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Modelling economic policy issues

The design of environmental policy for the olive oil sector in the presence of eco-friendly firms

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ABSTRACT

The olive oil sector in the European Union has recently exhibited an increase in the production of eco-friendly olive oil, which is consistent with the policy goals of increasing the production of eco-friendly products and addressing environmental degradation. Under current Common Agricultural Policy (CAP) 2023–2027 regulations, environmental policy in the European Union is predominantly of the command-and-control type with less emphasis on market-based policies. We study the design of environmental policy by comparing an emission tax (market-based policy) and a relative binding standard (command-and-control policy) in an industry where firms are transforming themselves into eco-friendly firms. We argue that an emission tax is a more flexible and efficient policy in this type of industry. Results underscore the role market-based environmental policies can play in promoting the European Union's policy goals. Additionally, results are applicable to olive oil producers globally, but also other industries transitioning into the production of eco-friendly products.

1. Introduction

1.1. Motivation

The global production of olive oil has been steadily rising to meet its growing global demand (IOC, 2022; Caja Rural de Jaén, 2020; Mielke, 2019). The cultivation of olives using high-intensive-yield techniques has become more prevalent as a result, but these techniques normally come at the expense of environmental degradation. When it comes to the extraction of olive oil not all firms are reducing their carbon footprint, where some firms rely on non-renewable energy sources to run operations or may not employ effective waste-reducing processes (Khdair and Abu-Rumman, 2020). This is in addition to the existing negative environmental impact inherent in olive oil production (Regional Activity Centre for Cleaner Production, 2000).[1] However, in the olive oil sector firms are increasingly transforming themselves into eco-friendly firms (Carrillo et al., 2016; Caja Rural de Jaén, 2020). This transformation is regarded as a key business strategy for the sector (Parras, 2020), but this transformation is also marked by asymmetries in pollution intensities and high degrees of product differentiation. As a result, there is interest in the design of environmental policy for the sector, but it is not clear what type of regulatory approach (i.e., emission taxes versus environmental standards) should be implemented.

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[1] For data on the pollution generated by the cultivation, extraction and distribution of olive oil see Poor and Nemecek (2018) and for a discussion of the production process of olive oil and its environmental impacts see Regional Activity Centre for Cleaner Production (2000).

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The approach to environmental policy design in the olive oil sector (from the cultivation of olives to the extraction of oil and its distribution) has been primarily a command-and-control type (Paraskeva and Diamadopoulos, 2006; Labella Carillo et al., 2017). For example, the EU is one of the largest producers of olive oil worldwide, representing about 67% of the world's olive oil production,[2] where environmental standards are a key policy within the EU-wide regulatory framework of "green growth", but also within the recently proposed reforms to the Common Agricultural Policy (CAP) 2023-2027.[3] Overall, environmental standards play an integral part in the design of policy, but at the same time firms are increasingly attempting to differentiate themselves as eco-friendly to exploit new markets and lower their negative impact on the environment. In this context less attention has been given to the design of market-based policies such as emission taxes. With this in mind, we seek to answer the following questions. Is a market-based approach (e.g., emission tax) welfare-enhancing relative to a command-and-control type (e.g., relative standard) in industries characterized by highly differentiated products and asymmetry in pollution intensities? Does an emission tax offer firms enough flexibility when it comes to supplying the market with eco-friendly products and at the same time policy-makers the ability to address damages from environmental degradation? As a follow-up question we also explore the design of policy under uncertainty, a key factor facing eco-friendly firms because it is not clear whether these can stay cost-competitive due to their relative higher costs.

The olive oil sector is a relevant example to study the aforementioned research questions because it is a sector characterized increasingly by firms which exhibit asymmetry in pollution intensities and product differentiation. In this context, we develop a model to analyze the welfare effects of a relative binding environmental standard vis-à-vis emission taxes. We argue that, although a relative binding environmental standard is welfare-equivalent to an emission tax under certain conditions, an emission tax is welfare-enhancing in an industry where firms increasingly attempt to differentiate themselves as eco-friendly. The analysis suggests that an emission tax offers enough flexibility to firms and policy-makers in said industries. This implies also that in those industries where the current policy approach is of the command-and-control type and where firms' strategies focus on differentiating themselves as eco-friendly, the policy approach may need to be revisited.

Our framework of analysis is applicable to the olive oil sector, a sector which has received very little attention in the literature. This is in spite of its growing importance globally, particularly in key olive oil producer countries such as Spain, Tunisia, Italy and Greece, which represent about 60% of total world land use for olive cultivation.[4]

The key policy implications from our analysis are the following. An emissions tax (a market-based policy) is a more flexible and efficient policy than a relative binding standard (a command-and-control policy) for policy-makers, particularly in industries where there is clearly a set of high-polluting and low-polluting firms (i.e., there is sufficient asymmetry in pollution intensities), and where firms are attempting to differentiate themselves as eco-friendly firms (i.e., product differentiation). The key mechanism driving this result is twofold: the presence of sufficient asymmetry in pollution intensities and the presence of product differentiation. An emission tax encourages the production of the eco-friendly product and discourages the production of the non-eco-friendly product. This effect is strong enough with sufficient asymmetry in pollution intensities, where there is clearly a set of high-polluting and low-polluting firms. With an emission tax the high-polluting firms pay a sufficiently higher penalty, thereby lowering industry emissions and raising welfare. And an emission tax will be able to exert this effect even more as firms differentiate themselves as eco-friendly firms since in this case the degree of asymmetry in pollution intensities intensifies. The emission tax is more flexible and efficient than a binding standard because the relative binding standard requires firms to exhibit a specific abatement cost structure to attain similar results. In this sense the standard is a more restrictive policy option.

The theoretical analysis is relevant to the European Union for two reasons. First, one of the goals of the European Union is to increase the production of eco-friendly goods so our analysis offers policy guidance to achieve this goal. Second, the current CAP 2023–2027 regulatory framework points to more room for the implementation of market-based environmental policies, but command-and-control policies still dominate the regulatory framework. As a result, the key policy recommendation from the analysis (i.e., the need for market-based policy) is feasible under the current policy framework.

Our findings set the stage for future empirical analysis to test whether a market-based environmental policy framework is better at promoting the production of eco-friendly products in industries with a clearly identifiable set of high-polluting and low-polluting firms, and where there is a clear difference between the production of eco-friendly and non-eco-friendly products. This type of analysis would be relevant to, for example, the olive oil sector, the wine sector and energy sector where these market features are present, and would contribute to the existing empirical literature e.g., Tietenberg (2013), Cardoso-Marques et al. (2019), Almeida-Neves et al. (2020), Liu et al. (2023a,b).

1.2. Background: Eco-friendly production and product differentiation in the olive sector

The olive oil sector exhibits three features relevant to our analysis, which point to a sector increasingly characterized by large asymmetries in pollution intensities and degrees of product differentiation. First, the sector shows an increase in global demand with

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[2] European Commission, https://ec.europa.eu/info/food-farming-fisheries/plants-and-plant-products/plant-products/olive-oil_en.

[3] See https://ec.europa.eu/environment/green-growth/index_en.htm, and the European Commission, Commission Staff Working Document, "Analysis of links between CAP Reform and Green Deal", Brussels, 20.5.2020 SWD(2020) 93 final.

[4] Our results are also applicable to industries in which firms' strategies consist of differentiating themselves as environmentally-friendly firms. Examples include the energy sector, where evidence points to firms attempting to differentiate themselves by supplying renewable energy and adding renewable energy in their energy mix (Power Magazine, 2018; Lamb and Didriksen, 2017; Fikru and Gautier, 2021). Additionally, the wine industry is experiencing a similar transformation where firms are becoming environmentally friendly to cater to a specific consumer market (Kelley et al., 2017).

growing markets in Asia (Olimerca, 2021; Caja Rural de Jaén, 2020). There also has been an increase in the number of countries producing olive oil with varying degrees of production techniques and regulatory frameworks. Overall, the global production of olive oil has tripled in the last 60 years (IOC, 2016, p.21) with an associated increase in product variety and eco-friendly production/cultivation techniques (FIBL and IFOAM, 2016; Carmona-Torres et al., 2023).

Second, there has been an increase in the area of land used for the cultivation of olives in Adalusia, Spain (the largest producer of olive oil globally) using eco-friendly production/cultivation techniques, from 31,851ha in 2001 to 54,800.68ha in 2012 (Pleguezuelo et al., 2018, p. 20), where the share of organic olive oil production relative to total olive oil production has steadily grown since 2011 (Parra-Rivero et al., 2023). This transformation towards eco-friendly production and cultivation techniques is seen as a key business strategy for the sector (Carrillo et al., 2016; Caja Rural de Jaén, 2020). Further, the EU's Regulation No 834/2007 (EC 2007) sets regulation for the production of "aceites ecológicos" (eco-friendly) labeling certification and Protected Designations of Origin,[5] which allow olive oil producers to differentiate themselves by geographic-specific product characteristics, and by signaling that they employ eco-friendly production/cultivation techniques which include soil-protection and compost-based fertilizers.[6] Other eco-friendly production techniques include using the waste from olive oil extraction to generate renewable energy and the olive mill wastewater to obtain fertilizers and antioxidants for human consumption. Overall, there is evidence which indicates that eco-friendly production/cultivation processes have a much lower carbon footprint vis-à-vis the non-eco-friendly ones, where such eco-friendly production/cultivation processes are becoming increasingly relevant in the sector (e.g., Aguilera et al., 2015). Many olive oil producers seek to differentiate themselves by highlighting their use of some of these eco-friendly techniques.[7]

In terms of the environmental impact, Poore and Nemecek (2018) estimate the kilogram carbon dioxide equivalent ($\mathrm{kgCO_2eq}$) per kilogram of olive oil produced at 5.42 kilograms. Although olive oil production ranks lower than, say, beef (with $\mathrm{kgCO_2eq} = 99.48$ kilograms) and coffee ($\mathrm{kgCO_2eq} = 28.53$ kilograms), it still poses important environmental challenges ranging from growing land and energy use for olive oil extraction to environmental harmful byproducts such as alperujo, alpechin (olive oil wastewater) and the reliance of open pools to deal with wastewater from the extraction of olive oil. For example, for each 100tons of olives about 20tons translate into olive oil and 80tons into residual byproducts such as alperujo (Budyk, 2022). Indeed, residual water from the extraction of olive oil produces methane and poses additional challenges due to its high organic load such as phytotoxic residual and polyphenols with potential health effects (Sakarika et al., 2022; Cassano et al., 2016). Many of these challenges still need to be addressed under the current regulatory framework. But it is noteworthy that there have been significant efforts by the olive oil sector to reduce the environmental impact from the extraction of olive oil by reusing wastewater, creating new value-added products (e.g., biomass, makeup products) and using technology to treat harmful byproducts. For example, forced evaporation and bio-chemical techniques such as reverse osmosis and ultra-filtration techniques are used to reduce harmful byproducts, but these are still relatively expensive and thus used to a lesser degree. The steps taken by the sector are consistent with the need to use technology and innovation to reduce environmental impact and achieve efficiency gains e.g., Hu et al. (2023a,b) and Bai et al. (2023).

In terms of the regulatory framework, the focus has been on a command-and-control approach with less attention on the potential role market-based environmental policy could play. Examples of the current command-and-control regulatory efforts to tackle environmental challenges in the sector include the EU's *Farm to Fork* strategy, which seeks to reduce the sector's carbon footprint by reducing the use of chemical fertilizers by 50% by 2030 through the design of environmental standards. Additionally, the 2023–2027 CAP proposes a set of Eco-Regimes to reduce the reliance on fertilizers and a mandate to make sure that 25% of the agricultural land employs eco-friendly cultivation techniques by 2030 (Canga, 2022). It is noteworthy that the proposed 2023–2027 CAP offers some room for the use/design of market-based environmental policies, but the focus has been on a command-and-control approach.

1.3. *Contribution to the existing theoretical literature*

We now discuss our contribution to the existing theoretical literature. We develop a duopoly model from which we propose conditions on market parameters and degree of pollution intensities consistent with the design of welfare-enhancing environmental policy. Our analysis is the first to compare relative binding environmental standards and emission taxes through the lense of product differentiation and asymmetry in pollution intensities in the olive oil sector.

The environmental-standards-versus-emission-taxes literature is vast (see Bárcena-Ruiz and Begoña-Garzón (2022) for a brief survey).[8] The papers by Ulph (1992, 1996), Lahiri and Ono (2007), Kato (2011), Antoniou et al. (2012), Bárcena-Ruiz and Campo (2017), to name a few, delve into the taxation-versus-standards debate, but do not examine the role of product differentiation and asymmetry in pollution intensities, and their implications on welfare.

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[5] Of the 2.5 million ha of Spanish olive orchards, 688,245ha is registered by the 28 Protected Designations of Origin for olive oil (Pleguezuelo et al., 2018).

[6] Examples of certifications of low carbon footprint and bio-production in the olive oil sector include the non-profit organization DNV (dnv.com) and COPADE (Committee on Ecological Agriculture of Madrid, copade.es).

[7] DCOOP and Aceites Cazorla Sociedad Cooperativa are two important regional examples of olive oil producers which employ eco-friendly production techniques.

[8] Baumol and Oates (1988), Buchanan (1969), Barnett (1980), Spulber (1985) and Helfand (1991) are important starting point for this branch of the literature, while Bruce and Ellis (2023) offer an overview of standards and taxes from a non-technical perspective. Recent works compare emission taxes and standards under a myriad of contexts. For example, Shinozaki and Kunizaki (2022) and Ohori (2011) compare standards and taxation in the presence of foreign firms, where conditions under which each policy is Pareto superior are derived. Chang and Sellak (2023) compare these policies in the presence of vertically differentiated markets. Requate (2006) presents a survey of Cournot models under standards and emission taxes.

Overall, the conditions under which a tax is welfare-enhancing relative to an environmental standard (or vice-versa) depend on a variety of factors including, for instance, uncertainty (e.g., Weitzman (1974), Xu and Luo (2022)), information asymmetry (e.g., Ambec and Coria (2021)), profit-shifting incentives (e.g., Ulph (1992, 1996), Antoniou et al. (2012)), free-entry and exit (e.g., Lahiri and Ono (2007)), and cross-ownership (e.g., Bárcena-Ruiz and Campo (2017), Bárcena-Ruiz and Sagasta Elorza (2021)). We add to this literature by arguing that product differentiation and asymmetry in pollution intensities determine which policy is welfare-enhancing.[9] As explained in the previous section, this is important in industries where firms are increasingly transforming themselves into eco-friendly firms.

Our analytical strategy consists of two steps. First, we study the role of this transformation in the design of environmental policy by comparing two environmental policy regimes: an emission tax and a relative binding standard. To make comparisons across policy regimes tractable, the welfare-maximizing policy within each regime is characterized as a function of the degree of product differentiation and pollution intensity. We characterize an equivalency scenario where policy adjustment is identical across regimes and hence show the existence of a degree of product differentiation where such equivalency holds. Second, with these building blocks we argue that an emission tax is welfare-enhancing in industries where firms are becoming increasingly more eco-friendly, whereas the effects from a relative binding standard depend on the convexity of the abatement cost function. Indeed, we derive a sufficient condition where an emission tax is welfare-enhancing as long as there is sufficient asymmetry in pollution intensities.

Intuitively, the reason an emission tax is welfare-enhancing is because it controls emissions relatively more effectively as firms become more differentiated. This in turn offers policy-makers flexibility to set laxer policy. This kind of flexibility however is not possible under a relative binding standard because it requires a specific cost structure by the firm, meaning the standard offers less flexibility when it comes to allowing firms to control emissions as firms become more differentiated.

We then consider uncertainty to capture a challenge facing eco-friendly firms, namely, how to stay cost-competitive vis-à-vis firms which are not attempting to differentiate themselves as eco-friendly (Stacey, 2018). We argue *inter alia* that a stricter emission tax increases the chances of supplying the market with more eco-friendly products. This is because taxation renders the high-polluting firm less cost-competitive, thereby opening the possibility for a higher production of the eco-friendly product. In this sense, taxation and the production of eco-friendly products are complements. Because of this complementarity we show that the welfare-maximizing emission tax under uncertainty may exceed the tax under no uncertainty and even exceed marginal damages. This is because a stricter emission tax increases the chances for the eco-friendly firm to supply the market, which in turn helps the government to tackle emissions. Further, a stricter relative binding standard is also able to achieve a similar outcome, but only if the high-polluting firm exhibits high enough abatement costs. In this case, we regard the standard as more restrictive in terms of increasing the chances of supplying the market with eco-friendly goods. Our results point to the role an emission tax can play in implementing the EU's *Farm to Fork* strategy and also achieving the mandate where 25% of the agricultural land should employ eco-friendly cultivation techniques by 2030. Our policy recommendations are consistent with the proposed 2023–2027 CAP and thus implementable under said regulatory framework.

The rest of the paper is structured as follows. Section 2 spells out the general framework, where Sections 2.1 and 2.2 characterize the equilibrium under an emission tax and relative binding standard, respectively. Section 3 compares the two regimes through the lens of product differentiation and pollution intensities, where Section 3.1 looks at the effects on total emissions and Section 3.2 examines efficiency gains. Section 4 offers a numerical exercise to illustrate some of the results from the theory. Section 5 considers uncertainty and Section 6 concludes.

2. The general framework

The production of olive oil consists of three general stages: cultivation of olives, extraction of olive oil and its distribution. In our modeling strategy we focus on the extraction of olive oil stage. This is because at the extraction stage we are able to capture three aspects which are crucial when it comes to product differentiation, asymmetries in pollution intensities and thus how consumers perceive a product variety: (i) organically-grown olives which employ,say, fewer chemicals and soil-protecting methods, (ii) waste-reducing and energy-saving techniques employed during and after the extraction process, and (iii) product characteristics based on geographical characteristics and country of origin.

Product differentiation

Consider a duopoly model where each firm $k = i, j,\ i \neq j$ chooses its level of output (liters of extra virgin olive oil-EVOO-extracted), x_k, and emissions after abatement (abatement from the extraction process), e_k, simultaneously taking the competitor's choice of output and emissions as given. Firm i faces an inverse demand $p_i = a - \beta x_i - \gamma x_j$, where $i \neq j$ and $0 \leq \gamma \leq \beta$ indicates the degree of horizontal product differentiation.[10] Similarly, for firm j demand is given by $p_j = a - \beta x_j - \gamma x_i$. The consumer views organic and non-organic EVOO as imperfect substitutes, where the parameter γ represents the degree of product differentiation. If

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[9] Our work is closest to Lahiri and Ono (2007), where they compare a relative standard and emission tax starting at an equilibrium where neither policy is in place. They do this for tractability reasons, where they show that standard is welfare superior when the effects on emissions from of each policy is the same. This is because the emission tax increases the output distortion more than the standard. Our analytical framework allows for the comparison across regimes where policy is in place, since we use common parameters across policy regimes i.e., product differentiation and pollution intensities. In contrast to Lahiri and Ono (2007), we offer conditions for the emission tax to be welfare-superior to the standard.

[10] We borrow preferences from Cellini et al. (2004) and Fujiwara (2009) where preferences satisfy our demand structure.

products are completely differentiated (homogeneous), then $\gamma = 0$ ($\gamma = \beta$). For instance, *for same quality*, EVOO is differentiated as organic or non-organic product. The organic product entails a less pollution-intensive production process (e.g., employ less chemicals/fertilizers), where firms take steps to lower their impact on the environment and consumers perceive this product as less harmful to the environment. In contrast, the non-organic product employs a more pollution-intensive production process, where firms do not differentiate their product as organic but rather as having a positive impact on rural/small towns or as an EVOO with unique geographical characteristics e.g., Protected Designations of Origin such as Cazorla or Priego de Córdoba.

The organically-produced extra virgin olive oil, EVOO (which consumers perceive to be better for the environment and firms produce with a lower environmental impact) and the non-organically-produced EVOO (which consumers perceive as harmful to environment but as having positive effects on rural towns and with unique product features consistent with regional geographical characteristics) exhibit the same product quality. EVOO quality is measured via three main dimensions: (1) Phenolic/volatile compounds, where key here is the variety of olive e.g., Hojiblanca, Picual; (2) Collection — physical integrity of the olive during collection; (3) Other — Quality of physical capital e.g., decanter. The implication here is that there are EVOOs produced under different techniques which exhibit the same quality as per (1)-(3), and that these quality dimensions can be the same for EVOO produced organically or non-organically. Thus, we assume the same quality EVOO produced organically or non-organically and, consequently, our degree of product differentiation parameter, γ, captures horizontal product differentiation. We link product differentiation, pollution intensity and organic and non-organic production below.

Costs and pollution intensity

Total costs for each firm $k = i, j,\ i \neq j$ are represented by a function of the end-of-pipe $c_k(x_k, e_k) = \bar{c_k} x_k + g_k(\delta_k(x_k) - e_k)$. The first component denotes production costs, where the constant $\bar{c_k} > 0$ denotes marginal production costs. The function $g_k(\cdot)$ denotes abatement costs, where the function $\delta_k(x_k)$ denotes gross pollution and therefore $\delta_k(x_k) - e_k$ denotes abatement for each firm $k = i, j$, $i \neq j$. The properties of the cost function follow Lahiri and Symeonidis (2007), where costs are increasing and convex; that is, (subscripts denote partial derivatives and dropping the k subscript for notational simplicity): (1) $c_x > 0$, $c_{xx} > 0$; (2) $-c_e = g' > 0$, $c_{ee} = g'' > 0$; (3) $-c_{ex} = -c_{xe} = g''\delta' > 0$; (4) $c_{xx}c_{ee} - c_{ex}c_{xe} = g''g'\delta'' > 0$. Our cost function is consistent with pollution of the end-of-the-pipe type generated during the extraction of olive oil.

To capture the extent to which each firm differentiates itself as producing an organic or non-organic EVOO, we use the properties of the cost function to characterize the pollution intensity for each firm k; in particular, $-c_{ex}/c_{ee} = \delta'(x)$.[11] For instance, δ' denotes emissions per unit of EVOO extracted e.g., greenhouse gas emissions per liter of olive oil extracted or tons of alperujo per ton of olive oil extracted. Poore and Nemecek (2018) estimate the kgCO$_2$eq per kilogram of olive oil at 5.42, and on average 4tons of alperujo are generated for every ton of olive oil extracted.

We show that in equilibrium x_k is a function of γ and therefore the pollution intensity of firm k depends on the degree of product differentiation. As a result,

$$\frac{\partial \delta_k'(x_k)}{\partial \gamma} = \delta_k''(x_k)\frac{\partial x_k}{\partial \gamma} \quad ; k = i, j, i \neq j \tag{1}$$

where $\delta_k'' > 0$ from the properties of the cost function, but the sign of $\partial x_k/\partial \gamma$ is in general ambiguous. Eq. (1) links the degree of product differentiation and pollution intensity through the properties of the cost function. A positive sign in Eq. (1) means that a low pollution intensity (i.e., organic production process) is associated with a high degree of product differentiation (low γ). In this case firms differentiate themselves by producing an organic product and consumers perceive said product as friendly to the environment. Similarly, a negative sign in Eq. (1) means that a high pollution intensity (i.e., non-organic production process) is associated with a high degree of product differentiation (low γ). In this case firms differentiate themselves not by producing an organic product, but rather by having a positive impact on rural/small towns and by having a product with unique regional characteristics. In this case consumers perceive said product as less friendly to the environment, but having unique regional characteristics and a positive impact on rural/small towns.

The reason the sign of Eq. (1) is ambiguous is because as products become more differentiated (decrease in γ) there are two opposing effects in our duopoly model which affect the production of each firm. With a higher degree of product differentiation firm i enjoys additional market power and therefore restricts its output. But as firm j also enjoys additional market power (and restricts output, too) firm i reacts strategically by increasing output; this is because of the oligopolistic interdependence in the market (Lahiri and Symeonidis, 2007). We therefore do not set any restrictions *a priori* on the sign of $\partial \delta_k'(x_k)/\partial \gamma$, but discuss potential cases in the comparative statics analysis below.

A key feature of the model is that a decrease in the parameter γ works via two channels: (1) the demand function where firms enjoy a degree of extra market power through a higher degree of product differentiation, and (2) the pollution intensity function, δ', capturing the link between product differentiation and firms' ability to differentiate themselves as eco-friendly (or not) through organic (non-organic) production techniques. As a result, sector-wide and firm-specific channels are part of the modeling strategy. These channels are important because they reflect the olive oil sector-wide trend where firms seek to differentiate themselves to cater to a specific consumer market, but also potential asymmetries in pollution intensities. For example, given similar quality of EVOO, firms highlight features of their product variety based on country/region of origin, geographical characteristics where olives

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[11] We follow Lahiri and Symeonidis (2007), where $c_e = c_e(x, e) \Rightarrow \left.\frac{de}{dx}\right|_{dc_e=0} = -c_{ex}/c_{ee} = \delta'(x)$.

are grown, and the positive economic impact the olive oil sector has on rural and unpopulated areas. In contrast, given similar product quality firms seek to differentiate themselves by pointing to reductions in pollution intensities using some of the techniques mentioned in Section 1.2.

In what follows we consider two types of independent and separate policy regimes where the government sets policy. One regime considers an emission tax and the second regime a binding relative emission standard. The order of events within each regime is as follows. The government determines policy via welfare maximization, followed by the choice of output and emissions by each firm which takes place in a Cournot-Nash fashion. The model is solved via backward induction.

The analytical strategy consists of characterizing and comparing the equilibrium across regimes. To make comparisons across policy regimes tractable, the welfare-maximizing policy in each regime is characterized as a function of the degree of product differentiation, γ, and the level of pollution intensity, δ_k'. In comparing the two regimes we determine whether an emission tax or a binding relative standard is welfare-enhancing for varying degrees of product differentiation and pollution intensities.

2.1. Emission tax regime

In this regime each firm faces an identical per-unit emission tax, t. Profits for each firm are given by

$$\max_{x_k,e_k} \pi_k = p_k x_k - c_k(x_k, e_k) - t e_k \quad ; k = i, j, i \neq j \tag{2}$$

whence first-order conditions are given by

$$p_k - \beta x_k - \bar{c_k} - g_k' \delta_k' = 0 \tag{3}$$

$$g_k' - t = 0 \tag{4}$$

These implicitly characterize the equilibrium output and level of emissions for each firm $k = i, j$, $i \neq j$. Since the pollution intensity is a function of the degree of product differentiation we can write the equilibrium vector as $x_i^* \left(\gamma, \delta_i'(\gamma), \delta_j'(\gamma), t\right)$, $x_j^* \left(\gamma, \delta_i'(\gamma), \delta_j'(\gamma), t\right)$, $e_i^* \left(x_i^*, t\right)$, $e_j^* \left(x_j^*, t\right)$.

We use this equilibrium to derive the comparative statics effects on output with respect to the degree of product differentiation, γ (see Appendix A). As mentioned in the previous section each firm's output may fall or rise with a higher degree of product differentiation (decrease in γ). As a result, there are three potential cases each of which has implications on the sign of Eq. (1). But to keep the analysis tractable, for the remainder of the paper we focus on case (i): $\partial x_i^*/\partial\gamma < 0$, $\partial\delta_i'/\partial\gamma < 0$, $\partial x_j^*/\partial\gamma > 0$, $\partial\delta_j'/\partial\gamma > 0$.[12]

In case (i), firm i produces a non-organic product while firm j produces an organic product. This is because a higher degree of product differentiation (decrease in γ) is associated with an increase in firm i's output and pollution intensity, while firm j's output and pollution intensity decrease. This scenario means that firm i differentiates itself as a non-organic producer while increasing its production of EVOO. This is consistent with producers who are not organic producers (reflected by $\partial\delta_i'/\partial\gamma < 0$) but who tend to increase the volume of production (reflected by $\partial x_i^*/\partial\gamma < 0$). Examples include producers who employ high-intensive cultivation techniques and differentiate themselves as having a positive impact on rural/small towns and a product with unique regional characteristics, but who are producing a product which is relatively more harmful to the environment. In contrast, firm j differentiates itself as an organic producer ($\partial\delta_i'/\partial\gamma > 0$), which is associated with a lower volume of production of EVOO ($\partial x_i^*/\partial\gamma > 0$). Organically-produced EVOO tends to exhibit smaller yields and a lower impact on the environment.

Definition 2.1. Let firm j produce an organic product (i.e., firm j is the eco-friendly firm) and firm i a non-organic product (i.e., firm i is the non-eco-friendly firm). That is, $\partial x_i^*/\partial\gamma < 0$, $\partial\delta_i'/\partial\gamma < 0$, $\partial x_j^*/\partial\gamma > 0$, $\partial\delta_j'/\partial\gamma > 0$.

Next, we look at the implications on total emissions in order to show the role of asymmetry in pollution intensities. Our overarching policy implication is that total emissions fall in an industry facing an emission tax, where there is clearly a set of high-polluting and low-polluting firms (sufficient asymmetry in pollution intensities), and where some of these firms are differentiated as eco-friendly (product differentiation). The reason total emissions fall is because the tax encourages the eco-friendly firms and discourages the non-eco-friendly firms. These tax effects are exacerbated as some firms are differentiated as eco-friendly because with differentiated firms the asymmetry in pollution intensities becomes larger rendering the tax effect stronger.

Total emissions are given by the sum of emissions of firm i and j, $E = e_i + e_j$, where consistent with the literature each firm's emissions fall with an increase in the emission tax. In terms of product differentiation, since E and δ' are functions of γ, total emissions may fall or rise as products become more differentiated (decrease in γ). In particular, the effects on total emissions in the tax regime are given by

$$E = E\left(\gamma, \delta_i', \delta_j'\right) \Rightarrow \quad \frac{dE}{d\gamma} = \frac{\partial E}{\partial\gamma} + \left(\frac{\partial E}{\partial\delta_i'}\frac{\partial\delta_i'}{\partial\gamma} + \frac{\partial E}{\partial\delta_j'}\frac{\partial\delta_j'}{\partial\gamma}\right) \tag{5}$$

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[12] The other two cases are (ii) $\partial x_i^*/\partial\gamma < 0$, $\partial\delta_i'/\partial\gamma < 0$ $\partial x_j^*/\partial\gamma < 0$, $\partial\delta_j'/\partial\gamma < 0$; (iii) $\partial x_i^*/\partial\gamma > 0$, $\partial\delta_i'/\partial\gamma > 0$ $\partial x_j^*/\partial\gamma > 0$, $\partial\delta_j'/\partial\gamma > 0$. Case (ii) follows the same logic as case (i), but now we have a scenario where a higher degree of product differentiation is associated with a higher volume of production of both firms and a higher pollution intensity. This case captures the possibility where neither firm differentiates itself as an organic producer. As a result, we do not focus on this case since we are interested in the implications of potential asymmetries in pollution intensities (organic versus non-organic) arising from the presence of product differentiation. As for case (iii), we rule out this scenario since the signs on output are not consistent with the stability of the equilibrium.

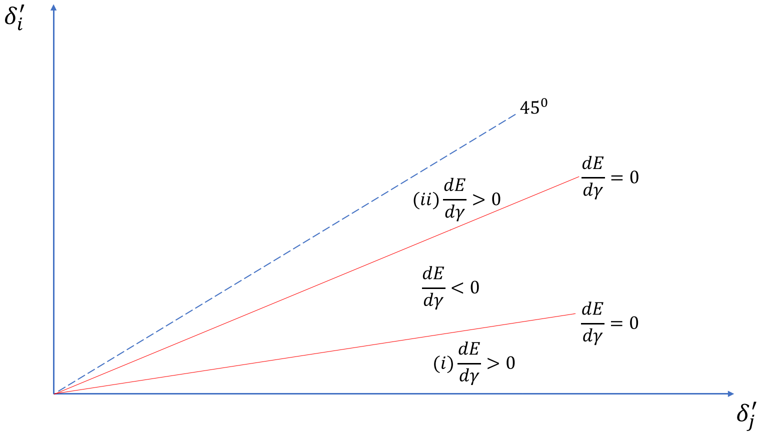


Fig. 1. Asymmetry in Pollution Intensities in the Tax Regime.

We use Eq. (5) and Fig. 1 to illustrate the role of asymmetry in pollution intensities with reductions in total emissions. Appendix B derives the results. The two areas in Fig. 1 (areas (i) and (ii)) associated with reductions in total emissions are also associated with asymmetry in pollution intensities; in-between these two areas we do not see sufficient asymmetry and thus total emissions do not decrease. The reason area (i) exhibits a reduction in total emissions is that a higher degree of product differentiation prompts a reduction in x_j (Definition 2.1), the relatively high-polluting firm. That is, with large enough δ_j' a reduction in output lowers total emissions. Similarly, the reason area (ii) shows a reduction in total emissions is because firm i exhibits a large enough pollution intensity, δ_i'. With large enough δ_i' firm i experiences higher costs and therefore lower output. A higher degree of product differentiation prompts a further increase in δ_i' (Definition 2.1) and a subsequent decrease in x_i, which reduces total emissions.

Remark 2.2. Consider a decrease in γ. There are pollution intensity pairs consistent with a reduction in total emissions in the tax regime, if there is sufficient asymmetry in pollution intensities.

Proof. See Appendix B ☐

The government sets an emission tax so as to maximize welfare, which is given by the sum of consumer surplus, profits, tax revenue, and damages from pollution:

$$\max_t W = CS(x_i, x_j) + \pi_i + \pi_j + tE - \varphi(E) \tag{6}$$

where the damage function φ is strictly increasing and convex in E. Eq. (6) gives a first-order condition $W_t(\gamma, \delta_i'(\gamma), \delta_j'(\gamma)) = 0$, which characterizes a positive second-best emission tax, less than marginal damages ($t^* < \varphi'$), as long as output distortion effects are not too large. This is a standard result in the literature. That is, we characterize the second-best tax, t^*, in terms of the degree of product differentiation and pollution intensity via the function $W_t(\gamma, \delta_i'(\gamma), \delta_j'(\gamma)) = 0$.

2.2. Relative binding standard regime

We follow Kayalica and Lahiri (2005) where each firm faces an identical relative binding standard, δ^s. Emissions by each firm are thus now given by $e_k^s = \delta^s x_k^s$, $k = i, j$, $i \neq j$. As a result, the cost function faced by each firm is given by $c_k^s(x_k^s, \delta^s x_k^s) = \bar{c}_k^{\,s} x_k^s + g_k^s(\delta_k(x_k^s) - \delta^s x_k^s)$, where the properties of the cost function are same as before. The superscript s denotes variables in the relative binding standard regime. This cost function says that each firm faces additional costs of pollution abatement for each unit of emissions exceeding the relative binding standard. In this setup each firm chooses output for given standard, taking its competitor's choice of output as given, where profits for each firm are given by:

$$\max_{x_k^s} \pi_k^s = p_k^s x_k^s - c_k^s(x_k^s, \delta^s x_k^s) \quad ; k = i, j, i \neq j \tag{7}$$

whence the first-order condition is given by

$$p_k^s - \beta x_k^s - \bar{c}_k^{\,s} - (\delta_k' - \delta^s) g_k^{s'} = 0 \tag{8}$$

Eq. (8) characterizes the equilibrium output and thus emissions for each firm under a standard. As before, in equilibrium the pollution intensity δ_k' is a function of the degree of product differentiation, γ, and the effects of γ on output are ambiguous. Further, consistent with Requate (2006, p. 128), in the normal case a laxer standard (increase in δ^s) raises output and thus emissions. This is because a laxer standard translates into lower marginal abatement costs.

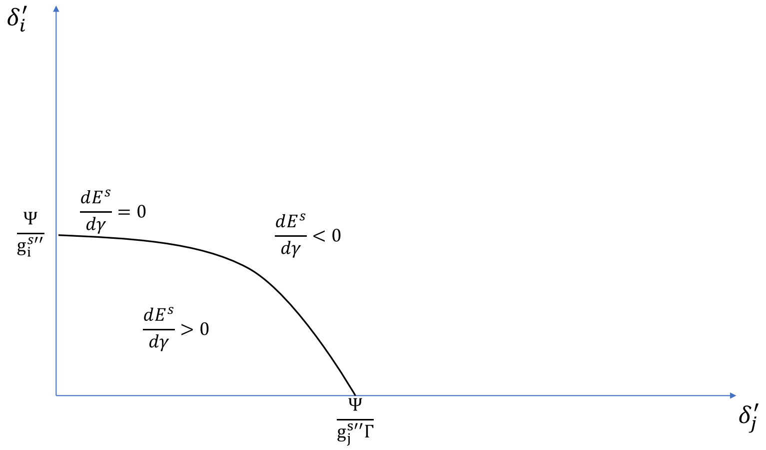


Fig. 2. Cut-off Points of Pollution Intensities in the Binding Standard Regime.

A change in total emissions, $E^s = \delta^s x_i^s + \delta^s x_j^s$, with respect to γ now works via changes in output since the standard is binding and set by the government. As in the tax regime we consider the case described in Definition 2.1. In particular, since E^s and δ_k' are functions of γ the effects on total emissions in the binding standard regime are given by

$$\frac{dE^s}{d\gamma} = \frac{\partial E^s}{\partial \gamma} + \left(\frac{\partial E^s}{\partial \delta_i'} \frac{\partial \delta_i'}{\partial \gamma} + \frac{\partial E^s}{\partial \delta_j'} \frac{\partial \delta_j'}{\partial \gamma} \right) \tag{9}$$

From Definition 2.1 a decrease in γ (for given pollution intensity), on one hand, raises x_i and lowers x_j, but overall total output rises thereby raising total emissions. The reason is that firms face a binding standard and therefore the change in total emissions work exclusively through changes in output. But on the other hand, a decrease in γ lowers the pollution intensity of firm j (which lowers firm j's costs thereby raising output and emissions of firm j), while raising the pollution intensity of firm i (which raises firm i's costs thereby lowering output and emissions of firm i). This yields a cut-off point such that total emissions remain unchanged. Fig. 2 shows the cut-off points and the areas associated with a decrease (increase) in total emissions inside (outside) the curve, $dE^s/d\gamma > (<) 0$. It is noteworthy that for relatively more convex abatement costs, $g_i^{s''}$, $g_j^{s''}$, the area in Fig. 2 associated with reductions in total emissions becomes smaller since now it is more expensive for each firm to abate emissions. This points to the role of the convexity of abatement costs in the binding standard regime, but not in the tax regime. We will bring this point to the discussion below as we compare outcomes across regimes.

Remark 2.3. Consider a decrease in γ. There are pollution intensity pairs consistent with an increase (decrease) in total emissions in the relative binding standard regime as long as firms exhibit sufficiently (not too) convex marginal abatement costs.

Proof. See Appendix B □

The government sets a relative binding standard, δ^s, so as to maximize a welfare function analogous to Eq. (6):

$$\max_{\delta^s} \tilde{W} = CS^s(x_i^s, x_j^s) + \pi_i^s + \pi_j^s - \varphi^s(E^s) \tag{10}$$

whence $\tilde{W}_{\delta^s}(\gamma, \delta_i'(\gamma), \delta_j'(\gamma)) = 0$ characterizes a positive second-best relative binding standard as long as damages are not too large. If damages from emissions were large enough, then the standard approaches zero i.e., a very strict standard. We characterize the second-best relative binding standard, δ^{s*}, in terms of the degree of product differentiation and pollution intensity via the function $\tilde{W}_{\delta^s}(\gamma, \delta_i'(\gamma), \delta_j'(\gamma)) = 0$.

3. Comparing regimes

We link the emission tax and binding relative standard policy regimes via the degree of product differentiation parameter, γ, and pollution intensity, δ_k'. We construct a space in pollution intensities and define an equivalency scenario which we use as a starting point to analyze the welfare effects arising from a higher degree of product differentiation. This is shown in Fig. 3 (see Appendix B for a derivation).

In the Figure, for given γ the function $W_t(\delta_i', \delta_j') = 0$ shows pollution intensity pairs consistent with the welfare-maximizing emission tax, while the function $\tilde{W}_{\delta^s}(\delta_i', \delta_j') = 0$ captures pollution intensity pairs consistent with the welfare-maximizing relative binding standard.

The tangency point shown in Fig. 3 is what we define as a welfare-equivalence scenario. Intuitively, welfare-equivalence is a point in pollution-intensity space at which policy adjustments across regimes are equivalent. We use this scenario as a starting point

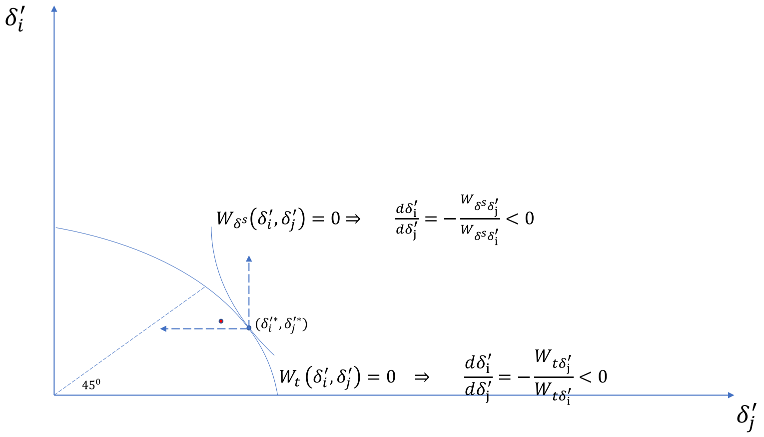


Fig. 3. Welfare Equivalence.

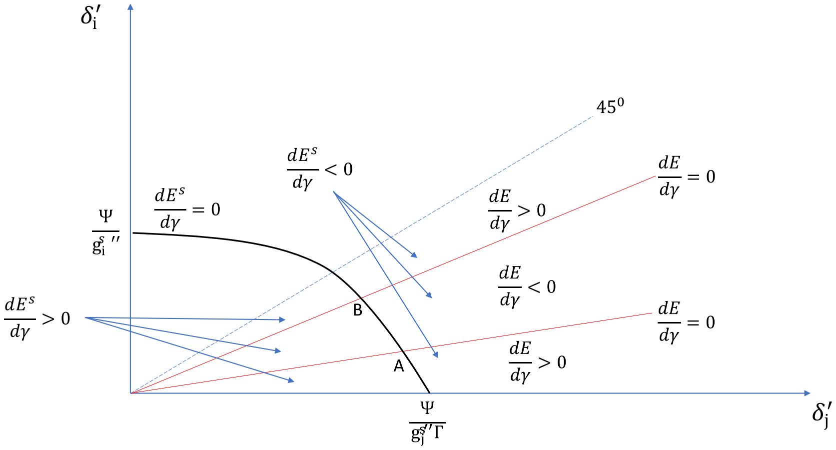


Fig. 4. Comparison Policy Regimes: Total Emissions.

to analyze the welfare effects arising from changes in γ. For example, starting at a welfare-equivalence scenario with pollution intensity pair $(\delta_i^{*'}, \delta_j^{*'})$, a higher degree of product differentiation (decrease in γ) affects output, emissions and therefore welfare. From Definition 2.1, starting at $(\delta_i^{*'}, \delta_j^{*'})$ a decrease in γ yields a new pollution intensity pair shown as, say, the red dot in Fig. 3, where $\delta_j'^*$ and $\delta_i'^*$ have decreased and increased, respectively. At the new pollution intensity pair (red dot) it is not clear what are the welfare gains/losses across and within regimes. In what follows we seek to disentangle these welfare effects into two parts: (i) total emissions and (ii) profits and consumer surplus. But before moving forward with the analysis we state the following definition and proposition.

Definition 3.1. At pollution intensities $(\delta_i^{*'}, \delta_2^{*'})$ there is welfare-equivalence whenever $-\tilde{W}_{\delta^s\delta_j'}/\tilde{W}_{\delta^s\delta_i'} = -W_{t\delta_j'}/W_{t\delta_i'}$.

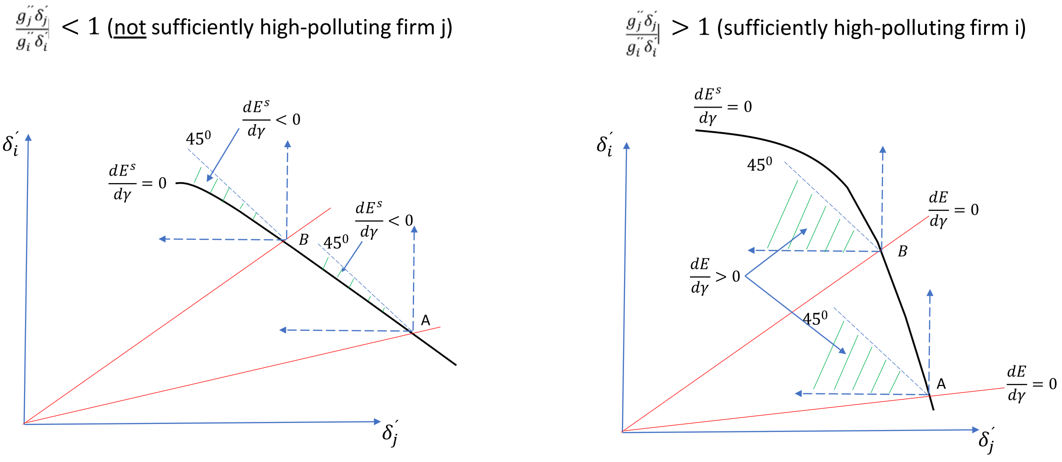
Proposition 3.2. *There is a degree of product differentiation, $\gamma^* \in (0, \beta)$, which obtains welfare-equivalence.*

Proof. See Appendix C ☐

3.1. Total emissions

To study the welfare effects via changes in total emissions, we combine Figs. 1 and 2 as shown in Fig. 4. Using Fig. 4 we can reach our first result, which we state in the following proposition.

Proposition 3.3. *Consider a decrease in γ starting at welfare-equivalence. If either firm (or both firms) exhibits sufficiently convex abatement costs in the standard regime and pollution intensities are sufficiently asymmetric in the tax regime, then total emissions fall only in the emission tax regime.*


$\frac{g_j''\delta_j'}{g_i''\delta_i'} < 1$ (not sufficiently high-polluting firm j)

$\frac{g_j''\delta_j'}{g_i''\delta_i'} > 1$ (sufficiently high-polluting firm i)

Fig. 5. Zooming in Points A and B: Total Emissions.

The intuition for this proposition is as follows. On one hand, it is relatively expensive to lower total emissions in the binding standard regime (Remark 2.3); and on the other, sufficient asymmetry in pollution intensities ensures reductions in total emissions in the tax regime (Remark 2.2).

To further explore the effects on total emissions, we consider the intersection between $dE/d\gamma = 0$ and $dE^s/d\gamma = 0$ (points A and B) as starting points. We argue that starting at point B (A) a higher degree of product differentiation results in lower (higher) emissions in the tax regime, but the effects on the binding standard regime are ambiguous. We use Fig. 5 to illustrate the analysis, where we "zoom in" on points B and A to see the effects on total emissions.

Starting at B and using Definition 2.1, a decrease in γ lowers total emissions in the tax regime. This is because in this case there is sufficient asymmetry in pollution intensities. But from the relative binding standard regime's perspective, total emissions may fall or rise depending upon the degree to which pollution intensities change. For example, from Definition 2.1 we know that a decrease in γ lowers δ_j', but raises δ_i'. If the reduction in δ_j' is large enough, then total emissions fall. Formally, if the reduction in δ_j' coupled with a sufficiently large pollution intensity in the sense that $g_j''\delta_j'/g_i''\delta_i' > 1$, then total emissions fall i.e., we end up inside the curve $dE^s/d\gamma = 0$. Results are reversed, if the reduction in δ_j' is not large enough. That is, if firm j is not sufficiently pollution intensive i.e., $g_j''\delta_j'/g_i''\delta_i' < 1$. Furthermore, if we were to start at point A, a decrease in γ raises total emissions in the tax regime, while the effects from the standard regime's perspective remain ambiguous. The reason for this is twofold: (i) in this case the asymmetry condition on pollution intensities does not hold and so in the tax regime total emissions rise, and (ii) similar to the analysis on point B, the effects on the standard regime depend on the degree to which pollution intensities change with respect to γ.

Proposition 3.4. *Consider a decrease in γ. Starting at point B (resp. A) total emissions in the tax regime fall (resp. rise), whereas the effect on total emissions in the relative binding standard regime is ambiguous.*

3.2. Efficiency gains

Because changes in pollution intensities arising from changes in the degree of product differentiation result in changes in output, there are potential implications on profits and consumer surplus. Overall, we argue that the results previously established hold as long as the condition on asymmetry in pollution intensities holds and, as a result, there are efficiency gains to be obtained. Efficiency is obtained through lower emissions, and negligible effects on profit and consumer surplus.

In Fig. 6 we superimpose the role of profits and consumer surplus into Fig. 1 (see Appendix D). The line labeled $dCS = 0$ denotes pairs of pollution intensities such that consumer surplus remains constant. This line has a slope equal to -1, which means that any gains in consumer surplus coming from changes in,say, firm j's pollution intensity are completely offset by a proportional change in firm i's pollution intensity. The dashed 45-degree line, Π, denotes pairs of pollution intensities consistent with profit maximization of firm j and i. Intuitively, the proportional change in the δ_k''s keeps firm j and firm i profits at their maximum level. The intersection point between these lines gives a pollution intensity pair which is consistent with profit maximization and consumer surplus maximum level, but also with reductions in total emissions. As a result, for a pollution intensity pair close to this intersection point (which satisfies the asymmetry in pollution intensity condition), there are efficiency gains in the tax regime. This is because the reduction in total emissions and the negligible effects on consumer surplus and profits result in lower environmental damages. With lower damages, in turn, the government has the ability (and flexibility) to address the output distortion due to the oligopolistic market imperfection via laxer taxation.

An analogous result applies to the case of the relative binding standard regime. But in this regime the key for obtaining efficiency gains requires firms to exhibit not too convex abatement costs. This is because with not too convex abatement costs firms are able

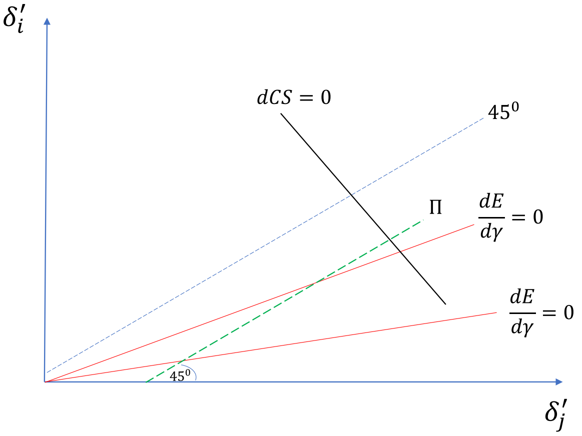


Fig. 6. Efficiency Gains.

to reduce total emissions relatively cheaply i.e., in Fig. 2 we are inside the curve where total emissions fall with a decrease in γ. The reduction in total emissions allows for a laxer standard in order to address the output distortion. But if abatement costs are convex enough, then total emissions rise and so welfare gains are not achieved. We summarize these results in the following proposition.

Proposition 3.5. *Consider a decrease in γ. Starting at welfare-equivalence there are efficiency gains in: (i) the tax regime if pollution intensities are sufficiently asymmetric, and (ii) in the relative binding standard regime if abatement costs are not too convex.*

This proposition says there are efficiency gains in industries which exhibit enough asymmetry in pollution intensities and that said gains are obtained under an emission tax. Under a relative binding standard policy regime the role of asymmetry in pollution intensities is negligible, where the convexity of the abatement cost function is more relevant. This implies that a market-based policy yields better outcomes in industries characterized by enough asymmetry in pollution intensities and a clear differentiation of eco-friendly products such as the olive oil industry, where organic versus non-organic production is becoming increasingly important.

4. Numerical exercise

In this section we test the strength of some of the relationships from our theoretical model. In particular, we test the strength of the impact of exogenous parameters δ_k', $k = i, j$ on the extent to which total emissions fall/rise with respect to γ. We seek to illustrate that in the tax regime sufficient asymmetry in pollution intensities is consistent with a reduction in total emissions when firms become more differentiated. Similarly, in the relative binding standard regime we argue that total emissions fall/rise with respect to γ when marginal abatement costs are sufficiently high. With these results we highlight the key implication from the analysis, namely, that an emission tax (a market-based policy) is a more flexible and efficient policy in industries with sufficient asymmetry in pollution intensities and where firms are differentiated as eco-friendly.

To keep the analysis tractable we rely on closed-form solutions which we work out in the Appendix and simplify calculations by assuming $\beta = 1$, $t = 1$ and $a = 150$, and consider $c_j = 50$, $c_i = 100$. We want to show that if a relatively polluting firm ($\delta_j' > \delta_i'$) becomes eco-friendly (in the sense of Definition 2.1), then total emissions fall in the tax regime if there is sufficient asymmetry in pollution intensities.

We perform a partial sensitivity analysis where each of the variables δ_i', δ_j' and γ vary one at a time following a uniform distribution. We also look at the case where these vary altogether. Following Maffia et al. (2020) we let the pollution intensities δ_i', δ_j' vary, respectively, between .22 and 1, and 1 and 3.3 following a truncated uniform distribution. These are the ranges for pollution intensities (low-polluting and high-polluting firms) in the olive oil sector based on data for olive oil production in the Mediterranean basin. We run 10,000 simulations based on a truncated uniform distribution for each partial sensitivity analysis.

Fig. 7 illustrates the results for the case of an emission tax. The left-hand-side chart shows parameters values for pollution intensities such that total emissions rise/fall with respect to changes in the degree of product differentiation for given γ. Positive (negative) values on the vertical axis indicate cases total emissions fall (rise) i.e., $dE/d\gamma > 0$ ($dE/d\gamma < 0$), where $d2$ and $d1$ in the figure represent δ_j' and δ_i', respectively. The right-hand-side chart maps the areas from Fig. 1 associated with the parameter values shown on the left-hand-side chart. In other words, the left-hand-side chart points to consistent results with our theoretical analysis.

Fig. 8 illustrates simulation results when δ_i', δ_j' and γ vary altogether. The Figure shows the shares of pollution intensities, δ_i'/δ_j', associated with a decrease in total emissions ($dE/d\gamma > 0$ in blue) and increase in total emissions ($dE/d\gamma < 0$ in absolute value in orange). If the pollution intensity of the eco-friendly firm is relatively large (small), then the values of the share δ_i'/δ_j' are relatively small (large) thus indicating sufficient asymmetry in pollution intensities, which are associated with reduction in total emissions ($dE/d\gamma > 0$ in blue). Similarly, for intermediate values (not sufficient asymmetry) we obtain pollution intensity shares associated

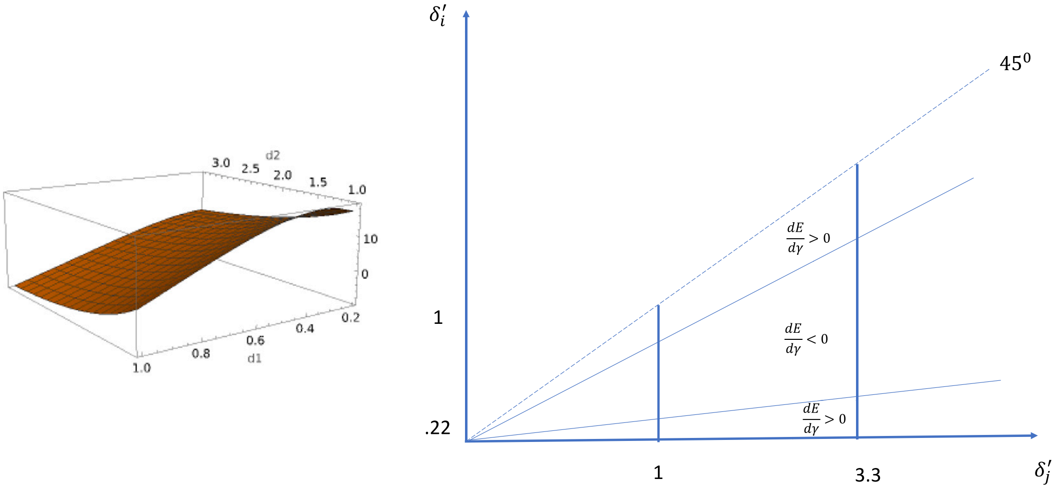


Fig. 7. Simulation Emission Tax Regime.

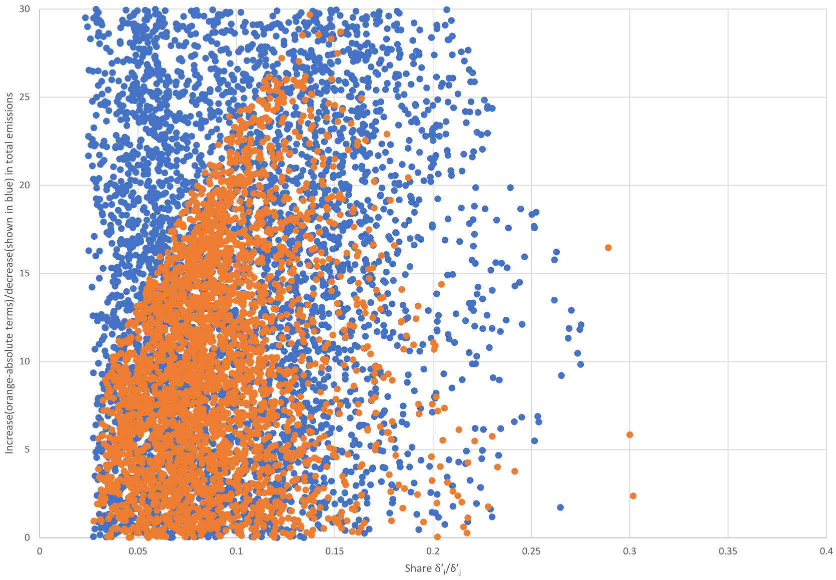


Fig. 8. Simulation Emission Tax: Share of Pollution Intensities and Changes in Total Emissions.

with an increase in total emissions ($dE/d\gamma < 0$ in orange). Overall, the Figure suggests that total emissions fall under sufficient asymmetry in pollution intensities.

In terms of the relative standard regime, we let δ_i', δ_j' and γ vary randomly altogether as in the case of the tax. We keep the values of β, c_k and a same as before (and $\delta^s = 1$) as well as the assumption on the distribution of δ_i', δ_j' and γ. But we find that for relatively high marginal abatement costs it becomes more expensive for firms to lower emissions as they differentiate themselves i.e., $dE/d\gamma < 0$ is more likely. We consider the range for marginal abatement costs in Bounadi et al. (2023) between $\$1,307$ and $\$1,644$. In the context of Fig. 2 this means that the area inside the curve $dE^s/d\gamma = 0$ becomes smaller with higher marginal abatement costs. For instance, for very low marginal abatement costs ($g_k' \simeq 0$, $k = i, j$) 99.94% out of the 10,000 simulations indicate reductions in total emissions ($dE/d\gamma > 0$). In contrast, for relatively high marginal abatement costs ($g_k' \simeq 1500$, $k = i, j$) 15.03% out of the 10,000 simulations indicate reductions in total emissions. This is shown on the right-hand-side pie charts in Fig. 9.

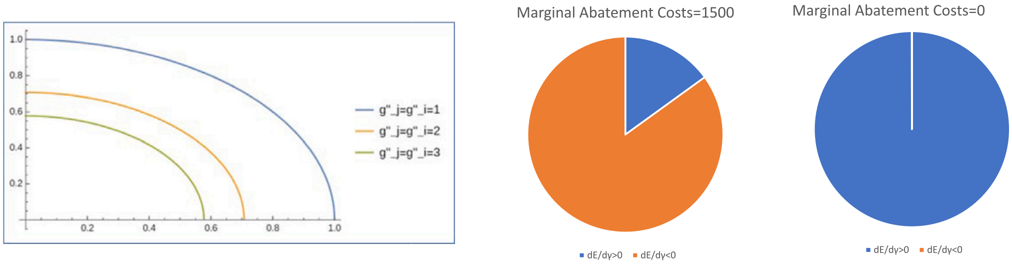


Fig. 9. Simulation Relative Binding Standard: Share of Reductions in Total Emissions and Marginal Abatement Costs.

We also explore the role of the convexity of the abatement cost function, where with relatively more convex abatement costs $dE/d\gamma < 0$ is more likely. This is shown on the left-hand-side chart in Fig. 9, where we plot the function $dE^s/d\gamma = 0$ for various levels of convexity of the abatement cost function, g_k'', $k = i, j$.

5. Uncertainty faced by environmentally-friendly firms

A key challenge for eco-friendly firms is the uncertainty on whether they can remain cost-competitive. For instance, there is evidence which points to higher yield variability in organic vis-à-vis non-organic conventional agriculture (Seufert and Ramankutty, 2017). Also, the presence of greater variability in weather patterns makes it harder on organic farmers to adopt methods to offset these weather effects on crops, but also cushion the higher incidence of pests that comes from weather variability and increase in temperature (Stacey, 2018). Further, although chemical fertilizers and pesticides used in conventional farming offer some buffering from variability in weather patterns, these may not be entirely consistent with environmentally-friendly production techniques (Bouttes et al., 2018). Overall, uncertainty affects the extent to which eco-friendly firms (in the olive oil extraction stage) supply the market with organic products cost-competitively.

In this section we argue that, in the presence of uncertainty, a stricter emission tax (relative binding standard) increases the chances for additional organic products to go into the market due to the presence of asymmetry in pollution intensities. This is because taxation renders the relatively high-polluting firm less cost-competitive thereby increasing the chances for the eco-friendly firm to supply the market. An analogous result holds for the standard, but only if the high-polluting firm exhibits high enough abatement costs. Moreover, the welfare-maximizing emission tax under uncertainty can be greater than the tax under no uncertainty and even exceed marginal damages. This is because a stricter emission tax increases the chances for the environmentally-friendly firm to supply the market, which in turn helps the government tackle emissions. The case for a relatively stricter relative binding standard under uncertainty is explained by the same forces, but under the standard the high-polluting firm must exhibit high enough abatement costs.

To incorporate uncertainty into the model we consider a three-stage game. In the first stage the government sets policy (whether an emission tax or relative standard) and in the second stage the uncertainty is resolved. Based on this, firms make a decision on the output and emissions in a Cournot-Nash fashion. In what follows we characterize the equilibrium under uncertainty in the emission tax and relative binding standard regimes.

5.1. Emission tax regime

To keep the analysis tractable, we let $i = 1$, $j = 2$ and assume an end-of-pipe cost function $c_k(x_k, e_k) = \bar{c}_k x_k + (\delta_k x_k - e_k)^2/2$, $k = 1, 2$ where $\delta_k > 0$ now denotes a constant pollution intensity for each firm. We follow Stathopoulou and Gautier (2019) and consider a market where firm 2 represents the environmentally-friendly firm, which exhibits higher marginal costs ($c_2 > c_1$), enjoys a smaller share of the market ($x_1 > x_2$) and exhibits a smaller pollution intensity ($\delta_1 > \delta_2$). Because firm 2 is eco-friendly, by definition it generates less pollution ($e_1 > e_2$). In this market firm 2 exhibits marginal costs, $\epsilon(c_2 + \delta_2 t)$. ϵ is a random variable uniformly distributed over the interval $[g, 1]$ with density function $f(\epsilon)$. We consider two scenarios. The first scenario captures the case where "full" environmentally-friendly production takes place, meaning that firm 2 (the eco-friendly firm) is able to supply the market to a greater extent. This case is labeled as "full EF". The second scenario represents the "partial" case, where the eco-friendly firm is able to supply the market to a lesser extent since it faces higher marginal costs. This case is labeled as "partial EF". Overall, ϵ captures the presence of uncertainty on the level of environmentally-friendly production that goes into the market. The implications on the equilibrium show up on the production levels by each firm:

$$\eta x_1^u = 2\beta\left(\alpha - c_1 - \delta_1 t\right) - \gamma\left(\alpha - \epsilon\left(c_2 + \delta_2 t\right)\right) \eta x_2^u = 2\beta\left(\alpha - \epsilon\left(c_2 + \delta_2 t\right)\right) - \gamma\left(\alpha - c_1 - \delta_1 t\right)$$

where $\eta > 0$ and the "u" superscript denotes uncertainty. The presence of uncertainty points to a decrease (increase) in the production of firm 1 (firm 2). This is because uncertainty prompts firm 2 to increase production to avoid losing market share, which in turn prompts firm 1 to react strategically by lowering output.

To formally define the "full" and "partial" scenarios, we derive a threshold for ϵ, $\bar{\epsilon}$, for which environmentally-friendly production goes into the market:

$$x_1^u < x_2^u \Leftrightarrow \epsilon < \frac{c_1 + \delta_1 t}{c_2 + \delta_2 t} = \bar{\epsilon} \tag{11}$$

whence we define the ranges under which "partial" and "full" scenarios take place:

$$\begin{aligned} \text{full EF if} \quad & \epsilon \in [g, \bar{\epsilon}) \\ \text{partial EF if} \quad & \epsilon \in (\bar{\epsilon}, 1] \end{aligned}$$

From Eq. (11) we find $\partial\bar{\epsilon}/\partial t > 0$, since $\delta_2 < \delta_1$, $c_2 > c_1$. That is, an increase in the emission tax renders the "full EF" scenario more likely. This is because $\bar{\epsilon}$ increases making the range for the "full EF" scenario longer. Intuitively, taxation affects the relatively high-polluting firm more, which forces that firm to lower production thereby increasing the chances of the eco-friendly product to go into the market. The implication of this result is that an emission tax is consistent with the policy objective of increasing the market share of eco-friendly products e.g., the "green growth" policy framework in the EU. In this sense, the emission tax and the environmentally-friendly production that goes into the market can be regarded as complements.

Proposition 5.1. *An increase in the emission tax makes the full EF scenario more likely.*

Next, we characterize the emission tax under uncertainty, t^u, and compare it to the case where uncertainty is absent, t^*. To make the analysis tractable to compare t^u and t^*, we assume a linear damage function i.e., $\varphi' = 1$. We define welfare under uncertainty as the sum of consumer surplus, tax revenue, profits minus damages as follows:

$$\begin{aligned} W^u = & \underbrace{\int_g^{\bar{\epsilon}} [CS_{fullEF} + \Pi_{fullEF} + tE_{fullEF} - E_{fullEF}] f(\epsilon) d\epsilon}_{W^u \text{ under full EF}} \\ & + \underbrace{\int_{\bar{\epsilon}}^1 [CS_{partialEF} + \Pi_{partialEF} + tE_{partialEF} - E_{partialEF}] f(\epsilon) d\epsilon}_{W^u \text{ partial EF}} \end{aligned} \tag{12}$$

where $\Pi = \pi_1 + \pi_2$. Integrating Eq. (12) yields a function $W^u(t, \bar{\epsilon}(t))$, from which the welfare-maximizing emission tax under uncertainty is characterized by

$$\frac{\partial W^u}{\partial t} + \frac{\partial W^u}{\partial \bar{\epsilon}} \frac{\partial \bar{\epsilon}}{\partial t} = 0 \tag{13}$$

where $\partial\bar{\epsilon}/\partial t > 0$ comes from (11).

Fig. 10 shows the main results (see Appendix F for a derivation of the Figure). First, absent any uncertainty and consistent with the literature (e.g., Requate, 2006) the welfare-maximizing second-best tax, t^*, (for any $\bar{\epsilon}$) falls short marginal damages to address the output distortion and encourage profits. Second, since $\bar{\epsilon}$ is a continuous and increasing function of the emission tax and since by definition $g < \bar{\epsilon} < 1$, then the welfare-maximizing emission tax under uncertainty may exceed marginal damages and, therefore, the welfare-maximizing tax absent any uncertainty i.e., $t^u > t^*$. The intuition for this result is that under uncertainty a higher emission tax makes the *full EF* scenario more likely. As a result, the government is able to address emissions from the high-polluting firm thereby increasing the chances for the eco-friendly (and less polluting) product to go into the market. This result points to the case where the emission tax and the eco-friendly production that goes into the market are complements.

Proposition 5.2. *The welfare-maximizing emission tax under uncertainty, t^u, may exceed marginal damages.*

5.2. Relative binding standard regime

To analyze uncertainty in the case of a relative binding standard, the eco-friendly firm, firm 2, faces marginal costs $\epsilon^s(c_2 + x_2(\delta - \delta^s)^2)$, where ϵ^s is the analogous term under the emission tax. Thus, the equilibrium under uncertainty is given by

$$\begin{aligned} \eta^{su} x_1^{su} &= (\alpha - c_1)\left(2\beta + \epsilon^s(\delta_2 - \delta^s)^2\right) - \gamma\left(\alpha - \epsilon^s c_2\right) \\ \eta^{su} x_2^{su} &= (\alpha - \epsilon^s c_2)\left(2\beta + (\delta_1 - \delta^s)^2\right) - \gamma\left(\alpha - c_1\right) \end{aligned}$$

where $\eta^{su} = \left(2\beta + \epsilon^s(\delta_2 - \delta^s)^2\right)\left(2\beta + (\delta_1 - \delta^s)^2\right) - \gamma^2 > 0$. Similar to the case of the emission tax, uncertainty increases the output of firm 2, the eco-friendly firm, to avoid losing market power, but this prompts firm 1 to react strategically by lowering output.

As before, we define the "full" and "partial" scenarios via a threshold ϵ, $\bar{\epsilon}^s$, for which environmentally-friendly production goes into the market:

$$x_1^{su} < x_2^{su} \Leftrightarrow \epsilon^s < \frac{c_1(2\beta + \gamma) + \alpha(\delta_1 - \delta^s)^2}{(\alpha - c_1)(\delta_2 - \delta^s)^2 + c_2\left(2\beta + \gamma + (\delta_1 - \delta^s)^2\right)} = \bar{\epsilon}^s \tag{14}$$

whence,

$$\text{full EF if} \quad \epsilon \in [g, \bar{\epsilon}^s)$$

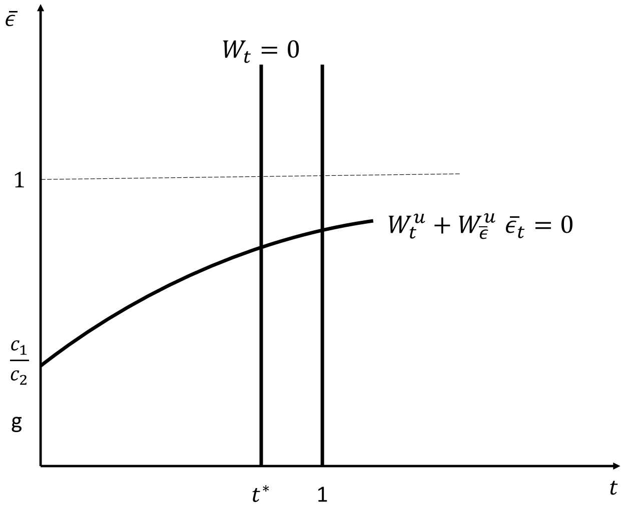


Fig. 10. The emission tax under uncertainty.

partial EF if $\epsilon \in (\bar{\epsilon}^s, 1]$

From (14) we find $\partial\bar{\epsilon}^s/\partial\delta^s < 0$, if abatement costs for the high-polluting firm, firm 1, are large enough. A decrease in the relative binding standard denotes a stricter policy. This means that a stricter standard renders the "full EF" scenario more likely. This is because an increase in $\bar{\epsilon}^s$ makes the range for the "full EF" scenario longer. Intuitively, a stricter relative binding standard affects abatement costs of the high-polluting firm enough so it reduces firm 1's output and thus makes the "full EF" scenario more likely. The standard increases the chances for the eco-friendly firm to increase its production. In this sense, a stricter standard and the eco-friendly production that goes into the market are complements. In contrast to the case of the emission tax, stricter policy here requires large enough abatement costs.

Proposition 5.3. *A stricter relative binding standard makes the full EF scenario more likely, if abatement costs of the high-polluting firm are large enough.*

We conclude the analysis by considering, similar to the case of the emission tax, a welfare function analogous to (12). Integration yields a function $W^{su}(\delta^s, \bar{\epsilon}^s(\delta^s))$, from which the welfare-maximizing relative binding standard under uncertainty, δ^{su*}, is characterized by $\partial W^{su}/\partial\delta^s + (\partial W^{su}/\partial\bar{\epsilon}^s)(\partial\bar{\epsilon}^s/\partial\delta^s) = 0$. To compare relative binding standards under uncertainty, δ^{su*}, and absent uncertainty, δ^{s*}, we use a Figure analogous to Fig. 10, which we show in Appendix G. We now offer an intuitive explanation of results. First, it is well known that the second-best relative binding standard is stricter the larger the damages from pollution i.e., $\delta^{s*} < 1$. Second, the relative binding standard under uncertainty may be even stricter. This is because a stricter standard makes the full EF scenario more likely so it helps control emissions coming from the high-polluting firm more effectively. This is because a stricter standard affects abatement costs of the high polluting firm more. But at the same time, it increases the chances for the environmentally-friendly product to go into the market. This result points to the fact that the relative binding standard and the production of the eco-friendly good are complements. Although the mechanism which leads to this result is similar to the case of the emission tax, the difference is the requirement that the polluting firm must exhibit high enough abatement costs.

Proposition 5.4. *The welfare-maximizing relative binding standard under uncertainty may be stricter than the relative binding standard absent uncertainty i.e., $\delta^{su*} < \delta^{s*}$, if abatement costs of the high-polluting firm are high enough.*

6. Conclusion

We study the design of environmental policy for the olive oil sector in the context of the 2023–2027 Common Agricultural Policy (CAP) regulatory framework and the EU's "green growth" initiative. To achieve objectives, we develop a model to compare the welfare effects of an emission tax and relative binding standard in an industry marked by asymmetries in pollution intensities and high degrees of product differentiation such as the olive oil industry. In other words, an industry where firms are differentiated as eco-friendly and where there is a set of high-polluting and low-polluting firms. In this context, we argue that an emission tax is welfare-enhancing because a tax is a more flexible and efficient policy option. Under a relative binding standard similar results are obtained as long as abatement costs are not too convex, which positions the standard as a more restrictive policy option.

In the context of the 2023–2027 CAP in the EU, the analysis suggests that more room may be given to market-based environmental policies as opposed to command-and-control policies, particularly when it comes to industries characterized by asymmetries in pollution intensities and where firms are differentiated as eco-friendly. Furthermore, our contribution to the existing theoretical literature rests on two fronts. First, we link the extent to which firms differentiate themselves in the market and their degree of pollution intensity through the properties of the cost function; in doing so we do not impose any conditions *a priori* on the link between product differentiation and pollution intensities thus allowing for a more general analysis. Second, the focus of the analysis is to examine the role of asymmetries in pollution intensities and convexity of abatement costs when it comes to the welfare effects under two environmental policies. These two aspects are key for an important set of industries such as the olive oil, wine and food production particularly when it comes to eco-friendly versus non-eco-friendly products.

We also look at the role of uncertainty in the design of environmental policy and show that an emission tax increases the chances for a higher production of the eco-friendly good in industries where asymmetry in pollution intensities is present. This is because a tax renders the high-polluting firm less cost competitive making the production of the eco-friendly good more likely. A corollary is that in the presence of uncertainty an emission tax may exceed taxation absent any uncertainty. We also show that a relative binding standard may yield analogous results but under more restrictive conditions i.e., sufficiently high abatement costs. Overall, we argue that an emission tax is welfare-enhancing because it encourages the production of the eco-friendly good, controls industry emissions and offers more flexibility to the eco-friendly firm. This suggests that the current design of environmental policy for industries which show uncertainty in the production of eco-friendly products may need to be revisited.

The model can be extended in several ways, but a natural extension is to consider the *n*-firm case. This would allow to look more explicitly at the role of market shares of eco-friendly firms, but also the entry of new firms of this type. That is, the extent to which the design of environmental policy may be altered as these types of firms enter the market and whether entry offsets the reduction in pollution that takes place by existing eco-friendly firms in the market. The literature points to the important role of free entry/exit in the design of policy (e.g., Katsoulacos and Xepapadeas, 1995; Lee, 1999) so its inclusion into the current framework is warranted. A second extension would be to consider not just the extraction stage of the production of olive oil. The olive oil sector consists of at least three stages production: cultivation, extraction and distribution. In this paper we focus on the extraction stage so modeling the interaction among these three stages would yield a richer analytical framework to capture the implications of policy.

Third, in the current model we consider horizontal product differentiation, but a different angle to look into the olive oil sector is to consider vertical differentiation. This would enable us to factor in three aspects when it comes to product quality: (1) Phenolic/volatile compounds i.e., variety of olive such as Hojiblanca or Picual, (2) the collection of olives i.e., physical integrity of the olive during collection, and (3) other quality aspects such as the quality of physical capital e.g., decanter.

Fourth, although we present a numerical exercise in Section 4, further empirical analyses are needed to validate some of the theoretical findings. Some of the aspects future empirical exercises may want to take into consideration include the structure of the industry, which consists of the collection and extraction of olive oil, and also its distribution. Additionally, region-specific and firm-specific characteristics, and current CAP regulations play an important role when it comes to the quantity of olive oil produced and whether eco-friendly techniques are being employed. Our theoretical findings set the foundation to empirically explore whether market-based environmental policy encourages the production of eco-friendly products and lowers emissions more effectively in industries where firms are transforming into eco-friendly firms (i.e., product differentiation) and where there is clearly a group of high-polluting and low-polluting firms (i.e., asymmetry in pollution intensities).

The analysis indicates that an emission tax is a better policy in industries where products are differentiated and there is clearly a set of high-polluting firms and a set of low-polluting firms. The reason an emissions tax is a better policy is because the presence of high-polluting and low-polluting firms (asymmetry in pollution intensities) promotes the production of the eco-friendly product and discourages the production of the non-eco-friendly product. As firms are differentiated as eco-friendly asymmetries in pollution intensities are reinforced thereby rendering the tax a more effective policy. This is consistent with empirical studies which point to carbon pricing as a way to reduce emissions and achieve efficiency gains in a myriad of industries (e.g., Tietenberg, 2013; Liu et al., 2023a,b. In contrast, with a relative binding standard abatement costs cannot be too convex to attain a similar outcome. That is, for the standard to be as effective as the tax firms need to satisfy this condition on their abatement cost structure. This condition offers less flexibility to firms and therefore policy-makers to lower emissions and increase the production of eco-friendly products.

CRediT authorship contribution statement

Luis Gautier: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Appendix A. Comparative statics

The section spells out the comparative statics analysis in the tax regime followed by the comparative statics analysis in the regime where the relative standard is set.

(i) The tax regime-

Consider the first-order conditions for firm i: $p_i - \beta x_i - \partial c_i(x_i, e_i)/\partial x_i = 0$ and $-\partial c_i(x_i, e_i) - t = 0$, where a similar set of equations applies to firm j: $p_j - \beta x_j - \partial c_j(x_j, e_j)/\partial x_j = 0$ and $-\partial c_j(x_j, e_j) - t = 0$. Then, costs are given by $c_k(x_k, e_k) = \bar{c}_k x_k + g_k(\delta_k(x_k) - e_k)$ for $k = i, j$. Hence,

$$\begin{aligned} p_i - \beta x_i - \bar{c}_i - t\delta_i' &= 0 \\ p_j - \beta x_j - \bar{c}_j - t\delta_j' &= 0 \end{aligned}$$

where $p_i = \alpha - \beta x_i - \gamma x_j$ and $p_j = \alpha - \beta x_j - \gamma x_i$. Differentiation with respect to the tax, t, and degree of product differentiation, γ, gives

$$\begin{aligned} -x_j d\gamma - 2\beta dx_i - \gamma dx_j - t\delta_i'' dx_i - \delta_i' dt &= 0 \\ -x_i d\gamma - 2\beta dx_j - \gamma dx_i - t\delta_j'' dx_j - \delta_j' dt &= 0 \end{aligned}$$

whence

$$\begin{aligned} \eta dx_i &= \left[\left(-2\beta - t\delta_j''\right)\delta_i' + \gamma\delta_j'\right] dt + \left[\left(-2\beta - t\delta_j''\right) x_j + \gamma x_i\right] d\gamma \\ \eta dx_j &= \left[\left(-2\beta - t\delta_i''\right)\delta_j' + \gamma\delta_i'\right] dt + \left[\left(-2\beta - t\delta_i''\right) x_i + \gamma x_j\right] d\gamma \end{aligned}$$

where $\eta = (2\beta + t\delta_i'')(2\beta + t\delta_j'') - \gamma^2 > 0$ comes from the determinant of the coefficient matrix.

Next, consider differentiation of total emissions, $E = e_i + e_j \Rightarrow dE = de_i + de_j$. Consider the first-order conditions: $g_i' - t = 0$ and $g_j' - t = 0$, where recall that $g_k = g_k\left(\delta_k(x_k) - e_k\right)$, $k = i, j$. Differentiation of first-order conditions $g_i' - t = 0$ and $g_j' - t = 0$ yields

$$\begin{aligned} g_i''\left[\delta_i' dx_i - de_i\right] - dt &= 0 \\ g_j''\left[\delta_j' dx_j - de_j\right] - dt &= 0 \end{aligned}$$

Substituting dx_i and dx_j gives

$$\eta de_i = \left[\delta_i'\left(-\beta - t\delta_j''\delta_i' + \gamma\delta_j'\right) - 1/g_i''\right] dt + \left[\delta_i'\left(-\beta - t\delta_j'' x_j + \gamma x_i\right)\right] d\gamma \tag{A.1}$$

$$\eta de_j = \left[\delta_j'\left(-\beta - t\delta_i''\delta_j' + \gamma\delta_i'\right) - 1/g_j''\right] dt + \left[\delta_j'\left(-\beta - t\delta_i'' x_i + \gamma x_j\right)\right] d\gamma \tag{A.2}$$

Then, (A.1) and (A.2) yield $dE = de_i + de_j$.

We complete this part of the comparative statics analysis by looking at the effects of the pollution intensity on output for given γ and t. Differentiation of firms' fisrt-order conditions gives

$$(4\beta^2 - \gamma^2) dx_i = -t2\beta d\delta_i' + t\gamma d\delta_j' \tag{A.3}$$

$$(4\beta^2 - \gamma^2) dx_j = -t2\beta d\delta_j' + t\gamma d\delta_i' \tag{A.4}$$

(ii) The binding relative standard regime -

Differentiation of the first-order conditions given by (8), $p_i^s - \beta x_i^s - \bar{c}_i^s - (\delta_i' - \delta^s) g_i^{s'} = 0$, $p_j - \beta x_j^s - \bar{c}_j^s - (\delta_j' - \delta^s) g_j^{s'} = 0$, where $p_i^s = \alpha - \beta x_i^s - \gamma x_j^s$, $p_j^s = \alpha - \beta x_j^s - \gamma x_i^s$ gives

$$\begin{aligned} \eta^s dx_i^s = &\left[g_i^{s'}\left(2\beta + g_j^{s'}\delta_j'' + g_j^{s''}\delta_j'(\delta_j' - \delta^s)\right) - \gamma g_j^{s'}\right] d\delta^s \\ &+ \left[-x_j^s\left(2\beta + g_j^{s'}\delta_j'' + g_j^{s''}\delta_j'(\delta_j' - \delta^s)\right) + \gamma x_i^s\right] d\gamma \\ &- g_i^{s'}\left[2\beta + g_j^{s'}\delta_j'' + g_j^{s''}\delta_j'(\delta_j' - \delta^s)\right] d\delta_i' + \gamma g_j^{s'} d\delta_j' \end{aligned} \tag{A.5}$$

$$\begin{aligned} \eta^s dx_j^s = &\left[g_j^{s'}\left(2\beta + g_i^{s'}\delta_i'' + g_i^{s''}\delta_i'(\delta_i' - \delta^s)\right) - \gamma g_i^{s'}\right] d\delta^s \\ &+ \left[-x_i^s\left(2\beta + g_i^{s'}\delta_i'' + g_i^{s''}\delta_i'(\delta_i' - \delta^s)\right) + \gamma x_j^s\right] d\gamma \\ &- g_j^{s'}\left[2\beta + g_i^{s'}\delta_i'' + g_i^{s''}\delta_i'(\delta_i' - \delta^s)\right] d\delta_j' + \gamma g_i^{s'} d\delta_i' \end{aligned} \tag{A.6}$$

where $\eta^s > 0$ denotes the determinant of the coefficient matrix in the relative standard regime. The two equations related to $[\cdot]d\gamma$ are ambiguous and $[\cdot]d\delta^s > 0$.

Next, total emissions in the relative binding standard regime are given by $E^s = e_i^s + e_j^s$, where $e_k = x_k^s \delta^s$, $k = i, j$. Then, differentiation and substituting (A.5) and (A.6) gives

$$\begin{aligned} dE^s &= \delta^s dx_i^s + x_i^s d\delta^s + \delta^s dx_j^s + x_j d\delta^s \\ &= \delta^s\left[-x_j^s\left(2\beta + g_j^{s'}\delta_j'' + g_j^{s''}\delta_j'(\delta_j' - \delta^s)\right) + \gamma x_i^s - x_i^s\left(2\beta + g_i^{s'}\delta_i'' + g_i^{s''}\delta_i'(\delta_i' - \delta^s)\right) + \gamma x_j^s\right] d\gamma \end{aligned}$$

$$
\begin{aligned}
&+\delta^s\left[-g_i^{s'}\left(2\beta+g_j^{s'}\delta_j''+g_j^{s''}\delta_j'(\delta_j'-\delta^s)\right)+\gamma g_i^{s'}\right]d\delta_i'\\
&+\delta^s\left[-g_j^{s'}\left(2\beta+g_i^{s'}\delta_i''+g_i^{s''}\delta_i'(\delta_i'-\delta^s)\right)+\gamma g_j^{s'}\right]d\delta_j'
\end{aligned}
$$

where the first line denotes $\partial E^s/\partial\gamma$ i.e., the effects on total emissions (for given pollution intensities) via $\partial x_i^s/\partial\gamma$ and $\partial x_j^s/\partial\gamma$. The second and third lines denote the effects on total emissions via changes in pollution intensities.

Appendix B. Derivation of Figs. 1–3

Derivation of Fig. 1

Consider total emissions $E = E(\gamma, \delta_i'(\gamma), \delta_j'(\gamma))$. Total differentiation gives

$$
\frac{dE}{d\gamma}=\frac{\partial E}{\partial\gamma}+\frac{\partial E}{\partial\delta_j'}\frac{\partial\delta_j'}{\partial\gamma}+\frac{\partial E}{\partial\delta_i'}\frac{\partial\delta_i'}{\partial\gamma}
$$

whence

$$
\begin{aligned}
\frac{dE}{d\gamma}&=\left[\frac{\delta_i'}{\omega_1}\left(-x_j(\beta+t\delta_j'')+\gamma x_i\right)+\frac{\delta_j'}{\omega_1}\left(-x_i(\beta+t\delta_i'')+\gamma x_j\right)\right]\\
&\quad+\left(-\delta_i'(\beta+t\delta_j'')+\delta_j'\gamma\right)\frac{t}{\omega_2}\frac{\partial\delta_i'}{\partial\gamma}+\left(-\delta_j'(\beta+t\delta_i'')+\delta_i'\gamma\right)\frac{t}{\omega_2}\frac{\partial\delta_j'}{\partial\gamma} \qquad \text{(B.1)}
\end{aligned}
$$

where $\omega_1 > 0$, $\omega_2 > 0$ denote the determinant of the coefficient matrix from the comparative statics.

To derive Fig. 1 we look at separately the first line and second line in (B.1). From the first line we consider $\partial E/\partial\gamma = 0$, whence

$$
\frac{\partial E}{\partial\gamma}=0\Leftrightarrow\frac{\delta_i'}{\delta_j'}=-\frac{\left(-x_i(\beta+t\delta_i'')+\gamma x_j\right)}{\left(-x_j(\beta+t\delta_j'')+\gamma x_i\right)}=-\frac{\partial x_j/\partial\gamma}{\partial x_i/\partial\gamma}>0 \qquad \text{(B.2)}
$$

Any pair of pollution intensities above (below) the expression in (B.2) means $\partial E/\partial\gamma > (<)0$, which implies that the term $dE/d\gamma$ is pushed upwards(downwards).

Next, set the second line in (B.1) equal to zero:

$$
\Psi=\left(-\delta_i'(\beta+t\delta_j'')+\delta_j'\gamma\right)\frac{t}{\omega_2}\frac{\partial\delta_i'}{\partial\gamma}+\left(-\delta_j'(\beta+t\delta_i'')+\delta_i'\gamma\right)\frac{t}{\omega_2}\frac{\partial\delta_j'}{\partial\gamma}=0
$$

whence,

$$
\Psi=0\Leftrightarrow\frac{\delta_i'}{\delta_j'}=-\frac{\left(-(\beta+t\delta_i'')\frac{\partial\delta_j'}{\partial\gamma}+\gamma\frac{\partial\delta_i'}{\partial\gamma}\right)}{\left(-(\beta+t\delta_j'')\frac{\partial\delta_i'}{\partial\gamma}+\gamma\frac{\partial\delta_j'}{\partial\gamma}\right)}>0 \qquad \text{(B.3)}
$$

where $\partial\delta_j'/\partial\gamma > 0$, $\partial\delta_j'/\partial\gamma < 0$, $\delta_k'' > 0$ $k = i, j$. Any pair of pollution intensities above (below) the expression in (B.3) means $\Psi > (<)0$, which implies that the term $dE/d\gamma$ is pushed upwards(downwards).

It is not clear how $\Psi = 0$ and $\partial E/\partial\gamma = 0$ relate with each other. So we consider two possibilities. In the first case, pollution intensity pairs captured by $\Psi = 0$ are above those pollution intensities pairs captured by $\partial E/\partial\gamma = 0$. In this case, there must be pairs of pollution intensities in between $\Psi = 0$ and $\partial E/\partial\gamma = 0$ such that $dE/d\gamma = 0$. In the second case, pollution intensity pairs captured by $\Psi = 0$ are below those pollution intensity pairs captured by $\partial E/\partial\gamma = 0$. Thus, there must be pairs of pollution intensities in between $\Psi = 0$ and $\partial E/\partial\gamma = 0$ such that $dE/d\gamma = 0$, too. These two cases are captured by the two lines in Fig. 1: the relatively steep line captures the first case (where pollution intensity pairs from $\Psi = 0$ are above those from $\partial E/\partial\gamma = 0$), whereas the second case captures the relatively flat line (where pollution intensity pairs from $\Psi = 0$ are below those from $\partial E/\partial\gamma = 0$).

To complete the construction of Fig. 1 need to show that $\Psi = 0$ and $\partial E/\partial\gamma = 0$ lie below the 45-degree line when $\partial\delta_j'/\partial\gamma > 0$, $\partial\delta_i'/\partial\gamma < 0$. First, suppose the expression in (B.2) from $\partial E/\partial\gamma = 0$ is greater than 1:

$$
-\frac{\left(-x_i(\beta+t\delta_i'')+\gamma x_j\right)}{\left(-x_j(\beta+t\delta_j'')+\gamma x_i\right)}\geq 1
$$

where the denominator (numerator) is negative (positive) since $\partial x_i/\partial\gamma < 0$ ($\partial x_j/\partial\gamma > 0$). Then,

$$
\begin{aligned}
&-x_i(\beta+t\delta_i'')+\gamma x_j > x_j(\beta+t\delta_j'')-\gamma x_i \geq 1\\
&x_i(-\beta-t\delta_i''+\gamma)+x_j(-\beta-t\delta_j''+\gamma)\geq 0 \qquad \text{(B.4)}
\end{aligned}
$$

But this is a contradiction since the left-hand-side is negative.

Next, consider expression in (B.3) to be less than 1. This yields

$$
-\frac{\partial\delta_j'/\partial\gamma}{\partial\delta_i'/\partial\gamma}<\frac{\beta+t\delta_j''-\gamma}{\beta+t\delta_i''-\gamma}
$$

Thus, this inequality says that the pairs of pollution intensities given by $\Psi = 0$ are below the 45-degree line as long as the effect of γ on δ_j' is not too large.

Derivation of Fig. 2. Consider $dE^s/d\gamma = 0$ (i.e., Eq. (9)- the change in total emissions in the standard regime with respect to the degree of product differentiation):

$$\begin{aligned}\frac{1}{\delta^s}\frac{dE^s}{d\gamma} = 0 \Leftrightarrow \frac{x_j + g_i'\partial\delta_i'/\partial\gamma}{x_i + g_j'\partial\delta_j'/\partial\gamma}\left(-2\beta - g_j'\delta_j'' - g_j''\delta_j'(\delta_j' - \delta^s) + \gamma\right) - (2\beta + \gamma_i'\delta_i'' + \gamma) = \delta_i' g_i''(\delta_i' - \delta^s)\\ \Leftrightarrow \hat{\Psi} = (\delta_i')^2 g_i'' + (\delta_j')^2 g_j''\Gamma \qquad \text{(B.5)}\end{aligned}$$

where (B.5) is used to draw Fig. 2 and where

$$\begin{aligned}\Gamma &= \frac{x_j + g_i'\partial\delta_i'/\partial\gamma}{x_i + g_j'\partial\delta_j'/\partial\gamma} > 0\\ \hat{\Psi} &= \lambda + \delta_i' g_i''\delta^s + \delta_j' g_j''\delta^s\Gamma > 0\\ \lambda &= \frac{x_j + g_i'\partial\delta_i'/\partial\gamma}{x_i + g_j'\partial\delta_j'/\partial\gamma}\left(-2\beta - g_j'\delta_j'' + \gamma\right) - (2\beta + g_i'\delta_i'' + \gamma)\end{aligned}$$

Derivation of Fig. 3. We first derive the function $W_t = 0$ in Fig. 3. First, consider the first-order condition $\partial W/\partial t = 0$ from which we get

$$\delta_i'\frac{\partial x_i}{\partial t} + \delta_j'\frac{\partial x_j}{\partial t} = \frac{1}{g_i''} + \frac{1}{g_j''} - \frac{\beta}{(t - \varphi')}\left(x_i\frac{\partial x_i}{\partial t} + x_j\frac{\partial x_j}{\partial t}\right)$$

where the right-hand side is negative. At $\delta_j' = 0$ we obtain the vertical intercept in Fig. 3. Similarly, at $\delta_i' = 0$ we obtain the vertical intercept in the Figure.

Next, we derive the curvature of the function $W_t = 0$ for $\delta_i' < \delta_j'$. Consider again the first-order condition $\partial W/\partial t = 0$:

$$\delta_i'\frac{\partial x_i}{\partial t} + \delta_j'\frac{\partial x_j}{\partial t} = \frac{1}{g_i''} + \frac{1}{g_j''} - \frac{\beta}{(t - \varphi')}\left(x_i\frac{\partial x_i}{\partial t} + x_j\frac{\partial x_j}{\partial t}\right)$$

Substituting the expression for $\partial x_i/\partial t$ and $\partial x_j/\partial t$ yields

$$\begin{aligned}-\left(\frac{1}{g_i''} + \frac{1}{g_j''}\right)\eta &= (\delta_i')^2(\beta + t\delta_j'') + (\delta_j')^2(\beta + t\delta_i'') - 2\delta_i'\delta_j'\gamma\\ &\quad - \frac{\beta\delta_i'}{t - \varphi'}\left(x_i(\beta + t\delta_j'') + x_j\gamma\right) - \frac{\beta\delta_j'}{t - \varphi'}\left(x_j(\beta + t\delta_i'') + x_i\gamma\right)\end{aligned}$$

where $\eta > 0$. Then, for given g_k'', x_k, t, δ_k'', $k = i, j$, differentiation yields

$$\frac{d\delta_i'}{d\delta_j'} = -\frac{2(\beta + t\delta_i'')\delta_j' - 2\gamma\delta_i' - \frac{\beta}{t-\varphi'}\left(x_j(\beta + t\delta_i'') + x_i\gamma\right)}{2(\beta + t\delta_j'')\delta_i' - 2\gamma\delta_j' - \frac{\beta}{t-\varphi'}\left(x_i(\beta + t\delta_j'') + x_j\gamma\right)} \qquad \text{(B.6)}$$

To show the shape of the $W_t = 0$ function we evaluate (B.6) at $\delta_i' = \delta_j'$ and $\delta_i' < \delta_j'$.

At $\delta_i' = \delta_j'$ we obtain $d\delta_i'/d\delta_j' = -1$. Next, at $\delta_i' < \delta_j'$ we show that $|d\delta_i'/d\delta_j'| > 1$. We show this result by contradiction. Suppose (i) $|d\delta_i'/d\delta_j'| \le 1$ and (ii) $\delta_i' < \delta_j'$. Using (B.6) and collecting terms yields

$$\delta_j'\left(2(\beta + t\delta_i'') + 2\gamma\right) - \delta_i'\left(2(\beta + t\delta_j'') + 2\gamma\right) \le -\frac{\beta}{t - \varphi'}\left(x_i(-\beta - t\delta_j'') - x_j(-\beta - t\delta_i'') + \gamma(x_j - x_i)\right)$$

Since $\delta_i' < \delta_j'$, $x_j < x_i$. Then, assume $\delta_i'' = \delta_j''$, which gives

$$(\delta_j' - \delta_i')\left(2\beta + t\delta''\right) \le -\frac{\beta(x_i - x_j)}{t - \varphi'}\left(-\beta - t\delta'' - \gamma\right) < 0 \qquad \text{(B.7)}$$

As a result, $\delta_i' > \delta_j'$. But this contradicts (ii).

Next we derive the function $\tilde{W}_{\delta^s} = 0$ in Fig. 3. Consider $W_{\delta^s}(\delta_i', \delta_j') = 0$, whence differentiation gives the expression for $d\delta_i'/d\delta_j'$. In particular,

$$\beta x_1\frac{\partial x_i}{\partial\delta^s} + \beta x_j\frac{\partial x_j}{\partial\delta^s} + x_i^2(\delta_i' - \delta^s) + x_j^2(\delta_j' - \delta^s) - \varphi'\frac{\partial E}{\partial\delta^s} = 0 \qquad \text{(B.8)}$$

It is noteworthy that the third and fourth terms denote the costs associated with the standard, where a higher x_k^2 captures a relatively more convex cost function in δ_k'. That is, firm k is relatively more sensitive with respect to the standard. Differentiation of (B.8) gives

$$0 = \left[\left(-\varphi'\frac{\partial^2 E}{\partial\delta^s\partial\delta_i'} - \varphi''\frac{\partial E}{\partial\delta^s}\frac{\partial E}{\partial\delta_i'}\right) + \frac{\partial x_1}{\partial\delta_i'}\left(\beta\frac{\partial x_i}{\partial\delta^s} + 2x_i(\delta_i' - \delta^s)\right) + \frac{\partial x_j}{\partial\delta_i'}\left(\beta\frac{\partial x_j}{\partial\delta^s} + 2x_j(\delta_j' - \delta^s)\right)\right.$$

$$\begin{aligned}
&+\beta x_i \frac{\partial^2 x_i}{\partial\delta^s \partial\delta'_i} + \beta x_j \frac{\partial^2 x_j}{\partial\delta^s \partial\delta'_i} + x_i^2 \Bigg] d\delta_i \\
&+ \left[\left(-\varphi' \frac{\partial^2 E}{\partial\delta^s \partial\delta'_j} - \varphi'' \frac{\partial E}{\partial\delta^s}\frac{\partial E}{\partial\delta'_j}\right) + \frac{\partial x_j}{\partial\delta'_j}\left(\beta\frac{\partial x_j}{\partial\delta^s} + 2x_j(\delta'_j - \delta^s)\right) + \frac{\partial x_i}{\partial\delta'_j}\left(\beta\frac{\partial x_i}{\partial\delta^s} + 2x_i(\delta_i - \delta^s)\right)\right. \\
&\left.+\beta x_i \frac{\partial^2 x_i}{\partial\delta^s \partial\delta'_j} + \beta x_j \frac{\partial^2 x_j}{\partial\delta^s \partial\delta'_j} + x_j^2 \right] d\delta'_j
\end{aligned} \tag{B.9}$$

where

$$\frac{\partial^2 E}{\partial\delta^s \partial\delta'_k} < 0, \frac{\partial E}{\partial\delta'_k} < 0, \frac{\partial x_k}{\partial\delta'_k} > 0, \frac{\partial x_k}{\partial\delta'_{-k}} > 0$$

From (B.9) consider damages to be sufficiently large so that they dictate the sign of $d\delta'_i/d\delta'_j$. In this case (B.9) becomes

$$\left[\left(-\varphi' \frac{\partial^2 E}{\partial\delta^s \partial\delta'_i} - \varphi'' \frac{\partial E}{\partial\delta^s}\frac{\partial E}{\partial\delta'_i}\right)\right] d\delta'_i + \left[\left(-\varphi' \frac{\partial^2 E}{\partial\delta^s \partial\delta'_j} - \varphi'' \frac{\partial E}{\partial\delta^s}\frac{\partial E}{\partial\delta'_j}\right)\right] d\delta'_j = 0 \tag{B.10}$$

As a result, $d\delta'_i/d\delta'_j < 0$. Next, suppose output distortion effects are large enough where own effects dominate; that is,

$$\frac{\partial x_k}{\partial\delta'_k}\left(\beta\frac{\partial x_k}{\partial\delta^s} + 2x_k(\delta'_k - \delta^s)\right) + \frac{\partial x_{-k}}{\partial\delta'_k}\left(\beta\frac{\partial x_{-k}}{\partial\delta^s} + 2x_{-k}(\delta'_{-k} - \delta^s)\right) + \beta x_k \frac{\partial^2 x_k}{\partial\delta^s \partial\delta'_k} + \beta x_{-k} \frac{\partial^2 x_{-k}}{\partial\delta^s \partial\delta'_k} < 0 \tag{B.11}$$

As a result, $d\delta'_i/d\delta'_j < 0$.

Next, consider $\tilde{W}_{\delta^s} = 0$ from (B.8), whence

$$\delta'_i = -\frac{x_j^2}{x_i^2}\delta'_j + \delta^s(x_i^2 + x_j^2) - \left(\beta x_i \frac{\partial x_i}{\partial\delta^s} + \beta x_j \frac{\partial x_j}{\partial\delta^s} - \varphi'\frac{\partial E}{\partial\delta^s}\right) \tag{B.12}$$

where with sufficiently convex costs for firm j in δ_j the term x_j^2/x_i^2 is large in absolute value. This depicts the relatively steepness of the curve $\tilde{W}_{\delta^s} = 0$.

Appendix C. Proof of Proposition 3.2 (welfare-equivalence)

In equilibrium, the δ'_i's and δ'_j's are the same across regimes and a function of γ. As a result, the γ across regime is the same. If $W_{t\delta_j}/W_{t\delta_i} = \tilde{W}_{\delta^s\delta_j}/\tilde{W}_{\delta^s\delta_i}$, then it follows that there is a unique γ^* which satisfies equality i.e., welfare equivalence holds.

Appendix D. Derivation of Fig. 6

We construct Fig. 6 by superimposing $dCS = 0$ and Π onto Fig. 1. Next, we derive the expressions for $dCS = 0$ and Π.

Consider $CS = CS(x_i, x_j)$, where differentiation gives

$$\begin{aligned}
dCS &= -x_i dp_i - x_j dp_j \\
&= -x_i\left(-\beta dx_i - \gamma dx_j\right) - x_j\left(-\beta dx_j - \gamma dx_i\right) \\
&= \left(\beta x_i + \gamma x_j\right) dx_i + \left(\beta x_j + \gamma x_i\right) dx_j
\end{aligned} \tag{D.1}$$

Next, to show that the slope of $dCS = 0$ is equal to -1 we use the following comparative statics analysis. From firms' first-order conditions we obtain

$$(4\beta^2 - \gamma^2)dx_i = -t2\beta d\delta'_i + t\gamma d\delta'_j \tag{D.2}$$

$$(4\beta^2 - \gamma^2)dx_j = -t2\beta d\delta'_j + t\gamma d\delta'_i \tag{D.3}$$

Substituting these into (D.1) and setting it equal to zero gives

$$dCS = 0 \Leftrightarrow \frac{d\delta'_i}{d\delta'_j} = -1 \tag{D.4}$$

Next, we turn to the expression for Π. Consider firms' first-order conditions:

$$p_i - \beta x_i - \tilde{c}_i - \delta'_i t = 0 \tag{D.5}$$

$$p_j - \beta x_j - \tilde{c}_j - \delta'_j t = 0 \tag{D.6}$$

Setting (D.5) and (D.6) equal to each other gives

$$\delta'_i = \frac{1}{t}\left(-(p_j - \beta x_j - \tilde{c}_j) + (p_i - \beta x_i - \tilde{c}_i)\right) + \delta'_j \tag{D.7}$$

where the term in parenthesis is negative since $\delta_i' < \delta_j'$ i.e., the analysis in the case $\partial\delta_i'/\partial\gamma < 0$, $\partial\delta_j'/\partial\gamma > 0$ is consistent for $\delta_i' < \delta_j'$ as shown in Fig. 1. Eq. (D.7) is what we denote as Π and draw in Fig. 6.

Differentiation of (D.7) and substituting (D.2) and (D.3) yields

$$\begin{aligned}
d\delta_i' &= \frac{1}{t}\left(-(dp_j - \beta dx_j) + (dp_i - \beta dx_i)\right) + d\delta_j' \\
d\delta_i' &= \frac{1}{t}\left(2\beta dx_j + \gamma dx_i - 2\beta dx_i - \gamma dx_j\right) + d\delta_j' \\
\frac{d\delta_i'}{d\delta_j'} &= \frac{(2\beta-\gamma)\left(\frac{\partial x_j}{\partial\delta_j'} - \frac{\partial x_i}{\partial\delta_j'}\right) + t}{-(2\beta-\gamma)\left(\frac{\partial x_j}{\partial\delta_i'} - \frac{\partial x_i}{\partial\delta_i'}\right) + t} \\
\frac{d\delta_i'}{d\delta_j'} &= -1
\end{aligned}$$

It is noteworthy that in the Figure because at the pollution intensity pair where $dE/d\gamma > 0$, the intersection between $dCS = 0$ and Π must take place at that same pollution intensity pair. That is, if we start at a pollution intensity pair where $dE/d\gamma > 0$ this must also be the pollution intensity pair where $dCS = 0$ intersects Π. We ensure this because of the slope of $dCS = 0$ is minus one, and the slope of Π is one.

Appendix E. Closed-form solution for the numerical exercise

In this section we spell out the specific functional forms we use to derive the closed-form solutions and thus run the numerical exercise in Section 5.

We consider the following cost function for each firm $k = i, j$: $c(x,e) = \left(\theta x^2/2 - e\right)^2$, where $\theta x^2/2$ denotes gross pollution (i.e., this is our δ function in the general setting). As a result, $\delta' = \theta x$; that is, as in our general setup δ' is a function of output and therefore, in equilibrium, a function of γ. Moreover, $\delta'' = \theta$ and the properties of the cost function imply (subscripts denote partial derivatives): $c_x = \bar{c} + \theta x\left(\theta x^2/2 - e\right)$; $c_{xx} = (\theta x)^2 + \theta\left(\theta x^2/2 - e\right)$; $c_{xe} = c_{ex} = -\theta x$; $c_e = -\left(\theta x^2/2 - e\right)$; $c_{ee} = \left(\theta x^2/2 - e\right)$. Keeping linearity of demand yields closed-form solutions for the tax and relative binding standards. We use these and the resulting comparative static analysis to run the numerical exercise in Section 5.

Appendix F. Derivation of Fig. 10

First, recall that marginal damages are equal to one because of the linearity assumption of the damage function. This gives the vertical line shown in figure. Second, under oligopoly the second-best tax, t^*, is less than marginal damages and since this is the case absent uncertainty we get the vertical line shown in figure. Third, from $\partial W^u/\partial t + (\partial W^u/\partial\bar{\epsilon})(\partial\bar{\epsilon}/\partial t) = 0$ we get $\partial\bar{\epsilon}/\partial t = -(\partial W^u/\partial t)/(\partial W^u/\partial\bar{\epsilon}) > 0$. This expression is positive from (11), where $\delta_1 > \delta_2$, and $c_2 > c_1$. Then, at $t = 0$, $\bar{\epsilon} = c_1/c_2 < 1$. To ensure $\bar{\epsilon} < 1$ for all t, we impose the condition $t(\delta_1 - \delta_2) > c_2 - c_1$.

Appendix G. Relative binding standard with and without uncertainty

Similar to Fig. 10 we have $\delta^{s*} < 1$ for any $\bar{\epsilon}^s$. Using (11) it can be shown that $\partial\bar{\epsilon}^s/\partial\delta^s < 0$, if abatement costs of the high-polluting firm, firm 1, are large enough; that is,

$$\partial\bar{\epsilon}^s/\partial\delta^s < 0 \Leftrightarrow \frac{\delta_1 - \delta^s}{c_1} - \frac{\delta_2 - \delta^s}{c_2} > \frac{\alpha(\delta_1 - \delta^s)(\delta_2 - \delta^s)(\delta_1 - \delta_2)}{c_1 c_2(2\beta + \gamma)} \tag{G.1}$$

Fig. 11 points to the fact that $\bar{\epsilon}^s < 1$ if abatement costs of firm 1 are large enough:

$$\bar{\epsilon}^s < 1 \Leftrightarrow \frac{(\delta_1 - \delta^s)^2}{\alpha - c_1} - \frac{(\delta_2 - \delta^s)^2}{\alpha - c_2} < \frac{(2\beta + \gamma)(c_2 - c_1)}{(\alpha - c_1)(\alpha - c_2)} \tag{G.2}$$

Combining (G.1) and (G.2) we get that with large enough abatement costs for firm 1, $\bar{\epsilon}^s < 1$ and $\partial\bar{\epsilon}^s/\partial\delta^s < 0$, which ensures $\delta^{us*} < \delta^{s*}$:

$$\frac{(2\beta + \gamma)(c_2 - c_1)}{(\alpha - c_1)(\alpha - c_2)} > \frac{(\delta_1 - \delta^s)^2}{\alpha - c_1} - \frac{(\delta_2 - \delta^s)^2}{\alpha - c_2} > \frac{\delta_1 - \delta^s}{c_1} - \frac{\delta_2 - \delta^s}{c_2} > \frac{\alpha(\delta_1 - \delta^s)(\delta_2 - \delta^s)(\delta_1 - \delta_2)}{c_1 c_2(2\beta + \gamma)}$$

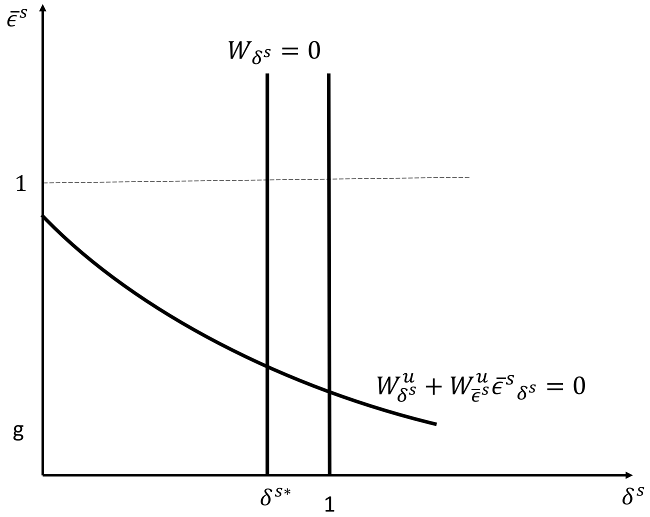

Fig. 11. Relative binding standard under uncertainty.

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