we always have $w_2>w_1$. However, the only two payoffs involving w_2 are $[w_4, w_2]$ and $[w_4, w_2]$ in the payoff matrix (see Table 3), and it is always possible for a firm to do better by unilaterally deviating from any of those two points. Therefore, there is only one Nash equilibrium point corresponding to the do-nothing strategy for both firms if the two inequalities from the proposition hold. □

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1 In our study we found that the mean Herfindahl-Hirschman Index (HHI), that represents the competitive intensity from our sample, is 0.08, indicating very competitive industries (the lower the more competitive). Just to compare to an extreme case, if we had 12 firms with equal shares for a competing resource, then the index would be 0.083, higher than our observed index.

2 The model can be extended by assuming that only a fraction of the limited resource can be replaced and the remaining consumption still depends on the limited resource. While the mathematical representation will change by doing so, after reorganizing the terms, the results supporting our hypothesis are equivalent to our results presented in the following sections. Also, notice that in a closed- loop system, there would be some loss of the input resource that cannot be recycled for many reasons and demand cannot be necessarily satisfied. However, for other systems, the recycled material could be obtained from other external industries that do not necessarily recycle their own output. For example, Minter (2013) reports that countries like China lack ready access to sufficient raw materials of its own to support many industries that build on metals (e.g., building tracks for subways), and so, they have become net importers of scrap copper, aluminum, steel, and other metals originating from other countries. However, without loss of generality, our model still holds even in the case of a closed-system because we assume that if a firm decides to switch to an alternative resource (new technology or recycling) the output demand faced by the firm after the switch is independent of the demand faced by the firm before the switch.

3 This is without loss of generality because the prices for the output good and the input factor can be expressed in appropriate units to account for the exchange coefficient: if demand for the good is D units, unit price for the

product is p, and one unit of output good requires q units of input factor, then the price of the input factor c is given in dollars per q units and the net revenue of the firm can then be expressed as $pD - cD = (p - c)D$.

4 We do not discuss the other asymmetric equilibrium in detail, as we only focus on cases in which the competition for the limited resource drives *some* firms to adopt environmentally sustainable strategies. As a result, we only focus on the equilibrium in which no firm switches to strategy r; if this equilibrium becomes less likely to achieve, then the likelihood of some firms switching to strategy r increases.

5 The assumption that the firms are competing in different markets can be relaxed without hurting the implications we derived, as long as the total consumption of the limited resources increases with the competition, which is also a reasonable condition in current practice. For example, both the smartphone and automobile industries use RE metals, but they do not compete in the same product market. Even within the smartphone market, new manufacturers enter the market, and the market size increases due to the infusion process of adopting smartphones, leading to an increased consumption of RE metals. Thus, to simplify our presentation, we only present the results under this assumption: firms are competing in different product markets.

6 Even though we can use other measures, such as a weighted average of the indicators that are weighted according to their importance, Ruf et al. (1998) note that the weights are neither time invariant nor generalizable to other groups of users. Hence, we use the same weight for each indicator.

7 As a robustness check, we also tested for price differences, and we obtained similar results in an unreported table.

8 The annual year-end prices (dollars per kilogram) of the bastnäsite concentrates from 2001 to 2010 were 4.08, 4.08, 4.08, 4.08, 5.51, 6.06, 6.61, 8.82, 5.73, and 6.87, respectively. We use the latest update for the price in the reports, as the previous year's report on the price quote can be an estimate. We use the price of the bastnäsite concentrates because (1) it contains the most commonly used RE elements: cerium, lanthanum, and yttrium; (2) the price for the monazite concentrates was not consistently reported; and (3) the price for mischmetal is presented in a range (instead of a number), making it challenging to use in regression models.

9 Other industry classifications, such as grouping firms with the same first two (or three) digits of SIC codes, give similar results, and hence are unreported.

10 Even though we exclude the firms without KLD data, the industry-aggregated measures still include all the samples in the Compustat dataset.

11 We constructed a set of panel data including 430 firms, with 2,854 non-missing firm-year observations. Among the 430 firms, 240 firms are indifferent to the changes in CLR (which is about 55%), but the strengths or concerns of the remaining 45% of firms have been recorded changes throughout the time window in our study. In our mathematical model, we show that, as CLR increases, more firms will switch to sustainable strategies. As illustrated in Fig. 1, one of the two firms could change from (n,n) to (r,r) when CLR increases, whereas the other maintains the choice of (n,n). Our data also reflect such a pattern; when CLR increases, on average, more firms will switch, but that does not mean that all firms will switch. In addition, the switches also depend on firm-level characteristics, such as the cost of adopting environmentally sustainable strategies, which are controlled using a firm's fixed effects. As a result, for some firms, it is costly to switch and, hence, they do not switch throughout the observation time window. To validate further the robustness, we also excluded the 240 indifferent firms and found the results consistent with Table 5; we do not report the results for the sake of conciseness.

12 Please see page 10 of the “xtreg” manual published by Stata (can be found at http://www.stata.com/manuals13/xtxtreg.pdf).

13 We made an implicit assumption that, in an industry, the firms source a similar set of inputs when selling the finalized product to the output market. As a result, the cost of goods sold represents how much a firm needs from the input market; hence, this definition measures the input-market competition. However, we acknowledge that this input-market competition, in practice, does depend on the output market sales, and is only an approximation.

14 Although we have 280 observations, but excluding the ones with missing independent variables, 233 observation is in the regression. We do not adopt the same random-effects panel regression with firm fixed effects because the

average number of reports per firm is only 3.5, which is too short for the inclusion of these firm fixed effects.

View Abstract