Horizontal agreements about the use of a natural resource

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Abstract: This paper studies sustainability agreements between competitors about their use of a natural resource. A symmetric Cournot duopoly model reveals the main effects. Two types of agreements are considered, specifying (1) the absolute usage of the natural resource per firm and (2) the relative usage of the natural resource, per unit of production. Whenever an agreement induces substitution towards other resources, production quantities decline. An agreement about the relative usage of the natural resource is ineffective unless returns to scale are decreasing. I argue that returns to scale are decreasing particularly in the short run after an agreement is made.

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1. Introduction

The transition towards more sustainable production practices, which better protect the environment and conserve natural resources, is widely being recognized as a critical and pressing challenge. Governments can use regulation and public investments to drive this transition. Furthermore, a recent debate asks whether competition policy can be instrumental to facilitate sustainability initiatives by corporations (OECD, 2020).[1] Agreements between horizontal competitors are particularly contentious. The European Commission (2021, 2022) is currently revising its guidelines on horizontal cooperation agreements and proposes a new chapter on sustainability agreements. Agreements need to be indispensable for their claimed benefits and the European Commission adopts a consumer welfare standard. Furthermore, competition should be preserved in respect of a substantial part of the products in question. Sustainability agreements between producers in the food industry are exempted from Article 101 TFEU but do need to satisfy indispensability. Several competition authorities worldwide, for example in Australia and South Africa, also incorporate sustainability considerations in their assessments.[2]

In this paper, I consider a symmetric Cournot duopoly where each firm's production depends on the combination of two inputs, a natural resource (e.g. water or raw materials) and a basket of other resources (e.g. a combination of reproducible capital and labour), according to a Cobb-Douglas production technology. Within this framework, the effects of permitting firms to horizontally coordinate their usage of the natural resource are analyzed. Two types of

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[1] Corporations are key actors in the green transition. For example, the transport sector and the industry sector represented 29% and 26% of the final consumption of energy in the EU in 2021, respectively, whereas households represented 28% (Eurostat, 2023).

[2] Holmes et al. (2021) offer a collection of perspectives.

usage targets are considered. First, I analyze the effects of permitting firms to jointly determine the absolute usage of the natural resource per firm. Second, I investigate what happens when firms jointly set a relative usage target, which formulates a usage intensity per unit of production. An agreement about the relative usage of the natural resource has the feature that firms can expand their absolute usage of the natural resource in proportion with their production quantity.

Both ways of measuring the usage of natural resources are relevant in practice. As an example, the European Plastics Pact, which is signed by major companies as well as governments, specifies an *absolute* target to reduce by 10% the usage of "virgin plastics" which are newly made from raw materials (Waste and Resources Action Programme, 2020, p.5). Also, goals to reduce greenhouse gas (GHG) emissions[3] are sometimes specified in absolute terms. To take one example, the furniture company IKEA reports the overall goal "by 2030, to reduce the absolute GHG emissions from the IKEA value chain by at least 15% compared to 2016" (IKEA, 2020, p.29). In the electronics sector, Apple's environmental progress report documents various indicators of its operations such as natural gas usage, emissions, amount of hazardous waste, and paper usage, all measured in absolute numbers (Apple, 2021, p.89). In contrast, a target to reduce *relative* emissions can be found in the Global Cement and Concrete Association (2021, p.4), which outlines a "proportionate reduction in CO2 emissions of 25% associated with concrete by 2030", where proportionate is defined as relating to per unit of product. As another example, the giant brewing company Anheuser-Busch InBev operates with a water use efficiency target of 2.5 hectoliter per hectoliter of production (AB Inbev et al., 2022, p.17). The purpose of this paper is to ask what happens when firms are permitted to enforce such targets by means of a horizontal agreement: would the usage of the natural

[3] We can view emissions (clean air) as an input in the production function (see, for example, Holland, 2012).

resource be any lower than under cost-minimization? And what are the effects on the production quantities?

A crucial question is whether there is an initial impetus to reduce the usage (absolute or relative) below the level which prevails under cost-minimization. A small reduction does not affect the *average* production cost, because the first-order condition for cost-minimization applies. However, the reduction can potentially raise the *marginal* cost of production. Any increase in marginal costs is desirable from the perspective of the firms because it induces them to produce lower quantities.[4]

Reducing the *absolute usage* of the natural resource decreases the marginal product of the basket of other resources, thereby raising the marginal cost of production. Consequently, there is a joint incentive to reduce the absolute usage of the natural resource below the level which prevails under cost-minimization. Doing so induces firms to substitute towards other resources, which are not the subject of the horizontal agreement. However, the production quantities are lower in comparison with the regime of cost-minimization. This effect harms consumers.

In contrast, the effectiveness of a horizontal agreement about the *relative usage* of the natural resource (per unit of production) depends on the production technology. When the production technology is characterized by constant returns to scale, the marginal cost function coincides with the average cost function. In this case, firms can only raise marginal costs while inducing an equivalent increase in average costs. Doing so is not profitable: firms jointly select the relative usage which prevails under cost-minimization.

However, in situations where the agreement comes into force quickly (such that firms do not have time to adjust every of their inputs), the production technology is likely to be

[4] The mechanism is related to Salop and Scheffman (1983) who analyze the incentive to raise rivals' costs as a predatory strategy from the perspective of a dominant firm.

characterized by decreasing returns to scale. In this case, the relative usage which minimizes average costs is too low from the perspective of minimizing marginal costs, because the marginal unit requires more resources to produce. A small reduction of the relative usage—below the level which prevails under cost-minimization—increases marginal costs and decreases the production quantities. Permitting the horizontal agreement is effective in the sense that it induces firms to substitute towards other resources. However it reduces the production quantities.

Taken together, the results outline the effects of horizontal agreements about the usage of a natural resource, which can differ along two dimensions. A distinction is made between agreements specifying an absolute and a relative usage of the natural resource. Furthermore, the presence of decreasing returns to scale (as opposed to constant returns to scale) is necessary for an agreement about the relative usage of the natural resource to be effective. A practical takeaway for competition authorities is therefore to be particularly sceptical towards agreements that specify a relative usage target and enter into force with many years of delay. Otherwise we can expect agreements about the usage of a natural resource to be effective, in the sense of inducing firms to substitute towards other resources, but to reduce the production quantities at the same time.

1.1 Related literature

The related literature on sustainability agreements has predominantly focused on demand-side spillovers. Schinkel and Spiegel (2017) and the subsequent studies Schinkel and Treuren (2021) and Schinkel et al. (2022) view sustainability as a dimension of quality. They consider models where firms can invest in sustainability to raise the willingness to pay of consumers. A higher investment makes a firm more aggressive in the product market.

Horizontal coordination with respect to investments in sustainability induces firms to consider the negative effect of investing on each other's profit. In such a context, investments in sustainability are found to decrease whenever spillovers are unlikely. This result closely resonates with the literature on R&D cooperation (d'Aspremont and Jacquemin, 1988). Castroviejo et al. (2021) discuss further the role of spillovers in the context of green agreements.

Inderst et al. (2022) investigate a different model where consumers have norm-based preferences. The utility function of consumers depends on the expected market share of the sustainable product variant. Firms can have an incentive to coordinate on the sustainable product variant whenever doing so enables them to sufficiently expand their aggregate market share. If this condition is not satisfied, firms can have an incentive to coordinate on the non-sustainable product variant. In recent work, Inderst (2023) analyzes preferences for sustainability on behalf of the firms which go beyond a pure profit motive. He shows that an agreement can increase sustainability, in particular when firms care about the sustainability choice of their rival.

Hirose, Lee and Matsumura (2020) analyze the adoption of emission cap commitments and emission intensity commitments by an industry association. Their model focuses specifically on end-of-pipe abatement of emissions, whereby the abatement technology has the feature that it reduces emissions without any effect on output. In contrast, I investigate the incentives for firms to make changes to their mix of inputs used for production.[5]

A few studies analyze circumstances where self-regulation is motivated by the strategic purpose to pre-empt government regulation (Maxwell et al., 2000; Dawson and Segerson, 2008). An aspect highlighted by Dawson and Segerson (2008) is the incentive of individual

[5] The reliance on inputs such as energy and raw materials is of primary importance for a company's environmental footprint.

firms to participate in a voluntary agreement. In this respect, my analysis requires the horizontal agreement to be enforced, which can happen for example through a monitoring system.

Even though production agreements are illegal in many countries, several studies have reported circumstances where it can yield an environmental benefit. Buchanan (1969) discusses the role of market structure when output generates a negative externality. He points out that there can be a welfare benefit from monopolization and discusses the effects of a tax.[6] Ahmed and Segerson (2011) develop a model with a brown and green product variety. Their analysis shows a joint incentive for firms to directly restrict their quantities offered of the brown product. Colombo and Labrecciosa (2018) focus on renewable resources and show how cooperation can mitigate the tragedy of the commons. Schinkel and Spiegel (2017), in their framework where sustainability is a dimension of quality, find that a production agreement (semi-collusion in the product market) can enhance sustainability investments.

An extensive literature investigates optimal environmental regulation on behalf of the government instead of the firms themselves. The comparison between various regulatory instruments has been studied by, for example, Spulber (1985), Helfand (1991), Holland (2012) and Hirose and Matsumura (2020). An important insight from this literature is that performance standards which are measured per unit of production tend to lead to higher production quantities and perhaps higher welfare in comparison with absolute standards. However, this literature operates from the perspective of a policymaker; it does not ask whether producers would be willing to implement any restrictive standard in the first place. On this front, only a few studies consider whether environmental regulation can be profitable for firms (Maloney and McCormick, 1982; Akhundjanov and Muñoz-García, 2019; Vehviläinen, 2022). Here

[6] Resource cartels are typically analyzed in dynamic frameworks (for example Berthod and Benchekroun, 2019). In some contexts the participants in the cartel are countries instead of firms.

Maloney and McCormick (1982) is closest by describing theoretical conditions under which an environmental regulation can enhance the value of firms, in a model of perfect competition. A general condition for this to happen is that the marginal cost curves are more responsive to the regulation than the average cost curves. However no systematic comparison is offered between different regulatory instruments.

Section 2 describes the model. The subsequent sections 3 to 6 perform the analysis. Concluding comments are offered in section 7.

2. The model

A symmetric duopoly model is presented to illustrate the main economic forces. The production quantity of firm i (whereby $i \in \{1,2\}$ and $j \neq i$) equals x_i. Products are homogenous in the eyes of consumers. The market-clearing price $P(X)$ is a function of the total production in the industry $X = x_1 + x_2$.

Assumption 1: The inverse demand curve is linear: $P'(X) < 0$ and $P''(X) = 0$.

Let A represent a productivity parameter, n_i denote firm i's usage of the natural resource[7], and let b_i denote its usage of a basket of other resources. The prices of the natural resource and the basket of other resources are denoted as p^n and p^b, respectively.[8]

[7] For example, natural resources such as water or raw materials can be directly used as inputs in the production process. However, the model can also capture other inputs such as plastics, energy, or even CO2 emissions, which are indirectly derived from natural resources.

[8] These market prices are exogenous. This means that firms do not enjoy buyer power in the market for the natural resource. Limiting the usage of the natural resource does not induce a reduction in its market price.

Assumption 2: Cobb-Douglas production function: $x_i = A n_i^{\alpha} b_i^{\beta}$, where $A > 0$, $0 < \alpha < 1$, $0 < \beta < 1$, and $\alpha + \beta \leq 1$.

The productivity parameter A is assumed to be sufficiently high relative to $P(0)$ to make producing profitable. The production technology is characterized by constant returns to scale (CRS) when $\alpha + \beta = 1$ and decreasing returns to scale (DRS) when $\alpha + \beta < 1$.[9]

Some agreements may specify a usage reduction which should be attained only in the long run—after an adjustment period of several years. Agreements of this type enable for firms to make substantial modifications to their input mix before they come into effect. In this case a reasonable presumption is that the production technology is characterized by CRS.

In contrast, other agreements may specify a usage reduction that enters into force quickly. Agreements of this type do not facilitate for firms to adjust their entire input mix before coming into effect. Some production factors, such as certain types of capital stock of the firms, are essentially fixed in the short run. The fixed production factors are captured in the model through the exogenous productivity parameter A, whereas the basket of other resources only represents variable production factors. In the presence of some production factors being fixed, it is plausible to presume that there are diminishing returns to the variable production factors.

Let R reflect the regime, such that $\mathrm{R} = cm$ represents cost-minimization, $\mathrm{R} = abs$ reflects an agreement about the absolute usage of the natural resource per firm, and $\mathrm{R} = rel$ reflects an agreement about the relative usage of the natural resource. An agreement about the absolute usage of the natural resource per firm sets $\gamma \equiv n_i \equiv n_j$. An agreement about the relative usage of the natural resource fixes the usage per unit of production: $\gamma \equiv n_i / x_i \equiv n_j / x_j$. I focus

[9] Increasing returns to scale (IRS) are ruled out as it leads to profit functions which may not satisfy concavity. Subsection 7.2 offers a discussion.

on symmetric agreements as they can be implemented without a side payment.[10] In each of the three regimes, production decisions are taken non-cooperatively. Table 1 summarizes the distinct regimes.

[Table 1 is supplied after the reference list and should be inserted here]

Remark 1 (Lack of internalization). According to Assumption 1, the willingness to pay of consumers does not depend on the combination of inputs which is used to make the product. This means that, if there is a negative externality associated with the usage of the natural resource, it is not understood or internalized by consumers.[11]

Remark 2 (The need for enforcement). An agreement cannot induce firms to move away from cost-minimization unless it is enforced. Enforcement could happen for example through a monitoring system.[12]

Remark 3 (Non-drastic reductions in usage of the natural resource). The framework takes as given the Cobb-Douglas production technology. A positive usage of the natural resource is required for firms to produce. The framework is not designed to analyze an agreement to completely abandon the use of the natural resource (a target of zero usage).

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[10] An asymmetric agreement which prohibits one of the firms from using the natural resource makes the other firm a monopolist. Such an asymmetric agreement would require the monopolist to make a side payment to its potential rival.

[11] I refer to Schinkel and Spiegel (2017) for an analysis when investments in sustainability raise the willingness to pay of consumers.

[12] For example, in its Draft Guidelines, the European Commission (2022) reports, as one of the conditions for a sustainability standardization agreement to fall outside Article 101(1), that “there should be a mechanism or a monitoring system in place to ensure that undertakings that adopt the sustainability standard indeed comply with the requirements of the standard.”

The next section establishes a few general properties associated with the production equilibrium.

3. The production equilibrium

Denote the revenue function of firm i as $R_i\left(x_i, x_j\right) \equiv P\left(X\right) x_i$. The production cost function of firm i can in general be written as $C_i^{\mathrm{R}}\left(x_i, \gamma\right)$ where R represents the regime and γ reflects the usage which was agreed in the regimes $\mathrm{R} \in \left\{abs, rel\right\}$. In the present section the parameter γ is treated as a general cost-parameter. Under cost-minimization ($\mathrm{R} = cm$), the parameter has no relevance ($\partial C_i^{cm} / \partial \gamma = 0$).[13]

The profit function of firm i equals

$$R_i\left(x_i, x_j\right) - C_i^{\mathrm{R}}\left(x_i, \gamma\right). \tag{1}$$

In the production equilibrium, the production quantities must satisfy the first-order conditions for optimization:

$$\frac{\partial R_i}{\partial x_i} - \frac{\partial C_i^{\mathrm{R}}}{\partial x_i} = 0 \quad \text{for } i = 1, 2 \,. \tag{2}$$

The first-order conditions require that the marginal revenue generated by an extra unit of production for a firm equals the associated increase in production cost.

The following properties are shown in the Appendix.

[13] For example, the parameter γ can be thought of as a joint target of usage which is not adhered to (because a formal contract is lacking).

Lemma 1. Assume that $\frac{\partial^2 C_i^{\mathrm{R}}}{\partial x_i^{\,2}} \geq 0$. There exists a production equilibrium $\left(x_i^*, x_j^*\right)$ which is symmetric, unique, and stable.

Lemma 2. Assume that $\frac{\partial^2 C_i^{\mathrm{R}}}{\partial x_i^{\,2}} \geq 0$. The effect of γ on the production quantity per firm equals

$$\frac{dx_i^*}{d\gamma} = \underbrace{\left(\frac{\partial^2 R_i}{\partial x_i^{\,2}} - \frac{\partial^2 C_i^{\mathrm{R}}}{\partial x_i^{\,2}} + \frac{\partial^2 R_i}{\partial x_i \partial x_j} \right)^{-1}}_{(-)} \frac{\partial^2 C_i^{\mathrm{R}}}{\partial x_i \partial \gamma} \text{ for } i = 1, 2. \tag{3}$$

The first term in (3) is negative because of Assumption 1 and the property that $\frac{\partial^2 C_i^{\mathrm{R}}}{\partial x_i^{\,2}} \geq 0$. The effect of γ on the production quantities happens through the effect on marginal costs. An induced reduction of the marginal costs ($\frac{\partial^2 C_i^{\mathrm{R}}}{\partial x_i \partial \gamma} < 0$) leads to an increase in the production quantities ($\frac{dx_i^*}{d\gamma} > 0$). Conversely, an induced increase in the marginal costs ($\frac{\partial^2 C_i^{\mathrm{R}}}{\partial x_i \partial \gamma} > 0$) leads to a decrease in the production quantities ($\frac{dx_i^*}{d\gamma} < 0$).

Lemma 3. Assume that $\frac{\partial^2 C_i^{\mathrm{R}}}{\partial x_i^{\,2}} \geq 0$. The effect of γ on the profit per firm equals

$$\frac{d\left(R_i - C_i^{\mathrm{R}}\right)}{d\gamma} = -\frac{\partial C_i^{\mathrm{R}}}{\partial \gamma} + \underbrace{\frac{\partial R_i}{\partial x_j}}_{(-)} \frac{dx_j^*}{d\gamma} \text{ for } i = 1, 2. \tag{4}$$

The first term in (4) denotes the direct effect of γ on firm i's production cost. The second term denotes the indirect effect on firm i's revenues which happens through the effect on firm j's production quantity. Since $\frac{\partial R_i}{\partial x_j} < 0$, firm i suffers (benefits) from an expansion (reduction) of j's production quantity.

The property that $\frac{\partial^2 C_i^{\mathrm{R}}}{\partial x_i^{\,2}} \geq 0$, which has formed the basis of Lemmas 1 – 3, will be shown to hold true in each of the three regimes, in their respective sections.

4. Cost-minimization

Irrespective of the regime we can state that, given n_i, the usage of the basket of other resources required to produce x_i equals

$$b_i = A^{\frac{-1}{\beta}} n_i^{\frac{-\alpha}{\beta}} x_i^{\frac{1}{\beta}} . \tag{5}$$

The total cost of producing x_i therefore equals

$$p^n n_i + p^b \underbrace{A^{\frac{-1}{\beta}} n_i^{\frac{-\alpha}{\beta}} x_i^{\frac{1}{\beta}}}_{b_i} . \tag{6}$$

The first-order condition for cost-minimization with respect to n_i equals

$$p^n + p^b A^{\frac{-1}{\beta}} \frac{-\alpha}{\beta} n_i^{\frac{-\alpha-\beta}{\beta}} x_i^{\frac{1}{\beta}} = 0 \tag{7}$$

or equivalently

$$n_i = A^{\frac{-1}{\alpha+\beta}} \left(\frac{\alpha / p^n}{\beta / p^b} \right)^{\frac{\beta}{\alpha+\beta}} x_i^{\frac{1}{\alpha+\beta}} . \tag{8}$$

Substituting (8) into (6), the production cost function under cost-minimization equals

$$C_i^{cm} = \underbrace{p^n A^{\frac{-1}{\alpha+\beta}} \left(\frac{\alpha/p^n}{\beta/p^b} \right)^{\frac{\beta}{\alpha+\beta}} x_i^{\frac{1}{\alpha+\beta}}}_{\text{expenditures on the natural resource}} + \underbrace{p^b A^{\frac{-1}{\beta}} \left[A^{\frac{-1}{\alpha+\beta}} \left(\frac{\alpha/p^n}{\beta/p^b} \right)^{\frac{\beta}{\alpha+\beta}} x_i^{\frac{1}{\alpha+\beta}} \right]^{\frac{-\alpha}{\beta}} x_i^{\frac{1}{\beta}}}_{\text{expenditures on the basket of other resources}} . \tag{9}$$

The first term in (9) represents the expenditures on the natural resource and the second term represents the expenditures on the basket of other resources, when n_i is chosen such that x_i is produced at the lowest possible cost.

The production cost function is convex ($\frac{\partial^2 C_i^{cm}}{\partial x_i^2} \geq 0$) because the exponents of x_i in the first and second term in (9) are greater than 1. In particular, it holds that $\frac{1}{\alpha+\beta} \geq 1$, because $\alpha+\beta \leq 1$. Furthermore, the condition $\frac{1}{\alpha+\beta}\frac{-\alpha}{\beta}+\frac{1}{\beta} \geq 1$ can be verified as well, because it is equivalent to $\frac{-\alpha}{\alpha+\beta}+1 \geq \beta$ or $\frac{\beta}{\alpha+\beta} \geq \beta$ which holds because $\alpha+\beta \leq 1$. By Lemma 1, there exists a production equilibrium which is symmetric, unique, and stable. The symmetric production quantities subsequently determine a unique usage of the natural resource per firm (through (8)).

The model can be viewed as a standard Cournot model with convex costs. However, the twist is that the cost function is not exogenous, but results from a Cobb-Douglas production technology where firms select their use of the natural resource to minimize costs. The following result is proven in the Appendix.

Proposition 1. Consider the regime of cost-minimization. There exists a production equilibrium which is symmetric, unique, and stable. It induces firms to produce quantities which are too high from the perspective of joint profit-maximization. Any further expansion of the symmetric production quantities would reduce the joint profit of the firms.

Proposition 1 is unsurprising. In the production equilibrium, firms do not take into account the effect of their own production decision on the profit of the rival firm. Consequently, production quantities are too high from the joint perspective. Any further expansion of the production quantities would harm the joint profit. An agreement about the use of a natural resource may or may not preserve the property of cost-minimization. The following Corollary can be stated.

Corollary 1. Firms never sign an agreement that leads to an increase in the symmetric production quantity.

Any profitable agreement about the use of a natural resource is prone to reduce the production quantities, thereby harming consumers.

5. Agreement about the absolute usage of the natural resource

An agreement about the absolute usage of the natural resource per firm sets $\gamma \equiv n_i \equiv n_j$. The total cost of producing x_i, taking as given γ, is obtained by substituting $\gamma \equiv n_i$ in (6) such that

$$C_i^{abs}\left(x_i,\gamma\right) = p^n\gamma + p^b A^{\frac{-1}{\beta}}\gamma^{\frac{-\alpha}{\beta}} x_i^{\frac{1}{\beta}}. \tag{10}$$

The marginal cost of production equals

$$\frac{\partial C_i^{abs}}{\partial x_i} = p^b A^{\frac{-1}{\beta}}\gamma^{\frac{-\alpha}{\beta}} \frac{1}{\beta} x_i^{\frac{1-\beta}{\beta}}. \tag{11}$$

The cost of production is convex ($\frac{\partial^2 C_i^{abs}}{\partial x_i^{\,2}} > 0$) because, when the usage of the natural resource is fixed, there are diminishing returns to the basket of other resources ($\beta < 1$ by Assumption 2).[14] Consequently, Lemmas 1 – 3 apply.

The agreement aims to maximize the joint profit of the firms. Since the agreement is symmetric and the profit per firm is identical (by Lemma 1), the agreement essentially aims to maximize firm i's profit. The associated necessary[15] first-order condition can be expressed by combining (3) and (4) using symmetry as follows

$$-\frac{\partial C_i^{abs}}{\partial \gamma} \quad + \quad \underbrace{\frac{\partial R_i}{\partial x_j}\left(\frac{\partial^2 R_i}{\partial x_i^{\,2}} - \frac{\partial^2 C_i^{abs}}{\partial x_i^{\,2}} + \frac{\partial^2 R_i}{\partial x_i \partial x_j}\right)^{-1}}_{(+)} \frac{\partial^2 C_i^{abs}}{\partial x_i \partial \gamma} \quad = \quad 0\,. \tag{12}$$

We can observe from (11) that

$$\frac{\partial^2 C_i^{abs}}{\partial x_i \partial \gamma} = p^b A^{\frac{-1}{\beta}} \frac{-\alpha}{\beta} \gamma^{\frac{-\alpha-\beta}{\beta}} \frac{1}{\beta} x_i^{\frac{1-\beta}{\beta}} < 0\,. \tag{13}$$

Fixing the absolute usage of the natural resource at a higher level lowers the marginal cost of production (by raising the productivity of the basket of other resources). In combination with (3), we can conclude that agreeing on a higher absolute usage of the natural resource per firm induces an expansion of the production quantities. Conversely, firms can achieve a reduction of their production quantities by selecting a lower absolute usage of the natural resource.

It is insightful to evaluate the effect of γ on the profit per firm, given by (12), when initially the condition for cost-minimization ($\frac{\partial C_i^{abs}}{\partial \gamma} = 0$) is satisfied. A slight reduction in

[14] The intuition behind the property of diminishing returns is that, when a firm increases its use of the basket of other resources, each unit of the basket of other resources can be combined with a smaller amount of the natural resource.

[15] The jointly optimal usage is interior because a usage equal to zero would result in zero profits.

absolute usage does not affect the production cost, as the usage satisfies the first-order condition for cost-minimization. But it raises the marginal cost and hence reduces the production quantities. This means that there is an initial impetus to reduce the absolute usage below the level associated with cost-minimization.

Figure 1 illustrates the effect of the absolute use of the natural resource on the average and marginal production cost in a numerical example. The production technology in the numerical example is characterized by CRS. The usage level which minimizes the average production cost equals $n_i = 10$. A small reduction in usage has a negligible effect on the average production cost (because the initial usage satisfies the first-order condition for cost-minimization) but raises the marginal cost of production. An increase in the marginal cost of production is beneficial from a joint perspective as it leads to a reduction of the production quantities.

[Figure 1 is supplied after the reference list and should be inserted here]

Formally, since $\frac{\partial^2 C_i^{abs}}{\partial x_i \partial \gamma} < 0$ as was shown in (13), the first-order condition for joint optimality with respect to γ (given by (12)) requires that $\frac{\partial C_i^{abs}}{\partial \gamma} < 0$. Furthermore, it is possible to verify using (10) that $\frac{\partial^2 C_i^{abs}}{\partial \gamma^2} > 0$. We can conclude that firms select an absolute usage of the natural resource which falls short from the perspective of cost-minimization. The basket of other resources (which is not the subject of the horizontal agreement) ends up being used more extensively in the production process.

The following result can be stated.

Proposition 2. Let γ represent the absolute usage of the natural resource per firm. An agreement about γ induces firms to:

a) under-utilize the natural resource from the perspective of cost-minimization, such that $\frac{\partial C_i^{abs}}{\partial \gamma} < 0$.

b) produce lower quantities, in comparison with the production equilibrium under cost-minimization.

Part b) of Proposition 2 rests on Corollary 1 which states that it is never profitable for firms to sign an agreement that induces production quantities to expand. Since an agreement about the absolute use of the natural resource breaks the property of cost-minimization (Part a) of Proposition 2), the agreement can only be profitable through a strict reduction of the production quantities.

6. Agreement about the relative usage of the natural resource

An agreement about the relative usage of the natural resource sets $\gamma \equiv n_i / x_i \equiv n_j / x_j$. The total cost of producing x_i, taking as given γ, is obtained by substituting $\gamma \equiv n_i / x_i$ in (6) such that

$$C_i^{rel} = p^n \gamma x_i + p^b A^{\frac{-1}{\beta}} \gamma^{\frac{-\alpha}{\beta}} x_i^{\frac{1-\alpha}{\beta}} . \tag{14}$$

The marginal cost of production equals

$$\frac{\partial C_i^{rel}}{\partial x_i} = p^n \gamma + p^b A^{\frac{-1}{\beta}} \gamma^{\frac{-\alpha}{\beta}} \frac{1-\alpha}{\beta} x_i^{\frac{1-\alpha-\beta}{\beta}} . \tag{15}$$

We can verify, using Assumption 2, that the production cost function is convex ($\frac{\partial^2 C_i^{rel}}{\partial {x_i}^2} \geq 0$). Consequently, Lemmas 1 – 3 apply.

The condition for the agreement to be jointly optimal can be expressed by combining (3) and (4) and using symmetry, as follows:

$$-\frac{\partial C_i^{rel}}{\partial \gamma} + \underbrace{\frac{\partial R_i}{\partial x_j}\left(\frac{\partial^2 R_i}{\partial {x_i}^2} - \frac{\partial^2 C_i^{rel}}{\partial {x_i}^2} + \frac{\partial^2 R_i}{\partial x_i \partial x_j}\right)^{-1}}_{(+)} \frac{\partial^2 C_i^{rel}}{\partial x_i \partial \gamma} = 0\,. \tag{16}$$

From (14) we can observe that the effect of the relative usage γ on the production cost per firm equals

$$\frac{\partial C_i^{rel}}{\partial \gamma} = p^n x_i + p^b A^{\frac{-1}{\beta}} \frac{-\alpha}{\beta} \gamma^{\frac{-\alpha-\beta}{\beta}} x_i^{\frac{1-\alpha}{\beta}}\,. \tag{17}$$

Furthermore, the effect of the relative usage on the marginal cost equals

$$\frac{\partial^2 C_i^{rel}}{\partial x_i \partial \gamma} = p^n + p^b A^{\frac{-1}{\beta}} \frac{-\alpha}{\beta} \gamma^{\frac{-\alpha-\beta}{\beta}} \frac{1-\alpha}{\beta} x_i^{\frac{1-\alpha-\beta}{\beta}}\,. \tag{18}$$

6.1 Constant returns to scale

When the production technology is characterized by CRS ($\alpha + \beta = 1$), the average cost of production (obtained by dividing (14) by x_i) equals the marginal cost of production (given by (15)), or $\frac{C_i^{rel}}{x_i} = \frac{\partial C_i^{rel}}{\partial x_i}$. The next figure illustrates this property in the context of our numerical example.

[Figure 2 is supplied after the reference list and should be inserted here]

Figure 2 displays the effect of the relative usage of the natural resource on the average and marginal production cost in our numerical example. Since the production technology is characterized by CRS, the average and marginal cost curves coincide. Firms cannot induce an increase in the marginal cost without inducing an equivalent increase in the average cost.

Using the property of CRS ($\alpha + \beta = 1$), we can observe from (17) and (18) that

$$\frac{\partial C_i^{rel}}{\partial \gamma} = x_i \frac{\partial^2 C_i^{rel}}{\partial x_i \partial \gamma} . \tag{19}$$

The necessary first-order condition associated with the optimal agreement, given by (16), can thus be simplified (also making use of Assumption 1) as

$$-x_i \frac{\partial^2 C_i^{rel}}{\partial x_i \partial \gamma} + x_i \underbrace{P'\left(3P' - \frac{\partial^2 C_i^{rel}}{\partial x_i^2}\right)^{-1}}_{<1} \frac{\partial^2 C_i^{rel}}{\partial x_i \partial \gamma} = 0 . \tag{20}$$

In (20), the term $P'\left(3P' - \frac{\partial^2 C_i^{rel}}{\partial x_i^2}\right)^{-1}$ is strictly less than 1 because $P' < 0$ and $\frac{\partial^2 C_i^{rel}}{\partial x_i^2} = 0$. Consequently, the first-order condition for optimality with respect to γ can only be satisfied when $\frac{\partial^2 C_i^{rel}}{\partial x_i \partial \gamma} = 0$. By (19), this means that $\frac{\partial C_i^{rel}}{\partial \gamma} = 0$ (the first-order condition for cost-minimization holds). There is a unique relative usage which satisfies $\frac{\partial C_i^{rel}}{\partial \gamma} = 0$, given by $p^n + p^b A^{\frac{-1}{\beta}} \frac{-\alpha}{\beta} \gamma^{\frac{-1}{\beta}} = 0$, and it is the one that firms adopt under cost-minimization (which can be verified using (7) and $\alpha + \beta = 1$).

These observations facilitate for us to draw the following conclusion.

Proposition 3. Assume that the production technology is characterized by constant returns to scale. Let γ represent the usage of the natural resource per unit of production. An agreement about γ:

a) induces firms to cost-minimize ($\frac{\partial C_i^{rel}}{\partial \gamma} = 0$).

b) does not change the production quantities, in comparison with the production equilibrium under cost-minimization.

Firms produce the same quantities as under cost-minimization because their constant marginal cost of production is identical. Proposition 3 tells us that permitting an agreement about the relative usage of the natural resource in the presence of CRS is ineffective.

6.2 Decreasing returns to scale

Now consider a production technology characterized by DRS ($\alpha + \beta < 1$). Initially, I illustrate the average and marginal cost curves in the presence of DRS using a numerical example.

[Figure 3 is supplied after the reference list and should be inserted here]

Figure 3 illustrates the effect of the relative usage of the natural resource on the average and marginal production cost in a new numerical example. The new numerical example sets $\beta = 1/4$ to capture DRS and is otherwise identical to the numerical example which was employed earlier. We can observe from Figure 3 that the marginal cost curve is higher than the average cost curve, reflecting DRS. Furthermore, the relative usage which minimizes the average cost is lower than the relative usage which minimizes the marginal cost of production. This reflects that the marginal unit of production is more difficult to produce, which makes it cost-efficient to rely more on the natural resource. A small reduction in usage below the level under cost-minimization has a negligible effect on the average production cost (because the initial usage satisfies the first-order condition for cost-minimization). However, it raises the marginal cost of production. There is pressure to reduce the relative usage of the natural resource to induce an increase in the marginal cost of production and hence a reduction of the production quantities.

In the general model, the condition (16) can be written using Assumption 1 as

$$-\frac{\partial C_i^{rel}}{\partial \gamma} + x_i \underbrace{P'\left(3P' - \frac{\partial^2 C_i^{rel}}{\partial x_i^2}\right)^{-1}}_{<1} \frac{\partial^2 C_i^{rel}}{\partial x_i \partial \gamma} = 0, \tag{21}$$

where the term $P'\left(3P' - \frac{\partial^2 C_i^{rel}}{\partial x_i^2}\right)^{-1}$ is positive and strictly less than 1 because $P' < 0$ and $\frac{\partial^2 C_i^{rel}}{\partial x_i^2} > 0$. I want to show that $\frac{\partial C_i^{rel}}{\partial \gamma} < 0$. To establish a contradiction, suppose that $\frac{\partial C_i^{rel}}{\partial \gamma} \geq 0$. Consequently, the first-order condition (21) would require that

$$x_i \frac{\partial^2 C_i^{rel}}{\partial x_i \partial \gamma} > \frac{\partial C_i^{rel}}{\partial \gamma}. \tag{22}$$

Substituting (17) and (18) in (22), we would obtain

$$x_i \left(p^n + p^b A^{\frac{-1}{\beta}} \frac{-\alpha}{\beta} \gamma^{\frac{-\alpha-\beta}{\beta}} \frac{1-\alpha}{\beta} x_i^{\frac{1-\alpha-\beta}{\beta}} \right) > x_i \left(p^n + p^b A^{\frac{-1}{\beta}} \frac{-\alpha}{\beta} \gamma^{\frac{-\alpha-\beta}{\beta}} x_i^{\frac{1-\alpha-\beta}{\beta}} \right) \tag{23}$$

which is simplified as

$$\frac{1-\alpha}{\beta} < 1. \tag{24}$$

Condition (24) reflects increasing returns to scale and therefore contradicts Assumption 2. We can conclude that $\frac{\partial C_i^{rel}}{\partial \gamma} < 0$: firms under-utilize the natural resource from the perspective of cost-minimization. This means that firms substitute towards other resources (the flip side of the same coin).

Proposition 4. Assume that the production technology is characterized by decreasing returns to scale. Let γ represent the usage of the natural resource per unit of production. An agreement about γ induces firms to:

a) under-utilize the natural resource from the perspective of cost-minimization, such that $\frac{\partial C_i^{rel}}{\partial \gamma} < 0$.

b) produce lower quantities, in comparison with the production equilibrium under cost-minimization.

Part b) of Proposition 4 rests on Corollary 1, in a way which is analogous to Part b) of Proposition 2.

We can conclude from Propositions 2, 3 and 4 that, in the presence of DRS, the effects of an agreement about the absolute usage and the relative usage of the natural resource are qualitatively similar. However, the analysis predicts that an agreement about the relative usage of the natural resource is ineffective when the production technology is characterized by CRS.

7. Concluding comments

7.1 Summary of the results

The results of the analysis are summarized in Table 2. It classifies agreements along two dimensions. Firstly, agreements which specify an absolute usage of the natural resource per firm differ from agreements which specify a relative usage, per unit of production. Secondly, agreements which enter into force quickly—in which case returns to scale are likely decreasing—may warrant a different policy approach than agreements which enter into force slowly. Table 2 is constructed using Propositions 2, 3, and 4. Situations where firms under-utilize the natural resource from the perspective of cost-minimization are described with the phrasing "substitution towards other resources".

[Table 2 is supplied after the reference list and should be inserted here]

On a general level, the analysis indicates that there is a trade-off between environmental objectives and consumer welfare. Whenever an agreement is effective—in the sense that it induces firms to substitute towards other resources—production quantities decline.

Article 101(3) TFEU requires that agreements are indispensable for attaining their objectives and that they may not eliminate competition further than necessary. In this respect, the results of the analysis are supportive of a condition whereby any agreement about the relative usage of a natural resource must enter into force quickly and be limited in time.

A few empirical studies have found that collaboration between competitors on the dimension of R&D risks inducing collusion in the product market (Duso et al., 2014; Sovinsky, 2022). A similar effect could explain why firms would want to make an agreement about the relative use of the natural resource that enters into force slowly (such that returns to scale are constant).

7.2 Increasing returns to scale

The model did not incorporate the possibility of increasing returns to scale (IRS), to formally guarantee that the production equilibrium is symmetric. Nevertheless, we can intuitively reason that the production equilibrium is likely to continue to satisfy symmetry, as long as the property of IRS is “not too pronounced”. By assuming that symmetry holds, we can apply the existing analysis in the paper for the case of IRS ($\alpha + \beta > 1$). Firstly, consider an agreement about the absolute usage of the natural resource. We can observe using (12) and (13) that it would induce firms to substitute towards the basket of other resources and to reduce their production quantities, just as for CRS or DRS. Secondly, consider an agreement about the relative usage of the natural resource. Here the presence of IRS does impact the qualitative effects. In particular, the relative usage which minimizes average cost is higher than the relative usage which minimizes the marginal cost of production, because with IRS the marginal unit requires less resources to produce. This means that there is an initial impetus to raises the relative usage above the usage associated with cost-minimization. It is possible to operate with a formal analysis which is analogous to that in subsection 6.2 (in particular equations (21) – (24)), with the key difference that now $\alpha + \beta > 1$ which reverses the conclusion. So an agreement about the relative usage of the natural resource would induce firms to *over-utilize* the natural resource form the perspective of cost-minimization and reduce their production quantities.

7.3 Comparison with a production agreement

Proposition 1 facilitates for us to conclude that a production agreement reduces the production quantities. Through this channel, it reduces the usage of the natural resource.[16] However, a production agreement does not incentivize firms to move away from cost-minimization. Firms would use the amount of the natural resource which minimizes their production cost.

In contrast, a horizontal agreement which is specifically about the use of the natural resource can reduce the usage of the natural resource on two fronts (Table 2 describes the conditions for an agreement to be effective). Through a reduction of the production quantities, the cost-minimizing usage of the natural resource declines. However, firms use even less of the natural resource, because they also under-utilize the natural resource from the perspective of cost-minimization. This second channel through which the usage declines is not present when firms coordinate their production quantities. These observations are supportive of the current legal practice in many countries to prohibit output cartels.[17]

7.4 Agreements about the use of a sustainably sourced input

The natural resource is modelled as any other production factor. Consequently, the results apply identically to agreements about the use of a sustainably sourced input (hereafter:

[16] We can observe this formally by making use of expression (8).

[17] The Austrian Federal Competition Authority, which is one of the leaders in the debate on sustainability, explicitly prohibits hardcore restrictions such as pricing agreements or output agreements in its recent Sustainability Guidelines (2022).

SSI).[18] In particular, an agreement about the usage of a SSI (provided that the conditions for effectiveness outlined in Table 2 are satisfied) can decrease the production quantities and induce firms to under-utilize the SSI from the perspective of cost-minimization. In other words, an agreement about the usage of a SSI runs the risk of inducing substitution away from the SSI instead of towards it.

7.5 Consumer welfare standard

Any profitable horizontal agreement about the use of a natural resource decreases the production quantities, an effect which harms consumers. Nevertheless, there could be scope for consumer welfare to increase, if the usage of the natural resource exerts a sufficiently negative externality upon other consumers. The European Commission (2022, p.142-143) seems to be willing to take into account collective benefits that accrue to consumers in the relevant market. In this respect the model has assumed that consumers do not understand or consider the environmental impact when making purchasing decisions (for example because the effect of their individual purchase on the global usage of the natural resource is negligible).

7.6 Robustness

In my framework, the potential motivation for firms to agree to limit their use of the natural resource lies in their desire to reduce the production quantities. This insight is robust with respect to two features which can be added to the model. Firstly, firms may perceive an

[18] For example, the Netherlands Authority for Consumers and Markets (2021), in its revised draft guidelines on sustainability agreements, describes a hypothetical example whereby beverage companies agree about "using a certain weight percentage of recycled materials in the production of beverage packaging".

intrinsic cost per unit of their own usage of the natural resource.[19] The model parameter for the market price of the natural resource (p^n) can be interpreted to include such an intrinsic cost. The results of the analysis hold true as long as the intrinsic cost per unit of usage is the same with or without a horizontal agreement. Secondly, in a similar way, the parameter can also accommodate for an environmental tax per unit of usage of the natural resource. The analysis has essentially evaluated the effects of a horizontal agreement taking as given the potential presence of an environmental tax per unit.

7.7 Future research

A promising direction for future research would be to explore the role of asymmetric information. Two dimensions could be distinguished: asymmetric information among the firms and a potential informational disadvantage on behalf of the policymaker. In light of such an analysis it would be interesting to endogenize the type of agreement. Also it would be valuable to seek insights more broadly about how competition policy compares with alternative policy instruments such as a tax or regulatory cap related to the usage of the natural resource.

[19] In the terminology of Inderst (2023) such a preference for sustainability would be "narrow" in the sense that it relates to the firm's own sustainability choice.

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Regime	**Decision about the usage of the natural resource:**	**Production decisions**
Cost-minimization ($\mathrm{R} = cm$)	n_i minimizes firm i 's production cost	Non-cooperative
Agreement about the absolute usage of the natural resource per firm ($\mathrm{R} = abs$)	$\gamma \equiv n_i \equiv n_j$ maximizes joint profit	Non-cooperative
Agreement about the relative usage of the natural resource ($\mathrm{R} = rel$)	$\gamma \equiv n_i / x_i \equiv n_j / x_j$ maximizes joint profit	Non-cooperative

Table 1: The three regimes.

	Entry into force is quick (DRS)	**Entry into force is slow (CRS)**
Agreement about the absolute usage of the natural resource per firm	• Substitution towards other resources • Production quantities decline	• Substitution towards other resources • Production quantities decline
Agreement about the relative usage of the natural resource, per unit of production	• Substitution towards other resources • Production quantities decline	• No substitution towards other resources • Production quantities unaffected

Table 2: A summary of the results.

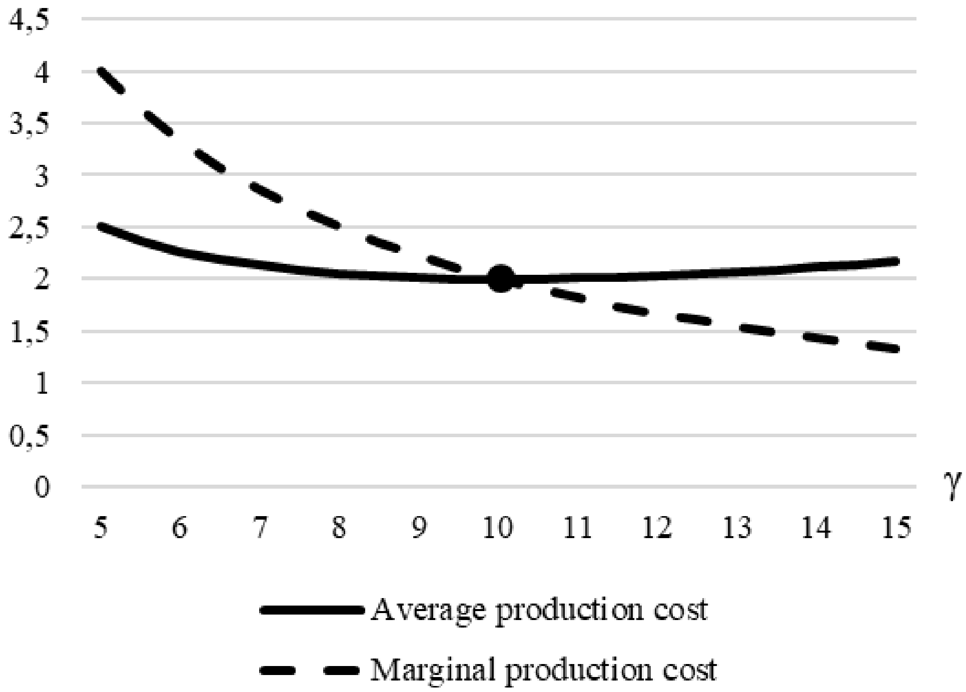

Figure 1: The effect of fixing the absolute usage of the natural resource on costs. The figure shows the effect of fixing the absolute usage of the natural resource per firm (γ) on the average and marginal production cost, in a numerical example. The numerical example sets the productivity parameter and input prices equal to $A = p^n = p^b = 1$, the output elasticities equal to $\alpha = \beta = 1/2$, and the production quantity equal to $x_i = 10$.

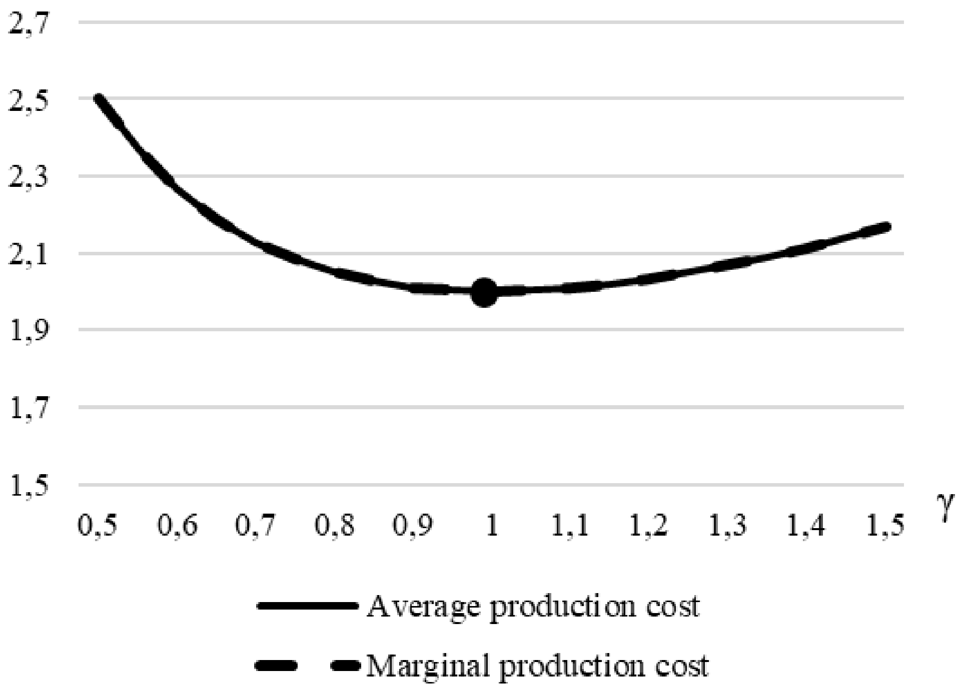

Figure 2: The effect of fixing the relative usage of the natural resource on costs, when returns to scale are constant. The figure shows the effect of fixing the relative usage of the natural resource (γ) on the average and marginal production cost, in a numerical example with constant returns to scale. The numerical example sets the productivity parameter and input prices equal to $A = p^n = p^b = 1$, the output elasticities equal to $\alpha = \beta = 1/2$, and the production quantity equal to $x_i = 10$.

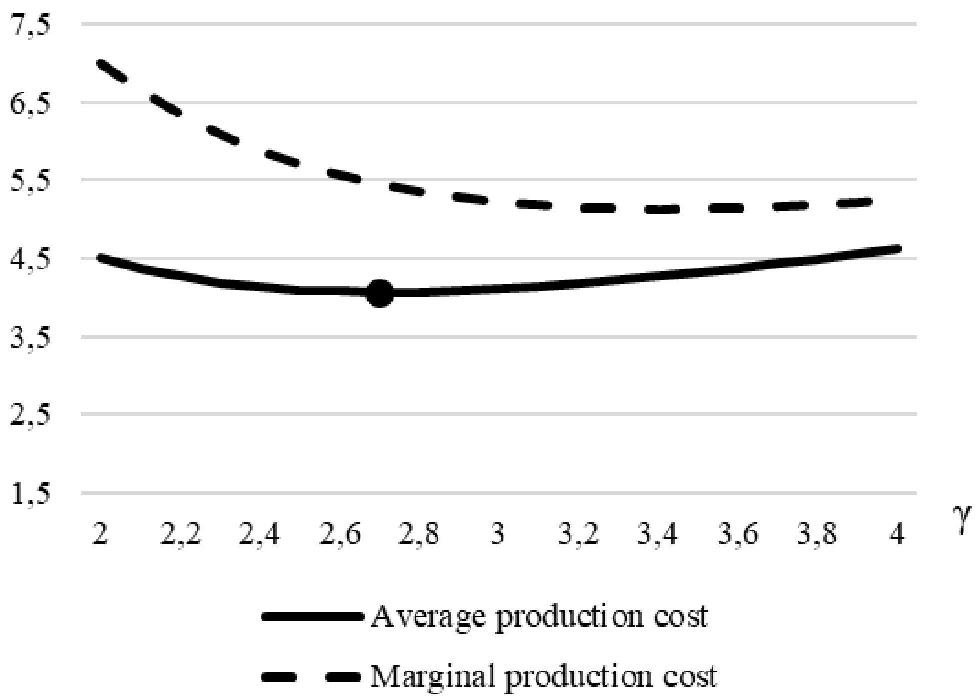

Figure 3: The effect of fixing the relative usage of the natural resource on costs, when returns to scale are decreasing. The figure shows the effect of fixing the relative usage of the natural resource (γ) on the average and marginal production cost, in a numerical example with decreasing returns to scale. The numerical example sets the productivity parameter and input prices equal to $A = p^n = p^b = 1$, the output elasticities equal to $\alpha = 1/2$ and $\beta = 1/4$, and the production quantity equal to $x_i = 10$.

Appendix

Proof of Lemma 1.

There exists a symmetric intersection of the reaction curves $\hat{x}_i\left(x_j\right)$ because the setup is symmetric.

Furthermore, by implicit differentiation of the first-order conditions, given by (2), it holds true that

$$\frac{\partial^2 R_i}{\partial x_i \partial x_j} + \frac{d\hat{x}_i}{dx_j}\left(\frac{\partial^2 R_i}{\partial x_i^{\,2}} - \frac{\partial^2 C_i^{\mathrm{R}}}{\partial x_i^{\,2}}\right) = 0 \text{ for } i = 1,2 \tag{A1}$$

which means that the slopes of the reaction curves are

$$\frac{d\hat{x}_i}{dx_j} = -\frac{\partial^2 R_i}{\partial x_i \partial x_j} \Bigg/ \left(\frac{\partial^2 R_i}{\partial x_i^{\,2}} - \frac{\partial^2 C_i^{\mathrm{R}}}{\partial x_i^{\,2}}\right) \text{ for } i = 1,2\ . \tag{A2}$$

By Assumption 1, the revenue functions satisfy $\frac{\partial^2 R_i}{\partial x_i^{\,2}} < \frac{\partial^2 R_i}{\partial x_i \partial x_j} < 0$. Since it also holds true that $\frac{\partial^2 C_i^{\mathrm{R}}}{\partial x_i^{\,2}} \geq 0$, the slope of the reaction curves characterized by (A2) are negative and less than 1 in absolute value. The equilibrium is therefore unique and it satisfies stability.

Proof of Lemma 2.

Implicit differentiation of (2) yields

$$-\frac{\partial^2 C_i^{\mathrm{R}}}{\partial x_i \partial \gamma} + \frac{dx_i^*}{d\gamma}\left(\frac{\partial^2 R_i}{\partial x_i^{\,2}} - \frac{\partial^2 C_i^{\mathrm{R}}}{\partial x_i^{\,2}}\right) + \frac{dx_j^*}{d\gamma}\frac{\partial^2 R_i}{\partial x_i \partial x_j} = 0 \text{ for } i = 1,2\ . \tag{A3}$$

Lemma 2 is obtained by making use of the feature that the production quantities are symmetric (Lemma 1) such that $\frac{dx_i^*}{d\gamma} = \frac{dx_j^*}{d\gamma}$.

Proof of Lemma 3.

The production equilibrium is symmetric because of Lemma 1. Using (1) we can characterize the effect of γ on the profit of firm i as

$$\frac{d\left(R_i - C_i^{\mathrm{R}}\right)}{d\gamma} = -\frac{\partial C_i^{\mathrm{R}}}{\partial \gamma} + \frac{dx_i^*}{d\gamma}\underbrace{\left(\frac{\partial R_i}{\partial x_i} - \frac{\partial C_i^{\mathrm{R}}}{\partial x_i}\right)}_{=0} + \frac{dx_j^*}{d\gamma}\frac{\partial R_i}{\partial x_j} = 0. \qquad \text{(A4)}$$

The first-order condition with respect to firm i's production quantity makes it possible to simplify (A4) as in Lemma 3.

Proof of Proposition 1.

Symmetry, uniqueness, and stability of the production equilibrium is already established in the paragraphs preceding Proposition 1 in the main text. The proof therefore focuses on the further parts of Proposition 1.

Consider an exogenous change in the symmetric production quantity, denoted by $x^S \equiv x_i^* \equiv x_j^*$. The associated change in the profit per firm (which determines the joint profit of the firms because of symmetry) equals

$$\frac{\partial\left(R_i - C_i^{cm}\right)}{\partial x^S} = \frac{\partial R_i}{\partial x_i} - \frac{\partial C_i^{cm}}{\partial x_i} + \frac{\partial R_i}{\partial x_j}. \qquad \text{(A5)}$$

In the production equilibrium under cost-minimization, the first-order condition $\frac{\partial R_i}{\partial x_i} - \frac{\partial C_i^{cm}}{\partial x_i} = 0$ is satisfied. Consequently, since $\frac{\partial R_i}{\partial x_j} < 0$, the production quantities are too high from the perspective of joint profit-maximization.

Furthermore, the profit per firm is concave with respect to x^S, because

$$\frac{\partial^2 \left(R_i - C_i^{cm} \right)}{(\partial x^S)^2} = \frac{\partial^2 R_i}{\partial x_i^{\,2}} + \frac{\partial^2 R_i}{\partial x_i \partial x_j} - \frac{\partial^2 C_i^{cm}}{\partial x_i^{\,2}} + \frac{\partial^2 R_i}{\partial x_j \partial x_i} + \frac{\partial^2 R_i}{\partial x_j^{\,2}} < 0, \tag{A6}$$

where the expression is signed by making use of Assumption 1 and the property that $\frac{\partial^2 C_i^{cm}}{\partial x_i^{\,2}} \geq 0$ (established in the paragraphs below (9) in section 4).