Environmental Policy Design for the Olive Oil Sector

Luis Gautier
University of Texas at Tyler
Department of Social Sciences, 3900 University Blvd.,
Tyler, TX 75799, US
E-mail: lgautier@uttyler.edu

Abstract

In the olive oil sector firms are increasingly transforming themselves into environmentally-friendly firms. This transformation is marked by asymmetries in pollution intensities and high degrees of product differentiation. 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. The analysis suggests that with sufficient asymmetry in pollution intensities an emission tax and relative binding standard are welfare-equivalent, but an emission tax is welfare-enhancing in the presence of sufficiently high degree of product differentiation. 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. With these building blocks we argue that an emission tax is welfare-enhancing relative to the relative binding standard in industries where firms are becoming increasingly more environmentally friendly. We extend the analysis by incorporating uncertainty into our modelling strategy and show *inter alia* that an emission tax and the production of environmentally-friendly products are complements.

JEL Classification: Q5, G34

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1 Introduction

1.1 Background and motivation

The global production of olive oil has been steadily rising to meet its growing global demand (Mielke, 2019; Caja Rural de Jaén, 2020). The cultivation of olives using high-intensive-yield techniques has become more prevalent as a result, but these normally come at the expense of environmental degradation. Further, 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, increasingly firms in the olive oil sector are transforming themselves by adopting environmentally-friendly cultivation and extraction techniques (Carrillo et al., 2016; Caja Rural de Jaén, 2020).[2] This transformation is regarded as a key business strategy for the sector (Parras, 2020). 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) would be welfare-enhancing.

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 (Parakeva and Diamadopoulos 2006; Labella et al., 2017). For example, the EU is one of the largest producers of olive oil worldwide, representing about 67% of

[1]For data on the pollution generated by the cultivation, extraction and distrubution 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).

[2]In Spain, for instance, the EU's "aceites ecológicos" (eco-friendly) labelling certification allows olive oil producers to differentiate themselves by signaling that they employ environmentally-friendly production techniques through the cultivation process, where soil-protection techniques and compost-based fertilizers are employed. In addition, waste from olive oil extraction (e.g., olive pomace) may be transformed into renewable energy and olive mill wastewater may be transformed into fertilizers and antioxidants for human consumption.

the world's olive oil production,[3] where environmental standards are a key policy within the EU-wide regulatory framework of "green growth", but also the recently proposed reforms on the common agricultural policy (CAP) which seek to promote sustainable food production.[4] 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 environmentally friendly to exploit new markets and lower their negative impact on the environment. However, in this context little 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 product differentiation and asymmetry in pollution intensities? Does an emission tax offer firms enough flexibility when it comes to supplying the market with environmentally-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 environmentally-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 can be 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 environmen-

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

[4] 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.

tally friendly. This implies that in those industries where the current policy approach is a command-and-control type and where firms' strategies focus on differentiating themselves as environmentally friendly, the policy approach may need to be revisited.

Results are 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, particulalry 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. But 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).

1.2 Contribution to existing studies

We now discuss our contribution to the existing 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.

The environmental-standards-versus-emission-taxes literature is vast (see Bárcena-Ruiz and Campo (2017) for a brief survey). 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.

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), profit-shifting incentives (e.g., Ulph 1992; Antoniou et al., 2012), free-entry and exit (e.g., Lahiri and Ono, 2007), and cross-ownership (Bárcena-Ruiz and Campo, 2017). We add to this literature by arguing that product differentiation and asymmetry in pollution intensities determine which policy is welfare-enhancing.[5] As explained in the previous section, this is important in industries where firms are increasingly attempting to differentiate themselves as environmentally friendly.

Our analytical strategy consists of two steps. First, we consider two types of regimes where the government sets policy. One regime considers an emission tax and the second regime a binding relative emission standard. 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 and pollution intensity. This analytical approach is new to the environmental economics literature. Second, in comparing the two regimes a rubric is derived to determine whether an emission tax or a binding relative standard is welfare-enhancing for varying degrees of product differentiation and pollution intensities. Even though we show that a tax and standard can produce welfare-equivalent outcomes under certain conditions, overall an emission tax is welfare-enhancing in the case where product differentiation becomes a key firm strategy. Indeed, we derive a sufficient condition where an emission tax is welfare-enhancing if pollution intensities lie in the convex set of the welfare-maximizing tax.

Intuitively, the reason the tax is welfare-enhancing is because it controls emissions rel-

[5] 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 show that the emission tax can be welfare-superior to the standard because under the tax the presence of product differentiation implies lower emissions.

atively more effectively as firms become more differentiated. This is because under taxation environmentally friendly firms have enough flexibility to control their pollution intensities sufficiently thereby controlling emissions. This is not possible under a relative standard because it is binding, meaning the standard offers less flexibility when it comes to allowing firms to control emissions via their pollution intensities i.e., as firms become more differentiated. But the reason both policies might be equivalent in the presence of sufficient asymmetry is because convex abatement costs allows the relative binding standard to control emissions as effectively as the tax. This is because with convex abatement costs in pollution intensities firms control emissions via lower output without the need for a too stringent standard.

We then add uncertainty into the model to capture a key challenge facing environmentally-friendly firms, namely, how to stay cost-competitive vis-à-vis firms which are not attempting to differentiate themselves as environmentally-friendly (Stacey 2010). We argue *inter alia* that a stricter emission tax increases the chances of supplying the market with more environmentally-friendly products. This is because taxation renders the high-polluting firm less cost-competitive, thereby opening the possibility for a higher production of the environmentally-friendly product. In this sense, taxation and the production of environmentally-friendly product 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 environmentally-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 environmentally-friendly goods.

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 lense of product differentiation and pollution intensities. Section 4 considers uncertainty and Section 5 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 modelling strategy we focus on the extraction of olive oil stage. This is because at the extraction stage we are able to capture two aspects which are crucial when it comes to product differentiation, asymmetries in pollution intensities and thus how consumers perceive an environmentally-friendly product: (i) organically-grown olives which employ,say, less chemicals and soil-protecting methods, and (ii) waste-reducing and energy-saving techniques employed during the extraction process.

With this in mind, consider a Cournot duopoly model where each firm $i = 1, 2$ chooses its level of output, x_i, and emissions after abatement, e_i, simultaneously. For instance, x_i and e_i represent, respectively, units of olive oil extracted and emissions after abatement coming from said extraction process. Preferences are captured through an inverse demand function $p_i = a - \beta x_i - \gamma x_j$, where $i \neq j$ and $0 \leq \gamma \leq \beta$ indicates the degree of product differentiation. If products are completely differentiated (homogenenous), then $\gamma = 0(\beta)$. For instance, a relatively low γ may denote an organically-grown olive oil crop versus a non-organic one from which olive oil is extracted, or an olive oil extraction technique with a lower carbon-footprint, both of which are known by consumers. Production and abatement costs for each firm are represented by a function of the end-of-pipe $c_i(x_i, e_i) = \bar{c}_i x_i + (\delta_i x_i - e_i)^2/2$, where the constant $\bar{c}_i > 0$ denotes marginal production costs and δ_i denotes pollution intensity for each firm i. For instance, δ may denote emissions per unit of olive oil extracted. This 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 environmentally friendly, we assume pollution intensity depends positively on the degree of product differentiation, $\delta_i = \delta_i(\gamma)$, where $\delta_i^{'}(\gamma) > 0$. The idea here is that relatively more differentiated products (decrease in γ) are also relatively less pollution intensive (decrease in δ). This type of setup is used in Fikru and Gautier (2016). For example, if olive oil extraction is based on organically-grown crops or employs less-polluting extraction techniques thus exhibiting low γ (this is differentiated from the non-organic crops or high-polluting extraction technique exhibiting high γ), then extraction is less energy intensive or less chemical intensive due to the organic crops and, consequently, exhibits a lower emissions per unit of output or low δ (high δ).

Two types of independent policy regimes are considered 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_i. This is possible because γ and δ are exogenous parameters across regimes. In comparing the two regimes a rubric is derived to determine whether an emission tax or a binding relative standard is preferable 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 $i = 1, 2$ are given by

$$\max_{x_i, e_i} \pi_i = p_i x_i - c_i(x_i, e_i) - t e_i \tag{1}$$

whence first-order conditions are given by

$$p_i - \beta x_i - \bar{c}_i - \delta_i(\delta_i x_i - e_i) = 0 \tag{2}$$

$$\delta_i x_i - e_i - t = 0 \tag{3}$$

These implicitly characterize the equilibrium output and level of emissions for each firm, x_1^*, x_2^*, e_1^*, e_2^*. Consistent with the literature total output, $x_1^* + x_2^*$, rises with: (i) a decrease in the emission tax, or (ii) a higher degree of product differentiation (i.e., decrease in γ). Appendix A derives the comparative statics results, which are consistent with the literature e.g., Requate (2006), Gautier (2015).

Total emissions are given by the sum of emissions by each firm, $E = e_1 + e_2$, where consistent with the literature fall with an increase in the emission tax. However, since δ_i is a function of γ, total emissions may fall or rise as products become more differentiated (decrease in γ). On the one hand, a decrease in γ lowers emissions for given level of output as pollution intensity falls (i.e., $\delta_i^{'}(\gamma) > 0$, $i = 1, 2$), but on the other emissions rise via changes in the output. This points to the existence of $\delta_i^{'}(\gamma)$ large enough such that total emissions do not rise i.e., $dE/d\gamma = 0$. This result holds under symmetry (i.e., $\delta_1 = \delta_2$, $\delta_1^{'} = \delta_2^{'}$) and asymmetry (i.e., $\delta_1 \neq \delta_2$, $\delta_1^{'} \neq \delta_2^{'}$) . Appendix A derives these results.

Remark 2.1. *In the tax regime there are $\delta_i^{'}(\gamma) > 0$, $i = 1, 2$ large enough such that total emissions do not rise as products become more differentiated (i.e., $dE/d\gamma = 0$).*

Proof. See Appendix A □

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:

$$\max_{t} W = CS(x_1, x_2) + \pi_1 + \pi_2 + tE - \varphi(E) \tag{4}$$

where the damage function φ is strictly increasing and convex in E. Equation (4) gives a first-order condition $W_t(\gamma, \delta_1(\gamma), \delta_2(\gamma)) = 0$, 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 (Requate 2006). That is, we characterize the second-best tax, t^*, in terms of the degree of product differentiation and pollution intensity via the function $W_t(\gamma, \delta_1(\gamma), \delta_2(\gamma)) = 0$.

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 $e_i = \delta^s x_i$, $i = 1, 2$. As a result, the cost function faced by each firm is given by $c_i(x_i, \delta^s x_i) = \bar{c}_i x_i + (\delta_i x_i - \delta^s x_i)^2/2$, where as before $\delta_i = \delta_i(\gamma)$, $\delta_i' > 0$. Intuitively, each firm faces additional costs of pollution abatement for each unit of emissions exceeding the standard. In this setup each firm chooses output for given standard, where profits for each firm are given by

$$\max_{x_i} \pi_i = p_i x_i - c_i(x_i, \delta^s x_i) \tag{5}$$

whence the first-order condition is given by

$$p_i - \beta x_i - \bar{c}_i - x_i(\delta_i - \delta^s)^2 = 0 \tag{6}$$

Equation (6) characterizes the equilibrium output and thus emissions for each firm under a standard i.e., x_1^s, x_2^s, e_1^s, e_2^s. 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 costs. Further, a decrease in γ raises total output.

A change in total emissions, $E = \delta^s x_1 + \delta^s x_2$, with respect to γ now works via changes in output since the standard is binding and set by the government. In fact, total emissions rise as products become more differentiated (decrease in γ). A consequence of this is that, in contrast to the tax regime, there are no $\delta_i'(\gamma) > 0$ such that total emissions do not rise as products become more differentiated. The comparative statics effects of the standard are shown in Appendix A.

Remark 2.2. *In the binding relative standard regime there are no $\delta_i'(\gamma) > 0$'s such that total emissions do not rise as products become more differentiated.*

Proof. See Appendix A □

The government sets a relative binding standard, δ^s, so as to maximize a welfare function analogous to equation (4):

$$\max_{\delta^s} W = CS(x_1, x_2) + \pi_1 + \pi_2 - \varphi(E) \tag{7}$$

whence $W_{\delta^s}(\gamma, \delta_1(\gamma), \delta_2(\gamma)) = 0$ 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 $W_{\delta^s}(\gamma, \delta_1(\gamma), \delta_2(\gamma)) = 0$.

3 Comparing regimes

We link the policy regime under an emission tax and binding relative standard via the degree of product differentiation parameter, γ, and pollution intensity parameter, δ_i. The strategy is twofold. First, we argue that the presence of a function $\delta_i(\gamma)$, used to describe efforts by firms (i.e., firms which extract olive oil using organically-grown olives and less-polluting extraction techniques) to differentiate themselves as environmentally friendly, is relevant for policy recommendations. This is because the characterization of second-best policies depends on $\delta_i(\gamma)$. In the context of the model, we capture the notion of environmentally-friendly firms via a decrease in γ (more differentiated products) and the associated reduction in δ_i. Second, we argue that under sufficient asymmetry in pollution intensities an emission tax or a binding relative standard can yield similar outcomes consistent with welfare maximization. This is because under the standard abatement costs are increasing and convex in pollution intensities and, therefore, the standard can address emissions from the high-polluting firm adequately. That is, high enough abatement costs induces sufficient reductions in emissions via lower output. But we also argue there is a degree of product differentiation for which equivalency between the emission tax and relative binding standard holds, and that as firms become increasingly environmentally friendly, starting from equivalency, a tax is welfare-enhancing relative to the binding standard. This is because in the presence of $\delta_i(\gamma)$, changes in γ do not imply higher emissions in the tax regime, while under a standard this is not the case.

To compare policies across regimes we use Figure 1 (see Appendix B for a derivation). We derive pairs $\delta_1 - \delta_2$ consistent with the welfare-maximizing emission tax, $W_t(\delta_1, \delta_2) = 0$, and also the welfare-maximizing standard, $W_{\delta^s}(\delta_1, \delta_2) = 0$. The $\bar{\delta}_i$'s in the Figure denote upper-bounds of pollution intensities consistent with remark 2.1.[6]

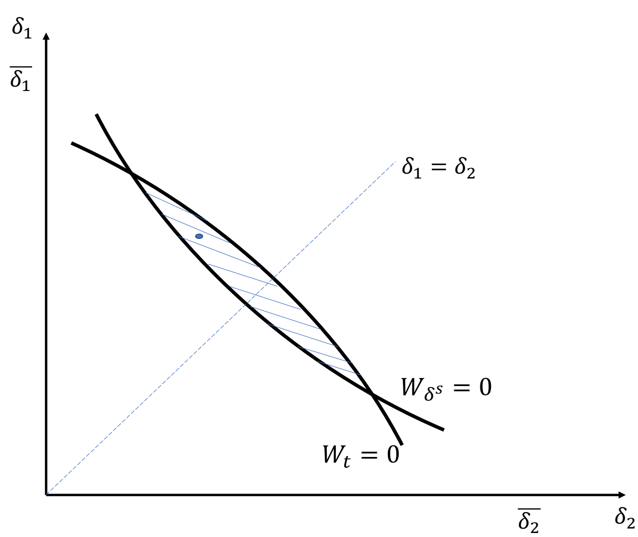
We offer an intuitive explanation of Figure 1. The function $W_t(\delta_1, \delta_2) = 0$ shows pollution intensity pairs consistent with the welfare-maximizing emission tax for given γ. The inverse relationship shows adjustments in the emission tax arising from changes in the δ_i's. These adjustments are driven by output distortion and damage from emissions effects arising from changes in the δ_i's, since the δ_i's affect emissions and output. But adjustments in the tax also depend on the relative size of the δ_i's. For instance, starting at a relatively high pollution intensity for firm 2, δ_2, an increase in δ_2 yields large adjustments in the tax vis-à-vis adjustments that take place from changes in δ_1. This is because output and damages from emissions effects, and the associated tax adjustment, are driven by changes in δ_2 since

[6] If the δ_i's were too large, then the existence of a $\delta_i^{'} > 0$ may not hold.

δ_2 is larger than δ_1. As a result, for increasingly large pollution intensity for firm 2 the curve $W_t(\delta_1, \delta_2) = 0$ becomes steeper. That is, $d\delta_1/d\delta_2 = -W_{t\delta_2}/W_{t\delta_1} < 0$ becomes larger in absolute value, where the term $W_{t\delta_2}$ ($W_{t\delta_1}$) denotes adjustments in the tax from changes in $\delta_2(\delta_1)$.

But Figure 1 also shows pollution intensity pairs consistent with the welfare-maximizing relative binding standard. Similar to the case of the tax, the inverse relationship shows adjustments driven by output and damage from emissions effects, and the relative size of the δ_i's. But in contrast to the tax, the $W_{\delta^s}(\delta_1, \delta_2) = 0$ function captures how a high enough firm 2's pollution intensity, say, is associated with high enough abatement costs. This is because firm 2's abatement cost function is increasing and convex in δ_2. This means that high enough pollution intensity, which exceeds the relative binding standard, increasingly raises abatement costs for the firm and, as a result, induces firm 2 to control emissions via lower output without the need for large adjustment in the standard. Thus, for increasingly large pollution intensity for firm 2 the curve $W_{\delta^s}(\delta_1, \delta_2) = 0$ becomes flatter. That is, $d\delta_1/d\delta_2 = -W_{\delta^s\delta_2}/W_{\delta^s\delta_1} < 0$ becomes smaller in absolute value, where the term $W_{\delta^s\delta_2}$ ($W_{\delta^s\delta_1}$) denotes adjustments in the standard from changes in $\delta_2(\delta_1)$.

Figure 1: Emission tax versus relative binding standard



With the properties of Figure 1 in mind, we compare the two policy regimes. The functions $W_{\delta^s}(\delta_1, \delta_2) = 0$ and $W_t(\delta_1, \delta_2) = 0$ can relate in a variety of ways. But we first point to the possibility shown in the Figure and consider alternative scenarios below. We first interpret the two intersection points as scenarios where the relative binding standard and the emission tax are consistent with welfare maximization when either firm is sufficiently more pollution intensive. That is, under sufficient asymmetry in pollution intensities. The reason behind this result is twofold. With a sufficiently high pollution intensity of, say, firm 2 the emission tax addresses damages arising from emissions coming from firm 2, the high polluting firm. But the relative binding standard is also able to achieve a welfare-equivalent outcome. This is because a sufficiently high pollution intensity for firm 2 implies that firm 2 controls emissions under the standard, since firm 2's abatement costs are convex in its own pollution intensity. Analogous results hold, if firm 1 exhibits sufficiently high pollution intensity. The implication of these two intersection points is that it does not matter which policy is chosen from a welfare-maximizing standpoint as long as policy-makers identify these pollution intensity pairs.

Proposition 3.1. *Let each firm i's abatement cost function be increasing and convex in its own δ_i. An emission tax and relative binding standard yield consistent welfare-maximizing outcomes when either firm is sufficiently more pollution intensive.*

We now point to the shaded area in Figure 1, which denotes pollution intensity pairs for which neither an emission tax nor a relative binding standard are consistent with welfare maximization. As a result, for said pollution intensity pairs an adjustment in either the emission tax or relative binding standard is needed in order to set policy consistent with welfare maximization. These pollution intensity pairs can be thought of as levels which are attainable via changes in the degree to which firms differentiate themselves as environmentally friendly (decrease in γ and corresponding reduction in δ) and the corresponding adjustment in the emission tax or relative binding standard. That is, starting at either the welfare-maximizing emission tax or relative binding standard regime, changes in γ obtain a given $\delta_1 - \delta_2$ pair in the shaded area.

For instance, starting at the emission tax regime (i.e., at the $W_t = 0$ function in Figure 1), as firms become relatively more environmentally friendly (decrease in γ) pollution intensities decrease, which prompts a reduction in the emission tax. This is captured through an inward shift of the $W_t = 0$ function up to a given pollution intensity pair in the shaded area. The reason there is a reduction in taxation is because the reduction in pollution intensities via γ controls emissions (i.e., remark 2.1), which gives the government room to set a laxer emission tax. In contrast, starting at the relative binding standard regime, as firms become relatively *less* environmentally friendly (i.e., increase in γ) pollution intensities rise, which prompts a laxer standard. This is because the increase in γ controls emissions. This is captured through an outward shift of the $W_{\delta^s} = 0$ function up to a given pollution intensity pair in the shaded area. Overall, in setting policy consistent with pollution intensity pairs in the shaded area an emission tax is welfare-enhancing in an industry where firms differentiate themselves as more environmentally friendly. This is because the emission tax controls emissions and encourages output and profits, whereas a laxer standard may not. Put together the above results are generalized in the following proposition.

Proposition 3.2. *Consider $\hat{\delta}_1 < \bar{\delta}_1$ and $\hat{\delta}_2 < \bar{\delta}_2$ in the convex set of $W_t = 0$. Then, an emission tax is welfare-enhancing over a relative binding standard as firms become relatively more environmentally friendly i.e., as products become more differentiated (decrease in γ).*

Proof. See Appendix C □

This proposition offers a sufficient condition under which an emission tax is welfare-enhancing over a relative binding standard in industries where firms are becoming environmentally friendly. It is noteworthy that a pollution intensity pair in the shaded area as shown in Figure 1 implies that said pair is in the convex set of $W_t = 0$ *and* $W_{\delta^s} = 0$. But even in the case where a pollution intensity pair is in the convex set of $W_t = 0$ but not in the convex set of $W_{\delta^s} = 0$, proposition 3.2 holds. This is because in this case to achieve said intensity pair would require a stricter standard to control rising emission resulting from higher degree of product differentiation; that is an inward shift of the $W_{\delta^s} = 0$ function.

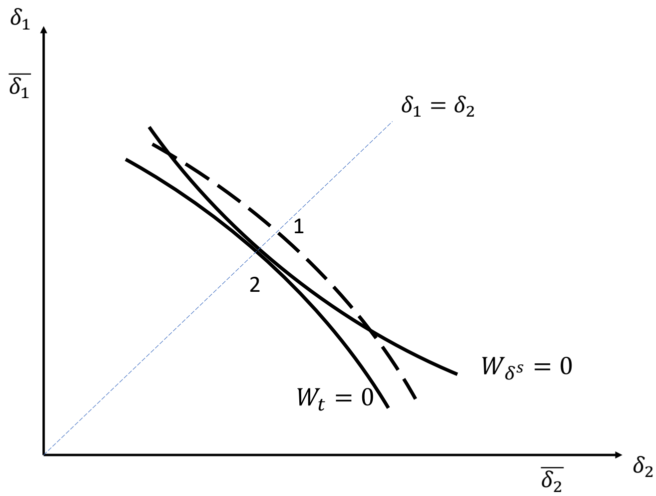
To derive our next set of results we state the following definition.

Definition 3.3. *For pollution intensities $\delta_1^* < \bar{\delta}_1$, $\delta_2^* < \bar{\delta}_2$ there is equivalence between the emission tax and relative binding standard whenever $-W_{\delta^s\delta_2}(\delta_1^*, \delta_2^*)/W_{\delta^s\delta_1}(\delta_1^*, \delta_2^*) = -W_{t\delta_2}(\delta_1^*, \delta_2^*)/W_{t\delta_1}(\delta_1^*, \delta_2^*)$.*

Definition 3.3 states that equivalence occurs when the adjustment of the emission tax and relative binding standard are the same at a given pollution intensity pair for given γ i.e., tangency holds. This definition implies the emission tax and relative binding standard are welfare-equivalent at (δ_1^*, δ_2^*). Using this definition we argue there exists a degree of product differentiation (and thus a pair of pollution intensities) which obtains equivalence between the emission tax and relative binding standard. Intuitively, different degrees of product differentiation result in different levels of pollution intensities and, consequently policy. Thus, starting at any pollution intensity pair $\delta_1 \neq \delta_1^*$, $\delta_2 \neq \delta_2^*$ on, say, the $W_t = 0$ function, there is a change in γ, and a corresponding adjustment in the δ_i's such that equivalence is obtained. Equivalence is also obtained starting at $W_{\delta^s} = 0$.

Figure 2 illustrates the existence of a γ which obtains equivalence. Appendix D offers a formal proof. Starting at point 1 (dashed line), a decrease in γ shifts the $W_t(\delta_1, \delta_2) = 0$ function to point 2 (solid line). This is a tangency point and thus an equivalence between the tax and the standard. Intuitively, as firms become more environmentally friendly (i.e., decrease in γ) pollution intensities decrease, which prompts a reduction in the tax. This is because the reduction in pollution intensities via γ control emissions (i.e., remark 2.1) giving the government room to set a laxer tax, while positive consumer surplus and profits effects are encouraged.

Figure 2: Equivalence between emission tax and relative binding standard



Proposition 3.4. *There is a degree of product product differentiation which produces equivalence between the emission tax and relative binding standard.*

Proof. See Appendix D □

Next, we use the equivalence result from proposition 3.4 to argue that an emission tax is welfare-enhancing relative to the relative binding standard. If, starting at an equivalence scenario (i.e., point 2 in Figure), firms become environmentally friendly (decrease in γ), then a laxer emission tax is prescribed to achieve welfare maximization consistent with the newly lower pollution intensities. That is, starting at point 2, the $W_t = 0$ function shifts further inwards. The reason for a laxer emission tax is that emissions are controlled as firms become environmentally friendly (i.e., remark 2.1), while positive consumer surplus and profits effects encouraged. However, starting at an equivalence scenario the alternative policy adjustment would be a stricter standard since a decrease in γ raises emissions.

Proposition 3.5. *Consider a pair (δ_1^*, δ_2^*) consistent with equivalence between the emission tax and relative binding standard. Then, starting at (δ_1^*, δ_2^*), as firms become environmentally* *friendly an emission tax is welfare-enhancing relative to the relative binding standard.*

This result complements proposition 3.4. The existence of equivalence implies there must be a degree of product differentiation and thus associated pollution intensity pair such that the tax will always be welfare-enhancing. One application of Figure 2 is to think of an industry which is high polluting. If firms in that industry become environmentally friendly, then either an emission tax or relative binding standard is consistent with welfare maximization i.e., equivalence can be reached. But if firms further differentiate themselves as environmentally friendly, then a tax is welfare-enhancing realtive to the standard. This is because in this case lower taxation does not yield higher emissions while promoting profits and consumer surplus.

4 Uncertainty faced by environmentally-friendly firms

A key challenge for environmentally-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 2010). 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 environmentally-friendly firms (e.g., in the olive oil extraction stage) supply the market with environmentally-friendly 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 environmentally-friendly production to go into the market. This is because taxation renders the relatively high-polluting firm less cost-competitive thereby increasing the chances for the environmentally-friendly 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 larger 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 standandard) 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.

4.1 Emission tax regime

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 ($q_1 > q_2$) and exhibits a smaller pollution intensity ($\delta_1 > \delta_2$). Because firm 2 is environmentally-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 environmentally-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 environmentally-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:

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

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 lossing 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:

$$x_1^u < x_2^u \Leftrightarrow \epsilon < \frac{c_1 + \delta_1 t}{c_2 + \delta_2 t} = \bar{\epsilon} \tag{8}$$

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

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

$$\text{partial EF if} \quad \epsilon \in (\bar{\epsilon}, 1]$$

From equation (8) 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 environmentally-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 environmentally-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 4.1. *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:

$$\begin{aligned} W^u &= \underbrace{\int_g^{\bar{\epsilon}} [CS_{fullEF} + \Pi_{fullEF} + tE_{fullEF} - E_{fullEF}] f(\epsilon) d\epsilon}_{W^u \text{ under full EF}} \\ &+ \underbrace{\int_{\bar{\epsilon}}^1 [CS_{partialEF} + \Pi_{partialEF} + tE_{partialEF} - E_{partialEF}] f(\epsilon) d\epsilon}_{W^u \text{ partial EF}} \end{aligned} \quad (9)$$

where $\Pi = \pi_1 + \pi_2$. Integrating equation (9) yields a function $W^u(t, \bar{\epsilon}(t))$, from which the welfare-maximizing emission tax under uncertainty is characterized by

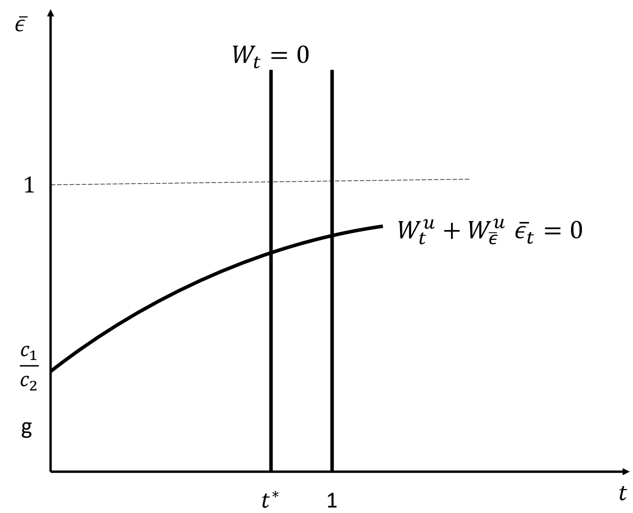
$$\frac{\partial W^u}{\partial t} + \frac{\partial W^u}{\partial \bar{\epsilon}} \frac{\partial \bar{\epsilon}}{\partial t} = 0 \quad (10)$$

where $\partial \bar{\epsilon} / \partial t > 0$ comes from (8).

Figure 3 shows the main results (see Appendix E 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 environmentally-friendly (and less polluting) product to go into the market. This result points to the case where the emission tax and the environmentally-friendly production that goes into the market are complements.

Proposition 4.2. *The welfare-maximizing emission tax under uncertainty, t^u, may exceed marginal damages.*

Figure 3: The emisson tax under uncertainty



4.2 Relative binding standard regime

To analyze uncertainty in the case of a relative binding standard, the environmentally-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

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

where $\eta^{su} = (2\beta + \epsilon^s(\delta_2 - \delta^s)^2)\,(2\beta + (\delta_1 - \delta^s)^2) - \gamma^2 > 0$. Similar to the case of the emission tax, uncertainty increases the output of firm 2, the environmentally-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:

$$x_1^{su} < x_2^{su} \Leftrightarrow \epsilon^s < \frac{c_1(2\beta + \gamma) + \alpha(\delta_1 - \delta^s)^2}{(\alpha - c_1)(\delta_2 - \delta^s)^2 + c_2\,(2\beta + \gamma + (\delta_1 - \delta^s)^2)} = \bar{\epsilon}^s \tag{11}$$

whence,

$$\text{full EF if} \quad \epsilon \in [g, \bar{\epsilon}^s)$$
$$\text{partial EF if} \quad \epsilon \in (\bar{\epsilon}^s, 1]$$

From (11) 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 sticter 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 environmentally-friendly firm to increase its production. In this sense, a stricter standard and the environmentally-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 4.3. *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 (9). Integration yields a function $W^{su}(\delta^s, \bar{\epsilon}^s(\delta^s))$, from which the welfare-maximing 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 Figure 3, which we show in Appendix F. 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 controls 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 environmentally-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 4.4. *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.*

5 Conclusion

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. We argue that for pollution intensities in the convex set of the second-best emission tax, policy adjustments arising from a higher degree of product differentiation suggest that an emission tax is welfare-enhancing relative to a relative binding standard. That is, an emission tax is welfare-enhacing in those industries where firms are increasingly differentiating themselves as environmentally friendly. The driver for this result is that an emission tax controls industry emissions while giving environmentally-friendly firms enough flexibility to produce the low-polluting good.

We also analyze 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 environmentally-friendly good. This is because a tax renders the high-polluting firm less cost competitive making the production of the environmentally-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-enhacing because it encourages the production of the environmentally-friendly good, controls industry emissions and offers more flexibility to the environmentally-friendly firm. This suggests that the design of environmental policy for industries which show a trend towards product differentiation 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 environmentally-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 environmentally-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 modelling the interaction among these three stages would yield a richer analytical framework to capture the implications of policy.

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Appendices

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-

Differentiation of the first-order conditions $p_i - \beta x_i - \bar{c}_i - \delta_i(\delta_i x_i - e_i) = 0$, and $\delta_i x_i - e_i - t = 0$ gives changes in output, x_i, arising from changes in the tax, t, and degree of product differentiation, γ:

$$\eta dx_1 = [-\delta_1 2\beta + \delta_2\gamma]\, dt + \left[-2\beta(x_2 + t\delta_1') + \gamma(x_1 + t\delta_2')\right] d\gamma$$

$$\eta dx_2 = [-\delta_2 2\beta + \delta_1\gamma]\, dt + \left[-2\beta(x_1 + t\delta_2') + \gamma(x_2 + t\delta_1')\right] d\gamma$$

where $\delta_i' \equiv \partial\delta_i/\partial\gamma > 0$ for $i = 1, 2$, and $\eta \equiv 4\beta^2 - \gamma^2 > 0$ is the determinant of the coefficient matrix. It is assumed that per-firm ouput falls with a tax increase. The effect of product differentiation on per-firm output is ambiguous. Hence, the effects on total output, $Q = x_1 + x_2$ are given by

$$\eta dQ = -(2\beta - \gamma)(\delta_1 + \delta_2)dt - (2\beta - \gamma)\left[(x_1 + t\delta_2') + (x_2 + t\delta_1')\right] d\gamma$$

whence $dQ < 0$ with respect to the tax and degree of product differentiation.

Next, consider total emissions, $E = e_1 + e_2 = \delta_1 x_1 - t + \delta_2 x_2 - t$. Differentiation gives

$$dE = \delta_1 dx_1 + \delta_2 dx_2 - 2dt$$

where $dE < 0$ with respect to the tax.

To see the effects with respect to γ consider

$$dE = \delta_1 dx_1 + x_1 d\delta_1 + \delta_2 dx_2 + x_2 d\delta_2 \tag{A.1}$$

where under symmetry $\delta_1 = \delta_2 = \delta$ and thus $\delta_1' = \delta_2' = \delta'$ (A.1) simplifies to

$$dE = [ddQ + Qd\delta]$$

whence

$$dE = \left[\delta Q_\gamma + Q\delta^{'}\right] d\gamma$$

As a result,

$$dE = 0 \Leftrightarrow \delta^{'} = -\delta Q_\gamma / Q > 0$$

Next, under asymmetry of pollution intensities $\delta_1 \neq \delta_2$ and $\delta_1^{'} \neq \delta_2^{'}$ (A.1) gives

$$dE = \left[\delta_1^{'}(\delta_1 x_{1\delta_1} + \delta_2 x_{2\delta_1} + x_1) + \delta_2^{'}(\delta_2 x_{2\delta_2} + \delta_1 x_{1\delta_2} + x_2) + \delta_1 x_{1\gamma} + \delta_2 x_{2\gamma}\right] d\gamma \quad \text{(A.2)}$$

where $x_{i\delta_i} = \partial x_i/\partial\delta_i < 0$, $x_{2\delta_1} = \partial x_2/\partial\delta_1 > 0$, $x_{1\delta_2} = \partial x_1/\partial\delta_2 > 0$. Now, if $\delta_1^{'} = \delta_2^{'} = \delta^{'}$, but still $\delta_1 \neq \delta_2$:

$$dE = 0 \Leftrightarrow \delta^{'} = \frac{-(\delta_1 x_{1\gamma} + \delta_2 x_{2\gamma})}{(\delta_1 x_{1\delta_1} + \delta_2 x_{2\delta_1} + x_1) + (\delta_2 x_{2\delta_2} + \delta_1 x_{1\delta_2} + x_2)} > 0$$

where the numerator is positive and it is assumed that the denominator is positive to be consistent with assumption $\delta^{'} > 0$. Now, if $\delta_1 \neq \delta_2$ and $\delta_1^{'} \neq \delta_2^{'}$:

$$dE = 0 \Leftrightarrow \delta_1^{'}(\delta_1 x_{1\delta_1} + \delta_2 x_{2\delta_1} + x_1) + \delta_2^{'}(\delta_2 x_{2\delta_2} + \delta_1 x_{1\delta_2} + x_2) = -(\delta_1 x_{1\gamma} + \delta_2 x_{2\gamma}) > 0$$

This means there is $\delta_1^{'} > 0$ and $\delta_2^{'} > 0$ such that $dE = 0$.

(ii) The binding relative standard regime -

Differentiation of the first-order conditions given by (6), $p_1 - \beta x_1 - \bar{c_1} - x_1(\delta_1 - \delta^s)^2 = 0$, $p_2 - \beta x_2 - \bar{c_2} - x_2(\delta_2 - \delta^s)^2 = 0$ gives

$$\begin{aligned}
\eta^s dx_1 &= \left[(2\beta + (\delta_2 - \delta^s)^2)2x_1(\delta_1 - \delta^s) - \gamma 2x_2(\delta_2 - \delta^s)\right] d\delta^s \\
&\quad + \left[-(2\beta + (\delta_2 - \delta^s)^2)(2x_1(\delta_1 - \delta^s)\delta_1^{'} + 2x_2(\delta_2 - \delta^s)\delta_2^{'} + x_1 + x_2)\right] d\gamma \\
&\quad -2x_1(\delta_1 - \delta^s)(2\beta + (\delta_2 - \delta^s)^2)d\delta_1 + 2x_2\gamma(\delta_2 - \delta^s)d\delta_2 \\
\eta^s dx_2 &= \left[(2\beta + (\delta_1 - \delta^s)^2)2x_2(\delta_2 - \delta^s) - \gamma 2x_1(\delta_1 - \delta^s)\right] d\delta^s \\
&\quad + \left[-(2\beta + (\delta_1 - \delta^s)^2)(2x_2(\delta_2 - \delta^s)\delta_2^{'} + 2x_1(\delta_1 - \delta^s)\delta_1^{'} + x_1 + x_2)\right] d\gamma \\
&\quad -2x_2(\delta_2 - \delta^s)(2\beta + (\delta_1 - \delta^s)^2)d\delta_2 + 2x_1\gamma(\delta_1 - \delta^s)d\delta_1
\end{aligned}$$

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 negative, which points to the result where output by each firm increases always as products become more differentiated (decrease in γ) even in the presence of a function $\delta(\gamma)$ such that $\delta' > 0$.

This implies that in the presence of a relative binding standard emissions can't fall with more differentiated products even in the presence of a function $\delta(\gamma)$.

It is noteworthy that in the case where $\delta_1 = \delta_2 = \delta$, using the first-order conditions gives

$$\begin{aligned} \eta^s dx_1 &= 2(\delta - \delta^s)\left[(2\beta + (\delta - \delta^s)^2)x_1 - \gamma x_2\right] d\delta^s = 2(\delta - \delta^s)(a - \bar{c_1})d\delta^s \\ \eta^s dx_2 &= 2(\delta - \delta^s)\left[(2\beta + (\delta - \delta^s)^2)x_2 - \gamma x_1\right] d\delta^s = 2(\delta - \delta^s)(a - \bar{c_2})d\delta^s \end{aligned} \tag{A.3}$$

where $a - \bar{c_i} > 0$, $i = 1, 2$.

B Derivation of Figure 1

The derivation of Figure 1 consists of the derivation of $\delta_1 - \delta_2$ pairs consistent with the welfare-maximizing tax, and $\delta_1 - \delta_2$ pairs consistent with welfare-maximizing relative binding standard.

Emission Tax - Consider $W_t(\delta_1, \delta_2) = 0$, whence differentiation gives $W_{t\delta_1} d\delta_1 + W_{t\delta_2} d\delta_2 = 0$, and thus $d\delta_1/d\delta_2 = -W_{t\delta_2}/W_{t\delta_1} < 0$. This gives the inverse relationship shown in Figure 1 consistent with welfare-maximizing emission tax. To derive this result consider the first-order condition with respect to the tax, $W_t = 0$:

$$\left(\delta_2(t - \varphi') + \beta x_2\right)(\partial x_2/\partial t) + \left(\delta_1(t - \varphi' + \beta x_2\right)(\partial x_1/\partial t) = 2(t - \varphi') \tag{B.1}$$

Total differentiation gives

$$\begin{aligned} 0 &= \Big[-\frac{\partial x_2}{\partial t}\delta_2\varphi'' E_{\delta_1} - \frac{\partial x_1}{\partial t}\delta_1\varphi'' E_{\delta_1} + 2\varphi'' E_{\delta_1} + (t - \varphi')\frac{\partial x_1}{\partial t} + (t - \varphi')(\delta_1 + \delta_2)\frac{(-2\beta + \gamma)}{\eta} \\ &\quad + \frac{\partial x_2}{\partial t}\beta\frac{\partial x_2}{\partial \delta_1} + \frac{\partial x_1}{\partial t}\beta\frac{\partial x_1}{\partial \delta_1} + \beta(x_1 + x_2)\frac{(-2\beta + \gamma)}{\eta}\Big] d\delta_1 \\ &+ \Big[-\frac{\partial x_1}{\partial t}\delta_1\varphi'' E_{\delta_2} - \frac{\partial x_2}{\partial t}\delta_2\varphi'' E_{\delta_2} + 2\varphi'' E_{\delta_2} + (t - \varphi')\frac{\partial x_2}{\partial t} + (t - \varphi')(\delta_1 + \delta_2)\frac{(-2\beta + \gamma)}{\eta} \\ &\quad + \frac{\partial x_1}{\partial t}\beta\frac{\partial x_1}{\partial \delta_2} + \frac{\partial x_2}{\partial t}\beta\frac{\partial x_2}{\partial \delta_2} + \beta(x_1 + x_2)\frac{(-2\beta + \gamma)}{\eta}\Big] d\delta_2 \end{aligned} \tag{B.2}$$

where $\eta > 0$. In B.2 the term $[\cdot]d\delta_1$ has two effects (same applies to $[\cdot]d\delta_2$), namely, effects via damages from pollution (frst line) and the effects via output distortion (second line). The terms associated with the effects via damages are positive since $\partial x_i/\partial t < 0$, $E_{\delta_1} > 0$, $t - \varphi^{'} < 0$, $-2\beta + \gamma < 0$. And the terms associated with the output distortion effects are positive, too, if the following condition holds i.e., direct effects on output dominate:

$$\frac{\partial x_i}{\partial t}\beta\frac{\partial x_i}{\partial \delta_i} + \frac{\partial x_j}{\partial t}\beta\frac{\partial x_j}{\partial \delta_i} + \beta(x_1 + x_2)\frac{(-2\beta + \gamma)}{\eta} > 0$$

Simplifying the expression in (B.2) gives $d\delta_1/d\delta_2 < 0$. This gives the downward-sloping nature of $W_t = 0$ in Figure 1.

Relative Binding Standard - Consider $W_{\delta^s}(\delta_1, \delta_2) = 0$, whence differentiation gives the expression for $d\delta_1/d\delta_2$. In particular,

$$\beta x_1\frac{\partial x_1}{\partial \delta^s} + \beta x_2\frac{\partial x_2}{\partial \delta^s} + x_1^2(\delta_1 - \delta^s) + x_2^2(\delta_2 - \delta^s) - \varphi^{'}\frac{\partial E}{\partial \delta^s} = 0 \tag{B.3}$$

It is noteworthy that the third and fourth terms denote the costs associated to the standard, where a higher x_i^2 captures a relatively more convex cost function in δ_i. That is, firm i is relatively more sensitive with respect to the standard. Differentiation of B.3 gives

$$\begin{aligned} 0 \;=\; & \left[\left(-\varphi^{'}\frac{\partial^2 E}{\partial \delta^s \partial \delta_1} - \varphi^{''}\frac{\partial E}{\partial \delta^s}\frac{\partial E}{\partial \delta_1}\right) + \frac{\partial x_1}{\partial \delta_1}\left(\beta\frac{\partial x_1}{\partial \delta^s} + 2x_1(\delta_1 - \delta^s)\right) + \frac{\partial x_2}{\partial \delta_1}\left(\beta\frac{\partial x_2}{\partial \delta^s} + 2x_2(\delta_2 - \delta^s)\right)\right. \\ & \left. + \beta x_1\frac{\partial^2 x_1}{\partial \delta^s \partial \delta_1} + \beta x_2\frac{\partial^2 x_2}{\partial \delta^s \partial \delta_1} + x_1^2\right] d\delta_1 \\ & + \left[\left(-\varphi^{'}\frac{\partial^2 E}{\partial \delta^s \partial \delta_2} - \varphi^{''}\frac{\partial E}{\partial \delta^s}\frac{\partial E}{\partial \delta_2}\right) + \frac{\partial x_2}{\partial \delta_2}\left(\beta\frac{\partial x_2}{\partial \delta^s} + 2x_2(\delta_2 - \delta^s)\right) + \frac{\partial x_1}{\partial \delta_2}\left(\beta\frac{\partial x_1}{\partial \delta^s} + 2x_1(\delta_1 - \delta^s)\right)\right. \\ & \left. + \beta x_1\frac{\partial^2 x_1}{\partial \delta^s \partial \delta_2} + \beta x_2\frac{\partial^2 x_2}{\partial \delta^s \partial \delta_2} + x_2^2\right] d\delta_2 \end{aligned} \tag{B.4}$$

where

$$\frac{\partial^2 E}{\partial \delta^s \partial \delta_i} < 0, \frac{\partial E}{\partial \delta_i} < 0, \frac{\partial x_i}{\partial \delta_i} > 0, \frac{\partial x_i}{\partial \delta_j} > 0 \forall i \neq j$$

From (B.4) consider damages to be sufficiently large so that they dictate the sign of $d\delta_1/d\delta_2$. In this case (B.4) becomes

$$\left[\left(-\varphi^{'}\frac{\partial^2 E}{\partial \delta^s \partial \delta_1} - \varphi^{''}\frac{\partial E}{\partial \delta^s}\frac{\partial E}{\partial \delta_1}\right)\right] d\delta_1 + \left[\left(-\varphi^{'}\frac{\partial^2 E}{\partial \delta^s \partial \delta_2} - \varphi^{''}\frac{\partial E}{\partial \delta^s}\frac{\partial E}{\partial \delta_2}\right)\right] d\delta_2 = 0 \tag{B.5}$$

As a result, $d\delta_1/d\delta_2 < 0$. Next, suppose output distortion effects are large enough where own effects dominate; that is, $\forall i \neq j$

$$\frac{\partial x_i}{\partial \delta_i}\left(\beta\frac{\partial x_i}{\partial \delta^s} + 2x_i(\delta_i - \delta^s)\right) + \frac{\partial x_j}{\partial \delta_i}\left(\beta\frac{\partial x_j}{\partial \delta^s} + 2x_j(\delta_j - \delta^s)\right) + \beta x_i\frac{\partial^2 x_i}{\partial \delta^s \partial \delta_i} + \beta x_j\frac{\partial^2 x_j}{\partial \delta^s \partial \delta_i} < 0 \tag{B.6}$$

As a result, $d\delta_1/d\delta_2 < 0$.

Next, consider $W_{\delta^s} = 0$ from B.3, whence

$$\delta_1 = -\frac{x_2^2}{x_1^2}\delta_2 + \delta^s(x_1^2 + x_2^2) - \left(\beta x_1 \frac{\partial x_1}{\partial \delta^s} + \beta x_2 \frac{\partial x_2}{\partial \delta^s} - \varphi' \frac{\partial E}{\partial \delta^s}\right) \tag{B.7}$$

where with sufficiently convex costs for firm 2 in δ_2 the term x_2^2/x_1^2 is large in absolute value. This depicts the relatively steepness of the curve $W_{\delta^s} = 0$ in figure 1.

Bounds $\bar{\delta_1}$ and $\bar{\delta_2}$ - To derive these bounds shown in the Figure we use the condition $dE/d\gamma = 0$. To be consistent with $dE/d\gamma = 0$ we get

$$dE/d\gamma = 0 \Rightarrow \frac{-x_j - \delta_j x_{j\delta_j}}{x_{i\delta_j}} < \delta_i < \frac{-x_i + \delta_j x_{j\delta_i}}{x_{i\delta_i}} \tag{B.8}$$

whence

$$\delta_j < \frac{(x_i/-x_{i\delta_i}) + \left(x_j/-x_{i\delta_j}\right)}{\left(-x_{j\delta_j}/x_{i\delta_j}\right) + \left(-x_{j\delta_i}/x_{i\delta_i}\right)} \tag{B.9}$$

This is the upper-bound for firm j. To obtain the upper-bound for firm i we substitute δ_j back into B.8.

When pollution intensities are symmetric - If $\delta_1 = \delta_2$, then the sloped of the $W_t = 0$ and $W_{\delta^s} = 0$ functions are equal to one, since in this case the adjustment in policy arising from the δ_i's are the same. That is, $d\delta_1/d\delta_2 = 1$.

C Proof of proposition 3.2

Need to show that for any pair of pollution intensities in the convex set of the second-best optimal tax, (i) a decrease in g (starting at the seocnd-best optimal tax), obtains said pollution intensity pair via a tax adjustment and (ii) that such tax adjustment is preferred to any adjustment in the standard to obtain the same pollution intensity pair. Consider a pair δ_1, δ_2 within the bounds $\bar{\delta_1}$ and $\bar{\delta_2}$. Suppose δ_1, δ_2 are in the convex set of $W_t = 0$. Then starting at $W_t = 0$ a decrease obtains δ_1, δ_2 via a reduction in the tax. This is because a decrease in γ lowers the δ_i's to the desired pair δ_1, δ_2 consistent with a new $W_t = 0$ (which shifts accordingly). This reduction in at least one of the δ_i's implies a reduction in tax. This is because a reduction in γ and the pollution intensity does not result in higher emissions and, therefore, more room to set a lower tax to encourage profits and output to deal with the outptu distortion. However, starting at $W_{\delta^s} = 0$ a reduction in γ and the resulting reduction in at least one of the δ_i^s's raises emissions, which translates into a stricter standard. A stricter standard raises costs. As a result, the tax is preferred over the standard. Note: if δ_1, δ_2 were not in the convex set of the tax regime, $W_t = 0$, then an increase in γ (not a decrease) obtains the desired δ_1, δ_2. Thus, for taxation to be preferred over the standard given a decrease in γ (when firms become more differentiated), it is required for the pollution intensities of interest to be in the convex set of $W_t = 0$.

D Proof of proposition 3.4

Consider $\delta_2 > \delta_1$ for all δ's. Let $\delta_{1*} > \delta_{1**}$, $\delta_{2*} > \delta_{2**}$.
Consider, in absolute value, $W_{t\delta_2}(\delta_{1*}, \delta_{2*})/W_{t\delta_1}(\delta_{1*}, \delta_{2*}) > W_{\delta^s\delta_2}(\delta_{1**}, \delta_{2**})/W_{\delta^s\delta_1}(\delta_{1**}, \delta_{2**})$. Then, starting at the tax regime a decrease in γ lowers δ_{2*} relatively more than δ_{1*} such that $\delta_{1*} = \delta_{1**}$, and $\delta_{2*} = \delta_{2**}$. As a result, the ratio $W_{t\delta_2}/W_{t\delta_1}$ becomes smaller; hence, $W_{t\delta_2}/W_{t\delta_1} = W_{\delta^s\delta_2}/W_{\delta^s\delta_1}$. That is, equivalence holds. Same argument applies if $W_{t\delta_2}/W_{t\delta_1} \leq W_{\delta^s\delta_2}/W_{\delta^s\delta_1}$.

E Derivation of Figure 3

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 (8), 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 $t(\delta_1 - \delta_2) > c_2 - c_1$.

F Relative binding standard with and wihtout uncertainty

Similar to Figure 3 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,

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

Figure 4 points to the fact that $\bar{\epsilon}^s < 1$ if abatement costs of firm 1 are large enough:

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

Combining (F.1) and (F.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 $\delta^{us*} < \delta^{s*}$:

$$\frac{(2\beta+\gamma)(c_2-c_1)}{(\alpha-c_1)(\alpha-c_2)} > \frac{(\delta_1-\delta^s)^2}{\alpha-c_1} - \frac{(\delta_2-\delta^s)^2}{\alpha-c_2} > \frac{\delta_1-\delta^s}{c_1} - \frac{\delta_2-\delta^s}{c_2} > \frac{\alpha(\delta_1-\delta^s)(\delta_2-\delta^s)(\delta_1-\delta_2)}{c_1c_2(2\beta+\gamma)}$$

Figure 4: Relative binding standard under uncertainty