Recycling an Exhaustible Resource

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Abstract

We examine the monopolist's best extraction strategies for an exhaustible resource that is recycled by an independent competitive company with fixed costs upon entry. Our findings provide insight on the possibility of socially inefficient extraction of the virgin resource. When recycling is relevant, the first-best solution requires to accommodate or promote recycling by increasing prior extraction since the recycled material generates additional resources. The monopolist-extractor, however, sees recycling as a threat and hence, it strategically chooses prior extraction to influence the future price of the resource. Specifically, the monopolist will either increase or decrease prior extraction in equilibrium, depending on whether it wishes to deter or accommodate recycling. We also examine the effects of resource scarcity and fixed costs magnitudes on the extraction of the virgin resource.

Keywords: entry, exhaustible resource, monopolist, recycling.

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1 Introduction

Since the early work of Smith (1972), recycling waste or scrap into production has been viewed as an alternative to undesirable littering. It is also commonly recognized that recycling helps save natural resources through conservation. This basic idea however needs to be addressed regarding those exhaustible resources, such as phosphorus or aluminum, that can be partially recovered after use. Surprisingly enough, the economics literature on exhaustible resources has not much considered the possibility of recycling. Although developments in recycling techniques have raised the effective stocks of resources (see Dasgupta, 1993), it is not clear why recycling should curb the extraction of resources that tend to run out.

Our goal is to investigate the effects of recycling on the extraction of an exhaustible resource. We examine the strategic interaction between a resource extractor and an independent competitive recycler in a two-period model where the recycler incurs fixed costs upon entry. The analysis compares the virgin resource extraction prior to recycling when the extractor is a monopolist with the extraction that would be desirable by a social planner who takes into account both the value created by the recycler and that derived from extraction. The model assumes that recycling yields a perfect substitute for the virgin resource. On one side, recycling generates additional resources, which is socially desirable, especially when the resource is scarce. But on the other side, a monopolist-extractor views the recycler's entrant as a threat to its market power. The monopolist anticipates how its initial choice of extraction affects not only the present and future demands for the resource, but also the intensity of future competition with the recycler. Even though recycling is socially desirable, the monopolist may find it more profitable to prevent the recycler's entry under certain circumstances. Or, if the recycler is entering in any case, the arbitrage rule of Hotelling (1931) that the monopolist's marginal revenue from extraction rises at the rate of interest must be amended to take recycling into consideration. In a nutshell, resource extraction has a commitment value that signals to potential recyclers whether the monopolist-extractor will prevent or restrict competition against them. We characterize the equilibrium choice of prior extraction, depending on whether it is made by the social planner or the monopolist. We carry out some comparative statics to examine how various changes in the underlying parameters of recycling costs and resource scarcity affect prior extraction and hence the recycling possibilities.

As a result, the first-best solution requires the extraction sector to let the recycling company enter the market, provided that the resource is scarce enough and fixed costs of recycling are low enough. In the first-best outcome, the invitation to recycle can take two different forms depending on the fixed cost magnitudes. If the market is attractive enough to the recycling company because of significantly low fixed costs, the extraction sector must *accommodate* recycling by increasing prior extraction above the level prevailing with no possibility of recycling. Then, the resource price is rising more rapidly than the interest rate at the first-best, because prior extraction generates additional resources via recycling. Hence, accommodating recycling disrupts the standard rule of Hotelling that price is rising at the interest rate. In contrast, for higher fixed costs, the extraction sector must reduce prior extraction to encourage the recycling company to enter, thereby *promoting* recycling.

In the monopolist's outcome, however, the opposite may happen because recycling is perceived as a threat to future profits: the monopolist strategically chooses prior extraction to discourage recycling. For this, the monopolist may implement two slightly different strategies: either the monopolist will *ignore* recycling, thereby behaving as if recycling were irrelevant, if the resulting downward pressure on the future price of the resource is enough to make the market unattractive to the recycling company; or the monopolist will *deter* recycling by raising prior extraction above the level prevailing with no recycling to push the future price down far enough that the recycling company stays out. Recycling deterrence is the monopolist's best strategy when the fixed costs of recycling are not too high.

However, if both the fixed costs are so low and the resource is so scarce that recycling cannot be avoided, we find that the monopolist also accommodates recycling in equilibrium.

In that case, the arbitrage rule of Hotelling is disrupted again: the monopolist extracts strategically little prior to recycling— actually less than what would be extracted with no recycling —to soften future competition between recycling and extraction.

The paper is organized as follows. Section 2 presents a detailed review of the related literature. Section 3 introduces the two-period model. Section 4 presents the first-best solution. In Section 5, we analyze the case of a monopolist in the resource extraction sector faced with an independent competitive company in the recycling industry. Concluding remarks appear in Section 6.

2 Related literature

The history of exhaustible resources shows evidence that the extraction sector goes through various regimes of competition and the recycling market is often ill-organized. Martin (1982) recognizes that "many of the industries currently practicing recycling are highly concentrated".

One interesting example is phosphate extraction together with phosphorus recycling. The majority of global phosphate rock reserves are located in Morocco, providing this country with a monopoly position in supplying the virgin resource (see Cordell et al., 2009). Thus, one may expect governmental regulation in Morocco to play a leading role in choosing the quantity of virgin phosphate to be extracted. In turn, this regulation may be more or less benevolent, depending on various factors such as the pressure put on the government by shareholders of the extraction company, or the share of the consumer surplus that escapes the government's jurisdiction. At the same time, the sector of phosphorus recycling has no institutional or organizational home (Cordell et al., 2006; Livingston et al., 2005). Phosphorus recycling throughout the world is mainly based on the reuse of nutrient flows stemming from food production and consumption[1]. While the sanitation sector in cities, e.g. waste water

[1] There are various methods available to recover phosphorus, such as ploughing crop residues back into the soil, composting food waste from households, using human and animal excreta, etc.

treatment or sewage sludge plants, plays a key role in phosphorus recycling[2], this service is scarcely high on the agenda of extraction stakeholders. In addition, the process of recovering phosphorus from sewage or waste water often requires a specific infrastructure and high levels of technical skills. According to Weikard and Seyhan (2009), phosphorus recycling is mainly undertaken by developed countries, except for Pakistan, not only because they have advanced wastewater treatment technologies, but also because, unlike developing countries, they have phosphorus-saturated soils[3].

Another example of a recyclable exhaustible resource is aluminum. This is now well documented because aluminum has been recovered since the early 1900s[4]. The monopolistic nature of virgin aluminum production in 1945 was acknowledged by the famous Alcoa case (Swan, 1980[5]). In contrast, the recycling sector of the industry is generally considered as competitive throughout the literature. In the view of Friedman (1967), the competitive recycling company would tend to push the aluminum price down to the marginal cost of virgin aluminum production. Martin (1982) disputes this statement in a model where Alcoa is treated as a monopolist faced with an independent recycling company. Assuming that a fixed proportion of scrap is discarded by consumers, that author shows that the long run price sold by the monopolist is strictly greater than the marginal cost of virgin aluminum. Suslow (1986) argues that Alcoa's market power was barely eroded by the very competitive nature of recycling, because virgin and recovered aluminum were not perfect substitutes. This view conflicts with Swan (1980)'s intuition that the monopolist in the aluminum extraction sector

[2] "Around 41% of phosphorus from sewage sludge across the European Union is currently recovered and reused in agriculture"—the European Commission's expert seminar on the sustainability of phosphorus resources (2011, http://ec.europa.eu/environment/natres/pdf/conclusions_17_02_2011.pdf.) even now, according to Ensink et al. (2004), more than 25% of urban vegetables grown in Pakistan are being fertilized with municipal wastewater.

[3] These authors show that developing countries benefit in the short and medium run from phosphorus recycling in developed countries, but face stronger competition for the resource in the long-term.

[4] In 1989, about 28% of the total aluminum supply in the United States came from recovered aluminum (see http://www.epa.gov/osw/nonhaz/municipal/pubs/sw90077a.pdf).

[5] In 1945, Alcoa was judged to enjoy a strong monopoly position which was supported rather than threatened by competition from secondary aluminum, produced by recycling scrap aluminum. Swan (1980) provides empirical evidence that the price charged by Alcoa is only slightly below the pure monopoly price but is well above the purely competitive price. The question of whether Alcoa had maintained its monopoly position by strategically controlling the supply of scrap aluminum ultimately available to secondary producers has been debated at length in the economic literature. Grant (1999) provides a nice survey of this debate.

had a strong strategic control over the recycling industry. Building on the assumption that the two sectors of extraction and recycling were independent in the Alcoa case, Grant (1999) provides empirical evidence that, first, recycling mattered to Alcoa, second, the producer of the virgin resource enjoyed a significant degree of market power, and third, aluminum recycling was not efficient although the sector was competitive. Since then, the aluminum industry has gone through different regimes of imperfect competition, both in the extraction and the recycling sectors.

The early theoretical literature related to this paper has examined how market power in the extraction sector affects the Hotelling rule. Hotelling (1931) shows that the monopolist has a tendency to be more resource-conservative than "competition... or maximizing of social value would require". Stiglitz (1976) adds that the parsimony of the monopolist depends on the elasticity of demand and extraction costs. Except for the case where the elasticity of demand is constant and extraction costs are zero, the result that the monopolist extracts the resource at a lower rate than that of the competitive firm seems rather robust (see also Tullock, 1979, for the case of inelastic demand). Lewis (1975) however discovers conditions on the price elasticity of demand for which the monopolist depletes the resource faster than required by social efficiency. Furthermore, a growing number of Cournot competitors on the market for an exhaustible resource tends to increase early extraction (see Lewis and Schmalensee, 1980). Hoel (1978) analyzes a situation in which the monopolist in the extraction sector faces perfect competition with a perfect substitute for the exhaustible resource, and shows that the monopolist reduces initial extraction compared to the case where the monopolist controls both resource extraction and substitute production. In the present analysis, substitute production results from prior extraction, hence the extraction sector determines the amount of input available for substitute production.

The issue of recycling an exhaustible resource has developed more recently in the economic literature with the aforementioned debate on the Alcoa case. Besides that, Hollander and Lasserre (1988) investigate the case of a monopolist in the extraction sector which recycles the scrap from its own production. The monopolist has monopsony power in the scrap market and faces a fringe of price-taking recyclers. Those authors show that the extraction sector finds it profitable to preempt market entry by competitive recyclers when the cost of recycling is sufficiently high. In contrast, in the present paper we analyze the competition between the virgin resource and the recycled product that occurs after prior extraction, assuming that the extraction sector does not recycle its own output. Gaudet and Van Long (2003) examine how market power in the recycling industry affects the primary production of a non-exhaustible resource. They show that the possibility of recycling may increase the market power of the extraction sector. Clearly, this cannot occur in the present model since competition between the exhaustible resource and its recycled output mitigates the extraction sector's market power. Lastly, Fisher and Laxminarayan (2004) demonstrate that a monopolist may extract the exhaustible resource faster than a competitive company when the resource is sold at different prices on two separate markets with different iso-elastic demands and no arbitrage possibility between the markets.

3 The two-period model

In a market for an exhaustible natural resource, an extraction sector is facing one prospective recycling company, which must decide whether to enter the market. The extraction sector, indexed by $i = 1$, holds the stock of the exhaustible natural resource, equal to s. This sector can extract the resource and transport it to market at no cost. Exploration does not occur and s is the single known stock of the resource in the world of this model. The exhaustible resource market is characterized by an inverse demand function $P(q)$, hence the consumers' gross surplus is $S(q) = \int_0^q P(x)dx$. We will assume that $P(q)$ is twice continuously differentiable with $P'(q) < 0$.

The independent recycling company, indexed by $i = 2$, has the technology and skill to recover part of the resource from used quantities[6]. The buyers of the virgin resource dispose of

[6]Regarding phosphorus, for instance, sector 2 may be viewed as the group of developed countries with

the used resource within the recycling industry, e.g., because it cannot be used again without being recycled. The recycled resource is viewed by consumers as a perfect substitute for the extracted resource. Recycling the amount q of the extracted resource yields an output r that cannot exceed q due to the depreciation and shrinkage which are present in every recovery process[7]. Should the recycling company decide to enter, it must incur a set-up cost of F and the recycling technology is given by the cost function $c(r) = cr$, where the constant marginal costs c reflect the value of the used virgin resource together with the prices of all the factors needed to produce the recovered substitute of the resource.

We model the extraction process and the entry decision of the recycling company as a two-period game. This implies that the resource becomes worthless after two periods. The extraction sector divides the resource stock between both periods. Supply in the first period determines what is left to be sold in the second period. In the first period, the extraction sector chooses quantity q and the market clears at price $P(q)$. In the second period, the recycling company decides whether to enter the market. If entry occurs, the recycling company produces quantity r and, simultaneously, the remaining stock of the resource, $s - q$, is sold by the extraction sector; the market then clears at price $P(s - q + r)$. The recycling company is assumed to be perfectly competitive.

The objective of the extraction sector is to maximize the objective function

$$W^1 = \alpha(S_1 - \pi_1^1) + \pi_1^1 + \delta \left[\alpha(S_2 - \pi_2^1) + \pi_2^1\right] \tag{1}$$

where δ is the discount factor, $S_1 = S(q), \pi_1^1 = P(q)q, S_2 = S(s-q+r), \pi_2^1 = P(s-q+r)(s-q)$ and $\alpha \in \{0, 1\}$.

The objective function for the recycling company is given by

$$W^2 = S_2 - cr - F, \tag{2}$$

In the economies we have in mind, the recycling industry is similar to a fringe of small

phosphorus-saturated soils and advanced wastewater treatment technologies (see Weikard and Seyhan, 2009).

[7] See Martin (1982) for aluminum scrap recovery and Weikard and Seyhan (2009) for phosphorus recovery from sewage sludge.

price-taking firms and the extraction sector either exercises monopoly power within its own business ($\alpha = 0$) or behaves as a social planner ($\alpha = 1$) who internalizes the value created by the recycling company in addition to taking into account the consumer surplus derived from virgin resource extraction. The social planner's outcome obtained with $\alpha = 1$ will set the benchmark. The case $\alpha = 0$ is motivated by real-world features of the phosphorus and aluminum industries. The market for phosphorus is mainly characterized by high concentrations of phosphate reserves in a few countries, such as Morocco and China (see Cordell et al., 2009, or Weikard and Seyhan, 2009). The case $\alpha = 0$ is also closely related to Swan (1980)'s study of the market for aluminum, where the monopolist "Alcoa" is confronted by an independent competitive recycling company (see also Martin, 1982).

In the absence of recycling, we denote by q_0^e the socially efficient first-period resource extraction, in the sense that

$$P(q_0^e) = \delta P(s - q_0^e) \tag{3}$$

To ensure that, under perfect competition, the extraction sector is active in the absence of recycling, we will make the following assumption

$$P(q_0^e) > 0 \tag{4}$$

Since the first-period resource extraction determines what is left to be sold in the second period, the size of the stock constrains the extraction sector, which thus takes no strategic decision in the second period. The prior extraction decision is irrevocable: it has a commitment value, which influences the recycling company's decision. The recycling company observes the first-period extraction q, and decides whether to enter the market or to stay out. We normalize the welfare secured by the recycling company if it stays out to be zero. Thus, the recycling company becomes active if and only if it satisfies a participation constraint requiring that the social welfare W^2 exceeds zero. A (pure) strategy for the extraction sector is a choice q, and a strategy for the recycling company is a mapping $R : [0, +\infty) \rightarrow [0, +\infty)$. It follows that the equilibrium of the two-period entry game reduces to a pair $(q^*, R(.))$ of

Nash equilibrium with sequential move defined as follows:

1. $W^1(q^*, R(q^*)) \geq W^1(q, R(q))$, for all $q \in [0, s]$;

2. $W^2(q^*, R(q^*)) \geq W^2(q^*, r)$, for all $r \in [0, s]$,

   subject to $W^2(q^*, R(q^*)) \geq 0$.

This means that the extraction sector, by its initial commitment, can decide whether the recycling company enters the market or not. The participation constraint ensures that the recycling company finds it worthwhile to enter. In the case of entry, the extraction sector chooses a point on the recycling company's reaction function to maximize its own welfare.

To solve this game, the first step is to derive the subgame reaction function of the recycling company to the level q of prior extraction. The recycling company maximizes

$$W^2(q, r) = S(s - q + r) - cr - F. \tag{5}$$

We denote the recycling company's reaction function by $R(q)$. We neglect scales economies for a moment and concentrate on the levels of q that allow the recycling company to enter the market. In that case, $R(q)$ coincides with the output $\widetilde{r}(q)$ at which the market price equals the marginal cost of recycling,

$$P(s - q + \widetilde{r}(q)) = c. \tag{6}$$

To get the existence (and unicity) of $\widetilde{r}(q)$, it is sufficient that $P(q)$ be log-concave[8]. Hence, $\widetilde{r}(q)$ represents the optimal level of recycling whenever possible. One key feature of recycling is that full recycling is impossible. We will assume[9]

$$W_r^2(q, q) < 0, \tag{7}$$

[8] $P(q)$ is log-concave if $P''(.)P(.) - P'(.)^2 < 0$. This condition is satisfied when P is concave, linear or $P(q) = Aq^{\gamma-1}$ with $0 < \gamma < 1$ so that $1/(1-\gamma)$ is the elasticity of demand. Most of the commonly used demand functions are, in fact, log-concave. The limiting case is $P(q) = Ae^{-q}$, which is strictly convex and log-linear (hence log-concave). When $P(q)$ is log-concave, the recycling company's problem is concave.

[9] Throughout the article, a subscript will denote a derivative with respect to the relevant variable.

which amounts to $P(s) < c$, so that the output of recycling $\widetilde{r}(q)$ always falls short of the output q previously extracted. At $q = 0$, (7) implies $W_r^2(0,0) < 0$. As $W_r^2(0, \widetilde{r}(0)) = 0 > W_r^2(0,0)$ and $W_{rr}^2(q,r) = P'(s-q+r) < 0$, we also have $\widetilde{r}(0) < 0$. Furthermore, differentiating $W_r^2(q, \widetilde{r}(q)) = 0$, we get

$$\widetilde{r}'(q) = -\frac{W_{rq}^2(.)}{W_{rr}^2(.)} = 1. \tag{8}$$

As $\widetilde{r}(q)$ is upward sloping, there exists $\underline{q} > 0$ such that $\widetilde{r}(\underline{q}) = 0$, hence $\underline{q}$ is the minimum level of prior extraction that accommodates recycling. For recycling to be effective, we need that $\underline{q} < s$. For this, we assume further

$$W_r^2(s,0) > 0, \tag{9}$$

which amounts to $P(0) > c$, so that $W_r^2(s,0) > W_r^2(s, \widetilde{r}(s))$ implies $\widetilde{r}(s) < 0$ since $W_r^2(s,q)$ is strictly decreasing, and thus $\widetilde{r}(s) < \widetilde{r}(\underline{q})$. We see that extracting more of the resource in the first period induces the recycling company to produce more in the next period, provided that prior extraction allows the recycling activity. Hence, prior extraction creates the recycling activity, which yields a perfect substitute to the virgin resource produced by future extraction. Thus, increasing prior extraction generates additional resources via recycling and, at the same time, expands the future market share for the recycled substitute, which in turn reduces the future market share for the virgin resource.

We now introduce scale economies. Let $\widetilde{q}$ be the level of q (higher than $\underline{q}$) that makes the recycling company indifferent between staying out and entering, so that $R(\widetilde{q}) = \widetilde{r}(\widetilde{q})$ and $W^2(\widetilde{q}) = 0$, where $\mathbf{W}^2(q) = W^2(q, R(q))$ is the reduced-form function. The recycling company's reaction function is discontinuous at the level $\widetilde{q}$, where there is a jump of the same sign as $\frac{d\mathbf{W}^2(q)}{dq} \mid_{q=\widetilde{q}}$. The recycling reaction function is made up of two possible segments within $\left[\underline{q}, s\right]$. One segment corresponds to $R(q) = 0$, meaning that the recycling company is better off securing zero welfare. The other segment includes all the levels q that allows the recycling company to enter and produce $R(q) = \widetilde{r}(q)$. The position of the discontinuity depends on the underlying parameters of demand and recycling cost. From the envelope theorem, we can write $\frac{d\mathbf{W}^2(q)}{dq} = W_q^2(q, R(q))$, and so

$$\frac{d\mathbf{W}^2(q)}{dq} \mid_{q \geq \underline{q}} = -P(s - q + \widetilde{r}(q)). \tag{10}$$

As the sign of the derivative of $W^2(q)$ is negative for all $q \geq \underline{q}$, the recycling reaction function is downwards jumping at $\widetilde{q}$. Increasing prior extraction above $\widetilde{q}$ prevents entry because it reduces the second-period consumer surplus derived from virgin resource extraction by $P(.)$ for all the units of extracted resource. Hence, $\widetilde{q}$ is the maximum level of prior extraction below which the recycling company enters the market, choosing the output $\widetilde{r}(q)$. Formally, the recycling reaction function is

$$R(q) = \begin{cases} \widetilde{r}(q) \text{ when } \underline{q} \leq q \leq \widetilde{q}, \\ 0 \text{ otherwise.} \end{cases} \tag{11}$$

Anticipating(11), the extraction sector chooses q to maximize the reduced-form function $\mathbf{W}^1(q) = W^1(q, R(q))$. As $R(q)$ is discontinuous at $\widetilde{q}$, $\mathbf{W}^1(q)$ is also discontinuous at $\widetilde{q}$. Thus, $\mathbf{W}^1(q)$ is not concave in q, and it may achieve multiple local maxima, of which one accommodates the recycling company and the other does not. Let q^a denote the local maximum that accommodates the recycling company. It must satisfy the first-order condition

$$W_q^1(q, \widetilde{r}\,(q)) + W_r^1(q, \widetilde{r}\,(q))\widetilde{r}'\,(q) = 0, \tag{12}$$

where $\widetilde{r}'(q) = 1$ from (8). The total derivative of the extraction sector's welfare in the left-hand side of (12) gives the incentive to extract the resource prior to recycling. It can be decomposed into two effects. The first effect is W_q^1. This is a "balance effect" between the first and the second period: any welfare improvement produced in the first period by the extraction of the virgin resource is offset by a welfare deterioration in the second period. The balance effect would exist even if prior extraction of the resource were not recovered, and therefore recycling could not affect future extraction. The second effect, captured by W_r^1, is a "recycling effect" that results from the influence of prior extraction on the recycling decision. This dependence of recycling on extraction was pointed out by Judge Hand in the Alcoa case and debated at length in the economic literature.

Further calculations yield

$$W_r^1(q,r) = \delta\left[\alpha P(s-q+r) + (1-\alpha)\,P'(s-q+r)(s-q)\right] \tag{13}$$

Observe that $W_r^1(q,r) > 0$ (< 0) when $\alpha = 1$ (0). When the extraction sector behaves as a social planner, welfare increases with the recycled quantity due to valuable stock extension, whereas the monopoly revenue of the extraction sector decreases with the recycled quantity because the market price decreases in the second period. From the social planner's standpoint, recycling expands the stock of the natural resource sold in the second period, which enhances the consumer surplus in the second period by $P(.)$ for all the units of resource the recycling company is selling. In contrast, from the monopolist's standpoint, recycling puts a downward pressure on the second-period market price, reflected by $P'(.)$, which applies to $s - q$, i.e., all the units of the virgin resource left to be sold by the extraction sector. When $\alpha = 0$, the recycling effect in (12) is negative, since $\widetilde{r}\,(q)$ is upward sloping. Using the social planner's outcome as a benchmark, one can argue that there is a tendency of a monopolist-extractor to extract "too little" of the resource prior to recycling.

Moving ahead on the analysis proves difficult at the level of generality used so far. We will work with functional specifications to solve explicitly for the equilibrium outcome. We will use the following framework with quadratic welfare functions:

Quadratic Framework (QF).

- $S(q) = aq - q^2/2$, which yields the demand function $P(q) = a - q$,
- $\delta = 1$,
- $s < 2a$,
- $s > a - c$,
- $a > c$.

The three inequalities correspond respectively to $(4),(7)$ and (9), using the quadratic specifications. Within QF, the extraction sector's objective function is

$$W^1(q,r) = \alpha q^2/2 + (a-q)\,q + \alpha(a(s-q+r) - (s-q+r)^2/2 - (a-s+q-r)\,(s-q)) + (a-s+q-r)\,(s-q) \tag{14}$$

The recycling company's objective function is

$$W^2(q,r) = a(s-q+r) - (s-q+r)^2/2 - cr - F, \tag{15}$$

which yields

$$R(q) = \begin{cases} a-c-s+q \text{ when } \underline{q} \leq q \leq \widetilde{q}, \\ 0 \text{ otherwise}, \end{cases} \tag{16}$$

where $\underline{q} = s+c-a$. Substituting $\widetilde{r}(q)$ into (15), we obtain the reduced-form function

$$\mathbf{W}^2(q) = \frac{(a-c)^2}{2} + c(s-q) - F. \tag{17}$$

The solution of equation $\mathbf{W}^2(q) = 0$ yields the maximum level of prior extraction that accommodates the recycling company

$$\widetilde{q} = \min\left\{s, \frac{(a-c)^2 + 2cs - 2F}{2c}\right\}. \tag{18}$$

It follows that the minimum threshold of fixed cost above which the market is not attractive enough to the recycling company is

$$\overline{F} = \frac{a^2 - c^2}{2}. \tag{19}$$

More precisely, if the fixed cost F is weakly lower than $\overline{F}$, then $\underline{q} \leq \widetilde{q}$ and there exists q inside $[\underline{q}, \widetilde{q}]$, at which recycling can be accommodated. Otherwise, the recycling company stays out for all $q \in [0, s]$.

4 The first-best equilibrium ($\alpha = 1$)

In this section, we characterize the equilibrium outcome in which a social planner takes into account the consumer surplus derived both from virgin resource extraction and the recycled product sales. Anticipating the recycling company's reaction (11), the social planner chooses q in the first period to maximize

$$\mathbf{W}^1(q) = S(q) + \delta S(s - q + R(q)). \tag{20}$$

This function is discontinuous at $\widetilde{q}$, with a downward jump since $W_r^1(q,r) > 0$ from (13). Let q_e^a denote the optimal extraction that accommodates the recycling company in the social planner's outcome, subscript e meaning *efficient* from the social standpoint. The first-order condition at the local maximum q_e^a is

$$P(q_e^a) - \delta P(s - q_e^a + \widetilde{r}\,(q_e^a)) = -\delta P(s - q_e^a + \widetilde{r}\,(q_e^a))\widetilde{r}'\,(q_e^a)\,. \tag{21}$$

As previously seen, the welfare effect of prior extraction can be decomposed into the balance effect, captured by the left-hand side of (21), and the indirect welfare effect due to recycling, reflected by the right-hand side of (21). Condition (21) can be interpreted as a variant of the "Hotelling rule" for a non-renewable and recyclable resource. Indeed, this condition tells us that the extraction sector must be indifferent between selling a unit of resource today or tomorrow, given that the tomorrow resource is both extracted and recycled. As the natural stock size s is increased by the recycled amount $\widetilde{r}\,(q_e^a)$ in the second period, the value $P(q_e^a)$ of a unit of resource extracted in the first period must be the same as the present value $\delta P(s - q_e^a + \widetilde{r}\,(q_e^a))$ of a unit of resource sold in the second period, corrected by the recycling effect $\delta P(s - q_e^a + \widetilde{r}\,(q_e^a))\widetilde{r}'\,(q_e^a)$. Clearly, this is the spirit of the Hotelling rule. As $\widetilde{r}\,(q)$ is upward sloping, the second-period welfare is improved by $P(.)\widetilde{r}'\,(.)$ because recycling creates a valuable extension of the resource stock. Moreover, we are able to compare q_e^a with the efficient level q_0^e in the absence of recycling. From (3), we know that $P(q_0^e) = \delta P(s - q_0^e)$, and furthermore $W_r^1(q,r)\mid_{(q=q_0^e, r=0)} = \delta\,[P(s - q_0^e)]$. Assumption (4) implies that $W_r^1(q,r)\mid_{(q=q_0^e, r=0)} > 0$. Hence, the recycling possibility increases prior extraction at the first-best equilibrium. Moreover, the Hotelling rule is disrupted in that the resource price is increasing faster than the interest rate since

$$\frac{P(s - q_e^a + \widetilde{r}\,(q_e^a))}{P(q_e^a)} > \frac{1}{\delta}. \tag{22}$$

Proposition 1 *Under assumptions* $(4)\,,(7)$ *and* (9), *the prospect of recycling increases the first-best level of prior extraction so that the resource price is rising more rapidly than the interest rate.*

To obtain further insight into the existence and social desirability of recycling, we now turn to the specification within QF. We have previously seen that the recycling company enters the market for all q inside $[\underline{q}, \widetilde{q})$ provided that $F < \overline{F}$. Furthermore, solving (21) for q_e^a yields

$$q_e^a = \min\{a, s\}\,. \tag{23}$$

Hence, when the resource is scarce $(s < a)$, the best accommodation choice from the social planner's standpoint is to deplete the whole stock in the first period.

As (4) within QF requires $s < 2a$, we have $q_e^a > q_0^e$, where $q_0^e = \frac{s}{2}$ is the optimal prior level of extraction when the extraction sector ignores the recycling possibility. Moreover, one can check that $q_e^a > \underline{q}$. Assuming now that $F < \overline{F}$, the extraction sector anticipates the recycling reaction (16) and chooses q to maximize

$$\mathbf{W}^1(q) = \begin{cases} \frac{1}{2}(a^2 - c^2 + 2aq - q^2) \text{ if } \underline{q} \leq q \leq \widetilde{q}, \\ \\ as - s^2/2 + +sq - q^2 \text{ otherwise.} \end{cases} \tag{24}$$

This function is piecewise concave and discontinuous with a downward jump at $\widetilde{q}$. If $\widetilde{q} \leq q_0^e$, then $\mathbf{W}^1(q)$ is increasing on $[\underline{q}, \widetilde{q}]$ because $q_e^a > q_0^e$, and thus $W^1(q)$ achieves two local maxima at $\widetilde{q}$ and q_0^e. In that case, accommodating the recycling company cannot be an option. However, the social planner may choose to "promote" recycling by extracting $\widetilde{q}$ below q_e^a in the first period, in order to generate consumer surplus in the second period. As $P\,(\widetilde{q})$ exceeds the price $P\,(q_a^e)$ that would blockade the recycling company's entry, residual demand in the second period results from $P(s - \widetilde{q} + \widetilde{r}\,(\widetilde{q}))$, which raises the recycling company's welfare up to the minimum level that allows entry. If $q_0^e \leq \widetilde{q}$, then $\mathbf{W}^1(q)$ achieves two local maxima at

$\min\{\widetilde{q}, q_e^a\}$ and q_0^e. Any change that lowers $\widetilde{q}$ can be said to make recycling more difficult: if initially the entry of the recycling company is accommodated at q_e^a, it moves closer to being promoted at $\widetilde{q}$, which occurs when $\widetilde{q} \leq q_e^a$. From (18), an increase in the fixed cost for the recycling company reduces $\widetilde{q}$ below s, while leaving q_e^a unaltered, thus making entry more difficult. We can distinguish two cases depending on the resource abundance.

(i) The resource is scarce ($s < a$) so that the extraction sector commits to depleting the whole stock in the first period, i. e., $q_e^a = s$, when the recycling company is accommodated. This commitment is possible only if $q_e^a \leq \widetilde{q}$. From (18), this latter inequality holds when F falls below the minimum fixed cost for recycling to be promoted, i. e.,

$$F_s = \frac{(a-c)^2}{2}. \tag{25}$$

As $a > c$ from (9), we have $F_s < \overline{F}$.

(ii) The resource is relatively abundant ($a \leq s$). The extraction sector can commit to accommodating the recycling company only if $q_e^a \leq \widetilde{q}$, which holds when F falls below $\min\{F_a, \overline{F}\}$ [10], where

$$F_a = \frac{(a-c)^2}{2} + c\,(s-a)\,. \tag{26}$$

Figure 1 reproduces the relevant aspects of the case where $q_e^a = a$ and $F \leq F_a$, so that $q_e^a \leq \widetilde{q}$. The curves are drawn using QF in the case where $\alpha = \beta = 1$. They show how to find a unique geometric solution corresponding to the first-best equilibrium. The figure depicts the extraction sector's isowelfare curves and the reaction functions of both the extraction sector and the recycling company in (q, r) space. The dotted line GH represents the extraction sector's reaction function. This function cuts each of the extraction sector's isowelfare curves at its maximum. In particular, given $r = 0$, W^1 is maximized at the point G which coordinates are $(q_0^e, 0)$, with q_0^e equal to $\frac{s}{2}$ within QF. Holding q_0^e fixed, the extraction sector does better when r is higher because $W_r^1(q,r)\mid_{\left(q=q_0^e, r=0\right)} = a - \frac{s}{2} > 0$. Thus, higher isowelfare curves

[10] It turns out that $F_a \leq \overline{F}$ only if $s \leq 2a - c$.

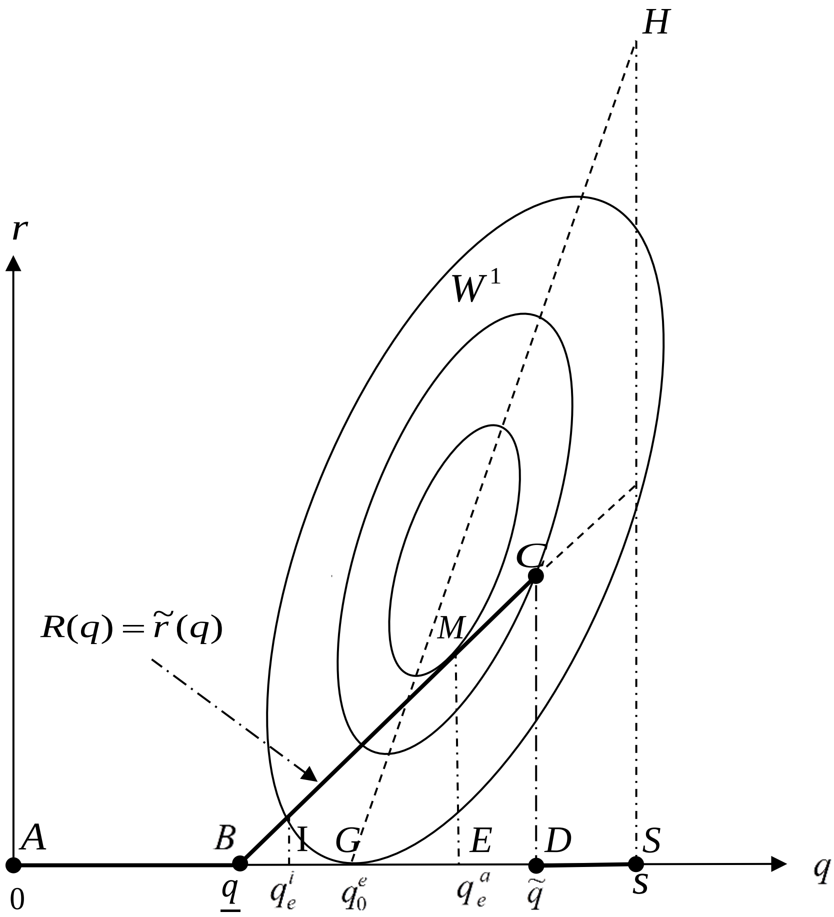

Figure 1
First-best solution

represent higher welfare levels for the extraction sector. The recycling reaction function $R(q)$ is made up of the three segments $[A, B]$, $[B, C]$ and $[D, S]$, where B, C, D and S have respective coordinates $(\underline{q}, 0)$, $(\widetilde{q}, \widetilde{r}(\widetilde{q}))$, $(\widetilde{q}, 0)$ and $(s, 0)$. The isowelfare curve tangent to $[C, D]$ at M meets the q-axis at E. Output q_e^a is vertically below M on the q-axis. The isowelfare curve passing through G intersects $[B, C]$ at the point which coordinates are $(q_e^i, \widetilde{r}(q_e^i))$, where

$$q_e^i = a - \frac{\sqrt{2\left(2a - s + c\sqrt{2}\right)\left(2a - s - c\sqrt{2}\right)}}{2} \tag{27}$$

provided that $s \leq 2a - c\sqrt{2}$. Figure 1 illustrates the case where $\underline{q} \leq q_0^e$, which happens only if $s \leq 2(a - c)$, and so q_e^i actually exists.

Assume for a moment that $s \leq 2(a - c)$. When $\widetilde{q}$ is lower than s, the expression (18) shows that the position of the point D depends on c, F, s and a. The comparison of q_e^a and $\widetilde{q}$ determines whether the extraction sector accommodates or promotes recycling in equilibrium. In Figure 1, the extraction sector does better than the point C by setting prior extraction at M, so that recycling is accommodated. From the case where $q_e^a \leq \widetilde{q}$, an increase in the fixed cost for the recycling company lowers $\widetilde{q}$ while leaving q_e^a unaltered, thus making entry more difficult. If the fixed cost of recycling is large enough that D lies to the right of I which coordinates are $(q_e^i, 0)$ and to the left of E— which occurs in two cases: first, when $s \leq a$ and $F_s \leq F$; and second, when $a \leq s \leq 2(a - c)$ and $F_a \leq F$ —, the extraction sector prefers extracting $\widetilde{q}$ over q_e^a to make entry worthwhile for the recycling company: the first-best requires to promote recycling.[11]

Finally, if the fixed cost of recycling is so high that D lies to the left of I, the extraction sector blockades the entry of the recycling company with q_0^e, i. e., the same level of prior extraction as that prevailing in the absence of recycling possibilities. Hence, the extraction

[11] If prior extraction is set equal to $\widetilde{q}$, the recycling company is actually indifferent between staying out and entering to yield the point C. However, its entry would increase the extraction sector's welfare substantially. Therefore, so long as the social planner thinks that there is a positive probability of entry with $\widetilde{q}$, there is a discontinuous upward jump in the expected welfare from D to C. We adopt the convention here that the recycling company chooses to enter the market when it is indifferent.

sector ignores recycling when $\widetilde{q}$ falls short of q_e^i, which is tantamount to $F_i \leq F < \overline{F}$, where

$$F_i = F_a + \frac{c\sqrt{2\left(2a - s + c\sqrt{2}\right)\left(2a - s - c\sqrt{2}\right)}}{2} \tag{28}$$

is the minimum fixed cost for recycling to be ignored. Further calculations show that $F_i \leq \overline{F}$ when $s \leq 2(a-c)$.

Let us now turn to the case where $s > 2(a-c)$ so that $q_0^e < \underline{q}$. Then, q_e^i does not exist for all s inside $(2(a-c), 2a - c\sqrt{2})$ because $W^1(q_e^a, \widetilde{r}(q_e^a))$ is strictly lower than $W^1(q_0^e, 0)$: hence, recycling cannot be accommodated in equilibrium. Clearly, in that case we also have that $\widetilde{q} > q_0^e$, and thus the first-best requires to ignore recycling.

The next proposition summarizes this discussion.

Proposition 2 *Under assumptions* (4), (7) *and* (9) *within QF, the first-best solution requires*

(1) to accommodate the recycling company

- *with* $q_e^a = s$ *when* $a - c < s \leq \min\{a, 2(a-c)\}$ *and* $F \leq F_s$*,*
- *with* $q_e^a = a$ *when* $a \leq s \leq 2(a-c)$ *and* $F \leq F_a$*;*

(2) to promote recycling with $\widetilde{q}$

- *when* $a - c < s \leq \min\{a, 2(a-c)\}$ *and* $F_s < F < F_i$*,*
- *when* $a \leq s \leq 2(a-c)$ *and* $F_a < F < F_i$*;*

(3) to ignore recycling with q_0^e *otherwise.*

The first-best solution requires to ignore recycling when the resource is abundant ($s > 2(a-c)$) or when it is scarcer but the fixed cost of recycling is too high ($F \geq F_i$). Hence, recycling is socially desirable only if the resource is sufficiently scarce and the fixed cost sufficiently low. Under these circumstances, the extraction sector either accommodates or promotes recycling. Recycling is accommodated when the entry of the recycling company is taken for granted. In that case, the first-best requires the extraction sector to set prior extraction above the level prevailing with no possibility of recycling: the consequent extension of the resource stock generates consumer surplus via recycled material. When the resource is significantly scarce ($s \leq a$), the social planner commits to depleting the whole resource stock in the first period in order to accommodate recycling.

However,the social planner cannot take entry for granted when the fixed cost has intermediate values ($F_s < F < F_i$ or $F_a < F < F_i$). Instead of accommodating recycling, the extraction sector must promote recycling by reducing prior extraction in a way that generates sufficient consumer surplus for the recycling company to enter. Whether the social planner accommodates or promotes recycling, the possibility of recycling increases prior extraction relative to what would be optimally extracted with no possibility of recycling.

5 A monopolist in the resource extraction sector ($\alpha = 0$)

In this section, we focus on the situation in which a monopolist in the resource extraction sector is confronted by an independent competitive company in the recycling industry. This will provide a useful comparison with the monopoly analysis of a non-recyclable exhaustible resource in Stiglitz (1976). We substitute $\alpha = 0$ into (1) to get the extraction monopolist's objective function. Bearing in mind the recycling reaction (11), the monopolist chooses q to maximize

$$\mathbf{W}^1(q) = P(q)q + \delta \left[P(s - q + R(q))(s - q) \right]. \tag{29}$$

The function $\mathbf{W}^1(q)$ is discontinuous at $\widetilde{q}$, where there is an upward jump since $W_r^1(q, r) < 0$ (see (13)). Let q_m^a denote the local maximum that accommodates recycling in the monopolist's outcome. The first-order condition at q_m^a is given by

$$\begin{aligned} & P(q_m^a) + P'(q_m^a)q_m^a - \delta P(s - q_m^a + \widetilde{r}(q_m^a)) + P'(s - q_m^a + \widetilde{r}(q_m^a))(s - q_m^a)) \\ = \; & -\delta P'(s - q_m^a + \widetilde{r}(q_m^a))\widetilde{r}'(q_m^a)(s - q_m^a). \end{aligned} \tag{30}$$

Condition (30) has a familiar interpretation in the economics of exhaustible resources (see

Stiglitz, 1976). The extraction monopolist compares the marginal revenue today with the discounted marginal revenue obtainable by postponing the extraction until tomorrow. The difference here from the previous literature is that recycling the resource both augments the stock size and gives rise to a perfect substitute for further quantities of the extracted resource. The left-hand side of (30) measures the aforementioned balance effect of prior extraction on the expected revenue in both periods, given that the available stock is $s + \widetilde{r}\,(q_m^a)$. Were this effect set equal to zero, it would correspond to the Hotelling rule in the case investigated by Stiglitz (1976), where the monopoly power is unrestrained by recycling. Bearing in mind the possibility of recycling, the monopolist strategically anticipates the impact of prior extraction on the interaction between recycling and further extraction. As previously shown, this strategic effect reduces the second period price, because $R\,(q)$ is upward sloping: increasing prior extraction triggers a more aggressive reaction by the recycling company, which decreases the second-period price by $P'(.)\widetilde{r}'\,(.)$. The resulting downward pressure on price scales down the second-period marginal revenue from extraction. This provides the monopolist with an incentive to look "friendly" from the start and extract less resources than the Hotelling rule would require in the absence of strategic effect. Such a strategy has the flavor of the so-called "puppy-dog" profile in the terminology of business strategies (see Fudenberg and Tirole, 1984). The extraction monopolist commits the recycling company to softening competition between recycling and further extraction. However, the "puppy-dog" strategy obeys here the inescapable logic of the extraction rule that the marginal revenue must rise at the rate of interest.

Proposition 3 *Under assumptions* $(4)\,,(7)$ *and* (9)*, the prospect of recycling reduces the level of prior extraction set by the monopolist to accommodate recycling.*

The monopolist may like the possibility of preventing rather than accommodating recycling. We examine now entry conditions using the specification within QF. We substitute

$\alpha = 0$ into (14) and write the extraction monopolist's objective function as

$$W^1(q,r) = (a-q)\,q + (a-s+q-r)\,(s-q). \tag{31}$$

Moreover, solving (30) for q_m^a within QF, we explicitly compute the optimal extraction that accommodates recycling as

$$q_m^a = \frac{a-c}{2}, \tag{32}$$

provided that $q_m^a > \underline{q}$, or, equivalently, $s < \frac{3}{2}(a-c)$: hence, the monopolist will not accommodate the recycling company if the resource is too abundant. Note that $q_m^a < q_0^m$, where $q_0^m = \frac{s}{2}$ is the monopolist's optimal output in the absence of recycling possibilities. This is consistent with the result stated in proposition 3 that the prospect of recycling induces the monopolist to extract strategically little in the first period. Anticipating the recycling reaction (16), the monopolist chooses q to maximize

$$\mathbf{W}^1(q) = \begin{cases} (a-q)q + c(s-q) \text{ if } \underline{q} \le q \le \widetilde{q}, \\ (a-q)q + (a-s+q)(s-q) \text{ otherwise.} \end{cases} \tag{33}$$

This function is piecewise concave and discontinuous with an upward jump at $\widetilde{q}$. Assume first that the resource is so abundant that $s \ge \frac{3}{2}(a-c)$. Then, $q_m^a \le \underline{q}$ and $\mathbf{W}^1(q)$ is decreasing on $[\underline{q}, \widetilde{q}]$, thereby achieving a maximum at $\max\{q_0^m, \widetilde{q}\}$. Straightforward calculations show that $q_0^m \le \widetilde{q}$ for all $F \le F_i^m$, where

$$F_i^m = \frac{(a-c)^2 + cs}{2} \tag{34}$$

is the minimum fixed cost for recycling to be ignored. In that case, the monopolist prefers extracting $\widetilde{q}$ over q_0^m to prevent recycling: this is a deterring strategy in the sense that the monopolist increases prior extraction above the level q_0^m that would be optimally extracted with no recycling. Note that q_0^m accommodates recycling in the present case. Increasing extraction up to $\widetilde{q}$ strengthens competition in the second-period, thereby reducing the second-period price down to the threshold at which the recycling company is not entering..

If the fixed cost exceeds the threshold F_i^m, then $\widetilde{q} < q_0^m$ and the best choice for the monopolist is to ignore recycling and exercise unrestrained monopoly with q_0^m.

Assume now that the resource is scarce so that $s < \frac{3}{2}(a-c)$, which amounts to $\underline{q} < q_m^a$. Then, $\mathbf{W}^1(q)$ has two local maxima whenever $q_m^a < \widetilde{q}$. Figure 2 shows how to find the unique geometric solution to this problem. The figure depicts the monopolist's isorevenue curves given by (31) and the recycling reaction (16) in (q, r) space. Given $r = 0$, W^1 is maximized at the point G which coordinates are $(q_0^m, 0)$. Holding q_0^m fixed, the extraction sector does worse when r is higher since $W_r^1(q, r) < 0$. Thus, lower isowelfare curves represent higher welfare levels for the monopolist. The isorevenue curve is tangent to $[B, C]$ at M, and this curve meets the q-axis at E which coordinates are $(\overline{q}, 0)$. Figure 2 illustrates the case where D lies between E which coordinates are $(\overline{q}, 0)$ and G which coordinates are $(q_0^m, 0)$. In that case, the monopolist does better than the point M by setting prior extraction at $\widetilde{q}$, so that the recycling company stays out.[12] Again, this is a deterring strategy that pushes prior extraction above q_0^m.

Deriving the explicit formula for $\overline{q}$ within QF, we get[13]

$$\overline{q} = \frac{s}{2} + \sqrt{2\left(s(2+\sqrt{2}) + c - a\right)\left(a - c - s(2-\sqrt{2})\right)}. \tag{35}$$

Further calculations show that $\widetilde{q} \leq \overline{q}$, as depicted in Figure 2, holds only if $F \geq F_a^m$, where

$$F_a^m = \frac{(a-c)^2}{2} + c(s-a) - c\frac{\sqrt{2\left(s(2+\sqrt{2}) + c - a\right)\left(a - c - s(2-\sqrt{2})\right)}}{4} \tag{36}$$

thus corresponds to the maximum fixed cost below which the monopolist accommodates the recycling company. Indeed, for all $F < F_a^m$, the point D lies to the right of E, in which case the monopolist finds it worthwhile to accommodate the recycling company with q_m^a. In

[12] If prior extraction is set actually equal to $\widetilde{q}$, the recycling company is indifferent between staying out and entering to yield the point C. However, its entry would increase the extraction sector's profit substantially. Therefore, so long as the monopolist thinks that there is a positive probability of staying out with $\widetilde{q}$, there is a discontinuous upward jump in the expected profit from C to D. We adopt the convention here that the recycling company chooses to stay out when it is indifferent.

[13] One can easily check that $a - c - s(2-\sqrt{2}) > 0$ for all $s < \frac{3}{2}(a-c)$.

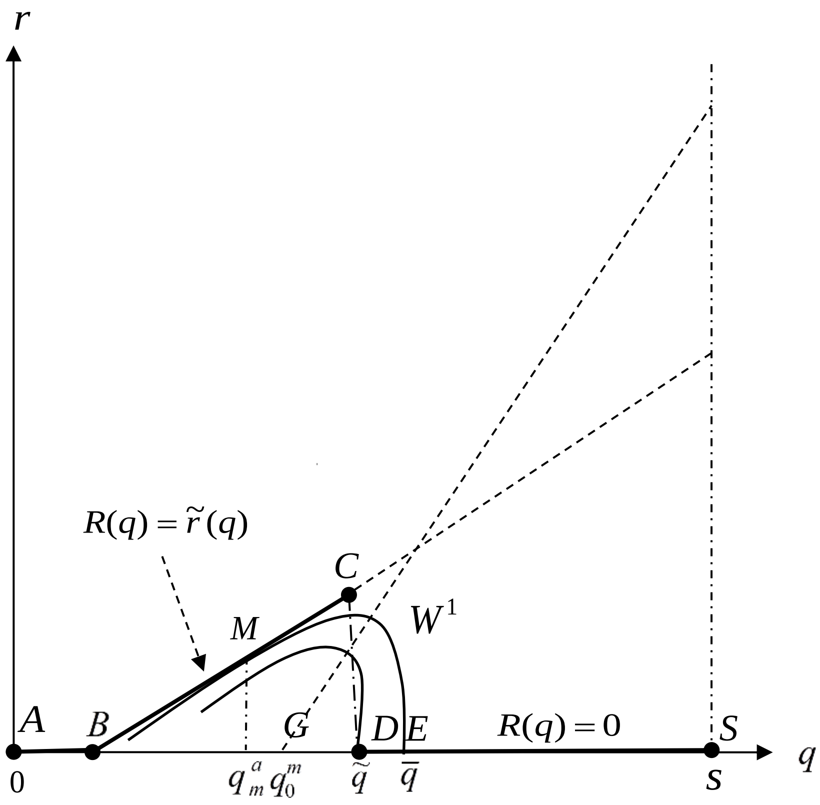

Figure 2:
Monopolist's solution

contrast, if the fixed cost is so high that D lies to the left of G, which is tantamount to $F > F_i^m$[14], the best choice for the monopolist is to ignore the recycling company, thereby blockading entry with q_0^m.

We can summarize our results as follows.

Proposition 4 *Under assumptions* (4), (7) *and* (9) *within QF, the best choice for the monopolist is:*

(1) to accommodate recycling with q_m^a when $a - c < s < \frac{3}{2}(a-c)$ and $F < F_a^m$,

(2) to deter recycling with $\widetilde{q}$

- *when $a - c < s \leq 2(a-c)$ and $F \in [F_a^m, F_i^m)$,*
- *or when $2(a-c) < s \leq 2a$;*

(3) to ignore recycling with q_0^m when $\frac{3}{2}(a-c) \leq s < 2(a-c)$ and $F \in \left[F_i^m, \overline{F}\right]$.

The monopolist accommodates recycling only if the resource is scarce ($s < \frac{3}{2}(a-c)$) and the fixed cost of recycling falls below the threshold F_a^m. In that case, the monopolist extracts strategically little in the first period— actually less than what would be extracted with no recycling —to soften competition between recycling and further extraction. If the fixed cost exceeds F_a^m when the resource is scarce, the monopolist finds it more profitable to prevent the entry of the recycling company, but cannot behave as if recycling were irrelevant. Recycling is actually seen as a threat by the monopolist which reacts by implementing the following deterrence strategy: the monopolist raises prior extraction above the level prevailing with no recycling in order to reduce the second-period price down to the threshold at which the recycling company is staying out. Recycling deterrence is also the monopolist's best strategy when the resource is abundant ($s > 2(a-c)$), or moderately abundant ($\frac{3}{2}(a-c) \leq s < 2(a-c)$) and the fixed cost is not too high ($F \in [F_a^m, F_i^m)$). For higher values of the

[14] Further calculations show, first, that $F_a^m < F_i^m$ for all $s < \frac{3}{2}(a-c)$, and second, that $F_i^m < \overline{F}$ for all $s < 2(a-c)$.

fixed cost in the case where the resource is moderately abundant, the monopolist can ignore recycling and its best strategy is to behave as if there were no threat of entry.

We finally compare the monopolist's optimal behavior to the first-best outcome. Table 1 summarizes the findings within QF stated in Propositions 2 and 4.

Table 1	**First-best outcome versus Monopolist's outcome**
Scarce resource	$a - c < s < \frac{3}{2}(a - c)$
First-best choice	$s \leq a$
	accommodate recycling with $q_e^a = s$ for all $F \leq F_s$
	promote recycling with $\widetilde{q}$ for all $F \in (F_s, F_i)$
	ignore recycling with q_0^e for all $F \in [F_i, \overline{F}]$
	$s \geq a$
	accommodate recycling with $q_e^a = a$ for all $F \leq F_a$
	promote recycling with $\widetilde{q}$ for all $F \in (F_a, F_i)$
	ignore recycling with q_0^e for all $F \in [F_i, \overline{F}]$
Monopolist's choice	accommodate recycling with $q_m^a = \frac{a-c}{2}$ for all $F < F_a^m$
	deter recycling with $\widetilde{q}$ for all $F \in [F_a^m, F_i^m)$
	ignore recycling with q_0^m for all $F \in \left[F_i^m, \overline{F}\right]$
Moderately abundant resource	$\frac{3}{2}(a - c) \leq s \leq 2(a - c)$
First-best choice	$s \leq a$
	accommodate recycling with $q_e^a = s$ for all $F \leq F_s$
	promote recycling with $\widetilde{q}$ for all $F \in (F_s, F_i)$
	ignore recycling with q_0^e for all $F \in [F_i, \overline{F}]$
	$s \geq a$
	accommodate recycling with $q_e^a = a$ for all $F \leq F_a$
	promote recycling with $\widetilde{q}$ for all $F \in (F_a, F_i)$
	ignore recycling with q_0^e for all $F \in [F_i, \overline{F}]$
Monopolist's choice	deter recycling with $\widetilde{q}$ for all $F < F_i^m$
	ignore recycling with q_0^m for all $F \in [F_i^m, \overline{F}]$
Abundant resource	$2(a - c) < s \leq 2a$
First-best choice	ignore recycling with q_0^e
Monopolist's choice	deter recycling with $\widetilde{q}$

Observe first that neither the social planner, nor the monopolist in the extraction sector allows recycling when the resource is abundant ($s > 2(a - c)$). In that case, the first-best requires to ignore recycling: the extraction sector can set prior extraction at the same level as that prevailing with no possibility of recycling. For its part, the monopolist cannot ignore recycling because in doing so, the market would be attractive enough to the recycling company. To counter what is seen as a threat, the monopolist overextracts the resource, which exerts a downward pressure on the second-period price and finally makes the market unattractive for recycling.

When the resource is less abundant ($s \leq 2(a-c)$), the first-best requires the extraction sector to let the recycling company enter the market, provided that the fixed cost of recycling is sufficiently low ($F < F_i$). The invitation to recycle can take the form of an accommodation to recycling if a low fixed cost ($F < F_i$) makes the market attractive enough to the recycling company. Otherwise, for intermediate values of the fixed cost ($F_s < F < F_i$ or $F_a < F < F_i$), the extraction sector must reduce prior extraction to make the invitation credible: recycling is then promoted. In contrast, the monopolist deters or ignores recycling when the resource is moderately abundant ($\frac{3}{2}(a-c) \leq s \leq 2(a-c)$). The monopolist also deters or ignores recycling when the resource is scarce ($s < \frac{3}{2}(a-c)$) for all values of the fixed cost inside $[F_a^m, F_s]$ or $[F_a^m, F_a]$ that allow recycling in the first-best outcome. The monopolist actually accommodates recycling only if the entry of the recycling company is an irrevocable fact, which happens when the resource is sufficiently scarce ($s < \frac{3}{2}(a-c)$) and the fixed cost sufficiently low ($F < F_a^m$). Although recycling is socially desirable in that case, the monopolist underextracts the resource relative to the first-best extraction to soften further competition with the recycling company.

6 Conclusion

In this paper, we have examined the best extraction strategies for an exhaustible resource that is recycled by an independent competitive company. For this, we have determined the equilibria of a two-period entry model in which an extraction sector chooses its best strategy bearing in mind the reaction of the recycling company.

Our findings allow for the comparison of the first-best solution and the monopolist-extractor's outcome. As the extraction sector creates its own competition whenever recycling proves feasible, the extraction choice prior to recycling is of great strategic importance. Unlike a social planner, the monopolist views recycling as a threat rather than an opportunity.

We find that, depending on the underlying parameters, the monopolist implements three kinds of equilibrium strategies in the face of recycling: the monopolist ignores, deters or accommodates recycling for decreasing values of the recycling fixed costs and increased scarcity of the virgin resource. Recycling deterrence departs from the strategy of ignoring recycling in that the monopolist increases prior extraction with the aim of pushing the future price of the resource down enough to make the market unattractive to potential recyclers. The monopolist may ignore or deter recycling under circumstances where, given the resource scarcity and the fixed costs magnitudes, the first-best requires to accommodate or promote recycling. When the resource is significantly scarce, it may happen that the monopolist accommodates recycling. This strategy implies extracting little to soften future competition against recycling, while, on the contrary, the first best requires to increase prior extraction when the recycling company is present.

The one-shot model with sequential moves takes only a limited account of the dynamics inherent in the problem of recycling an exhaustible resource. An improved treatment would be to switch to an infinite-horizon model from the two-period model. One possible approach for this involves the framework of a differential game that would provide a comparison between the cooperative solution and nondegenerate Markovian Stackelberg equilibria.

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