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On the evolutionary interplay between environmental CSR and emission tax[☆]

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ABSTRACT

This paper analyses the steady-state industry configuration of an oligopoly composed of profit-seeking (PS) and environmentally socially responsible (ECSR) firms in an evolutionary setting. Within this industry, an emission tax is levied, and firms may invest in emission abatement technology to reduce the tax burden. Our main findings show that, despite the commitment towards emission abatement, an ECSR firm may end up polluting more than its PS counterpart, leading to ill-fated effects on the environment. In contrast, the introduction of an emission tax puts competitive pressure to ECSR firms by inducing PS firms to invest in emission abatement. The industry configuration that minimises the environmental damage (and maximises social welfare) is mixed, with a small but relevant share of ECSR firms, combined with the adoption of a tax on emissions.

1. Introduction

The fact that human emissions of carbon dioxide and other polluting gases are a major driver of climate change is no longer a matter of debate. In response to this challenge, many firms worldwide are now willing to reduce polluting emissions in their production processes. Alongside the social impact, environmental concerns have also entered the business agenda. The KPMG Survey of Sustainability (2020) reports that 96% of the world's biggest companies introduced programs of social and environmental responsibility, and the survey "N100", which sampled 5,200 worldwide companies, showed that 80% of them have done the same (KPMG, 2020).

In the past years, discussions on the relevance of Environmental Corporate Social Responsibility (ECSR) have flourished in the academic debate on industrial organisation, particularly aimed at understanding the strategic role of these practices (Crifo and Forget, 2015; Kitzmueller and Shimshack, 2012; and Benabou and Tirole, 2010, among others). The general question is whether ECSR activities serve as a tool to gain a strategic advantage in interactions with competitors or the government. How is it that investing in emissions abatement, rather than improving production processes or product quality, can be beneficial for business? And how can firms adopting ECSR practices survive competition against profit-seeking (PS) competitors? One possible reason for a firm to willingly bear pollution abatement costs without any regulatory enforcement is that consumers have a preference for environmentally friendly products (Liu et al., 2015).

Alternatively, a commonly considered explanation is that ECSR combines environmental concern with social concern, resulting in an objective function that takes into account a share of consumer surplus and internalises part of its polluting emissions (Lambertini and Tampieri, 2015; Lambertini et al., 2016; Hirose et al., 2017; Nie et al., 2018; Fukuda and Ouchida, 2020; and Li and Wang, 2021, among others).[1] Thus, the inclusion of social concern boosts production and compensates for the increase in abatement cost. With the right conditions in terms of market size, ECSR commitment and cost of emission reduction technology, a generally accepted result is that firms may indeed implement ECSR activities to obtain higher profits than their PS competitors.

Another relevant question is how ECSR practices interact with the widespread adoption of environmental regulation, particularly an emission tax. Only the surface of this issue has been tackled in the literature: recent contributions consider the interaction between CSR practices (Xu and Lee, 2018; Leal et al., 2018) and the introduction of a tax on emissions, without focusing on environmental concerns. Fukuda and Ouchida (2020) is the first to consider the effects of an optimal tax on emissions issued by a time-consistent government and an ECSR monopolist who chooses the level of production and the level of emissions abatement. Their results show the conditions under which ECSR

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[1] Moreover, we will refer to "CSR" to firms that implement only consumer surplus in their objective function.

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practices might increase the monopolist's emissions. The increase in production due to the inclusion of social concern is what explains the potentially higher emissions from an ECSR than a standard PS firm. Note also that Fukuda and Ouchida (2020), by analysing a monopoly industry, focus on the strategic interaction between ECSR practices and environmental policy, by setting aside the strategic interaction among competitors and its role to adopt an ECSR statute. Xu et al. (2022) and Xu and Lee (2022) consider an optimal emission tax in a duopoly, the former by comparing Bertrand with Cournot competition, the latter by comparing cooperative versus noncooperative ECSR activities between firms. Importantly, these contributions (i) analyse duopolies and (ii) abstract away from the firms' decision to engage in ECSR activities, by assuming that they always behave as ECSR.

With these contributions in mind, one question that has been left unanswered is how the interplay between ECSR practices and an emission tax influences the endogenous long-run configuration of the industry, particularly when the industry consists of more than two firms. The relevance of this point is twofold. From a policy perspective, it is important to design the most effective regulatory measure based on market conditions. Given the widespread development of ECSR activities in several industries, it is policy relevant to disentangle the relationship between market composition and the level of emission tax. From the manager's point of view, it is key to know whether adopting ECSR practices is strategically effective to maximise profits. The scope of the present paper is to shed light on these matters.

We evaluate the endogenous industry structure of a continuous time, evolutionary oligopoly in which production is polluting and a tax on emissions is in place. In the industry, PS firms compete with ECSR firms in quantities. In every time period, firms choose whether to adopt an ECSR or PS statute for strategic reasons: they evaluate the expected profits obtained by the two business strategies and pick the most profitable. Then, they make their output and investment in emissions technology decisions simultaneously to maximise the chosen objective.

We first develop the static model with an exogenous market structure, namely, firms cannot choose their production strategy, so that we take as given whether they adopt a PS or ECSR statute. In this context, we outline the features of the static equilibrium which in a dynamic setting will be played in a continuous time setting.

As a second step, we introduce the dynamics in an evolutionary setting with a duopoly (Droste et al., 2002). In every time period, two firms are drawn from a population of firms to play the duopoly game. Thus, the share of ECSR and PS firms in the industry evolves based on the comparison of expected profits, even though production quantities are determined to maximise each firm's objective function. This framework yields analytical results, which are not obtainable in an oligopoly setting, but does not allow to study the endogenous industry configuration between more than two firms.

Finally, we determine the long-run market configuration in an industry with more than two firms. To do so, we rely on a generalised version of Droste et al. (2002) for oligopolies (De Giovanni and Lamantia, 2016 and Kopel and Lamantia, 2018, among others): here, two or more firms are drawn from the population, and the expected profits are calculated by considering every possible combination of PS and ECSR firms in the industry over the next time period.

In this evolutionary setting, we consider the implementation of an exogenous emission tax to fight pollution. To ease the tax burden, PS and ECSR firms may in turn invest in emission reduction technology. The focus of this work is on how the interaction between ECSR practices and the emission tax influences the long-run evolutionary equilibrium. In this sense, we differ from the aforementioned papers by Fukuda and Ouchida (2020), Xu et al. (2022) and Xu and Lee (2022), who instead assume the tax is endogenously determined by the government from social welfare maximisation. Here, our interest is to see how the industry configuration changes for different levels of the tax rate.

In line with the existing literature (Fukuda and Ouchida, 2020), our results show that an ECSR firm may pollute more than a PS firm, despite its commitment to emissions reduction. Although this result might seem surprising *prima facie*, it is quite simple to explain: to compete with PS firms, an ECSR firm must counterbalance its environmental concern with social concern, which implies corporate policies that increase demand and in turn the equilibrium quantity produced by the ECSR firm compared to the PS firm. Note that this intuition is robust to the alternative modelling of strategic ECSR, according to which the cost of environmental concern is offset by the presence of green consumers who prefer the ECSR to the PS product. Indeed, even in this case, the emissions reduction practices boost demand, with the possible effect of an increase in emissions compared with PS firms.

Our analysis indicates that the presence of ECSR firms in the industry is bad for the environment because emissions rise. However, things change with the introduction of an emission tax because the tax pushes also PS firms to invest in emission reduction technology. Through competition then, ECSR firms have an incentive to further lower their emissions. The environmental damage reaches its minimum (and social welfare its maximum) when a small but relevant share of ECSR firms stays in the industry in the long-run equilibrium configuration. The results are striking: the adoption of ECSR practices is not beneficial *per se*, but for the competitive pressure that puts on the industry through the investment in emissions reduction technology, provided that an emission tax is in place.

Our overarching conclusion is that, while environmental regulation and voluntary emission reduction practices have been regarded as alternative ways to pursue the containment of environmental damage, they appear to be complement features: their combination yields the best outcome for both the environment and society.

Together with the above-mentioned contributions in the literature on strategic ECSR and its interaction with an emission tax, the paper is also related to the literature on the endogenous market structure in mixed oligopolies with CSR (and ECSR) firms. This topic has been studied by Lambertini and Tampieri (2015) and Gioffré et al. (2021) in static settings. In evolutionary frameworks, it has been analysed by Kopel et al. (2014), Kopel and Lamantia (2018). The analysis of an evolutionary setting is relevant since it allows us to study the long-run market configuration in a mixed market. The present analysis is mainly linked to the latter two papers, in which firms compete *à la* Cournot and can choose whether to adopt a CSR or PS behaviour. Compared to our paper, Kopel et al. (2014), Kopel and Lamantia (2018) consider CSR rather than ECSR firms, which implement a fraction of consumer surplus but no environmental externality in their objective function. In addition, we take into account the implementation of a tax on emissions and how this interacts with the decision to invest in emissions reduction technology.

The remainder of the paper is organised as follows. Section 2 outlines the framework, while Section 3 and Section 4 develop the static and evolutionary equilibrium in a duopoly, respectively. The evolutionary oligopoly and the welfare analysis are illustrated in Section 5: more specifically, in Section 5.1 we illustrate the long-run industry configuration. In Section 5.2, we first analyse the market and welfare effects of an introduction of an emission tax and its variation; second, we evaluate the changes in equilibrium for different levels of ECSR internalisation of polluting emissions. Concluding remarks are in Section 6, while all the proofs can be found in Appendix.

2. The model

We analyse an industry composed of $N \geq 2$ firms that produce a unique homogeneous good and compete in quantities. Of these N firms, $m \in \{0, 1, 2, \ldots, N\}$ are profit-seeking (PS) and $N - m$ are environmentally socially concerned (ECSR). Throughout the paper, we denote a generic PS firm with subscript P and a generic ECSR firm with subscript E. The inverse demand of the good produced by the firms is given by the following linear function:

$$p = a - q_P - \sum_{i=0}^{m-1} q_i - q_E - \sum_{j=0}^{N-m-1} q_j, \tag{1}$$

In Eq. (1), PS firms different from P are labelled as i, while ECSR firms different from E are labelled as j, p is the unit price of the good, $a > 0$ is the market reservation price, while outputs are denoted by q.[2]

Each firm is subject to emission taxation so, to reduce the tax burden, each firm can invest to abate emissions. The abatement technology is of the *end-of-pipe* type: emissions by each firm are defined as output minus abatement investments: $e = q - z$. Notice that end-of-pipe technology may help reduce emissions of pollutants into the atmosphere, but they are not able to eliminate environmental damage. In practice, end-of-pipe technology may reduce emissions at the end of the production process. Examples of these technologies are catalytic converters on car tailpipes, smokestacks or filters that block emissions (Lahiri and Symeonidis, 2007).

Profits for each firm $k \in \{P, E\}$ are given by

$$\pi_k = (p - c)\, q_k - \frac{\theta}{2} z_k^2 - \left(q_k - z_k\right) \tau, \tag{2}$$

where $c > 0$ denotes marginal production cost, $\theta > 0$ captures the efficiency of the abatement technology, z_k represents emissions abatement investment and τ is the unit tax on emissions.

Each ECSR firm, E, maximises its profits plus a fraction of consumer surplus and internalises its share of emissions. The objective function of each firm E is the following (see Lambertini et al., 2016):

$$O_E = \pi_E - \alpha \left(q_E - z_E\right) + \beta CS. \tag{3}$$

In (3), $\alpha \in [0, 1]$ represents the fraction of emissions that is voluntarily internalised by an ECSR in its production process,[3] while $\beta \in [0, 1]$ is the ECSR firm's sensitivity with respect to social concern, represented by consumer surplus CS, which is denoted as

$$CS = \frac{\left[q_P + \sum_{i=0}^{m-1} q_i + q_E + \sum_{j=0}^{N-m-1} q_j\right]^2}{2}. \tag{4}$$

3. Static equilibrium

In the static equilibrium, firms take the industry configuration as given, i.e., each firm takes as given whether it is ESCR or PS. Firms simultaneously choose quantities and the investment in emissions reduction technology according to their objective function. The optimisation problem of each PS firm P is given by

$$\begin{aligned} \max_{q_P, z_P}\ \pi_P = \left(a - q_P - \sum_{i=0}^{m-1} q_i - q_E - \sum_{j=0}^{N-m-1} q_j - c\right) q_i - \frac{\theta}{2} z_P^2 - (q_P - z_P)\tau, \\ \text{s.t. } q_P \geq 0,\ z_P \geq 0,\ q_P - z_P \geq 0. \end{aligned} \tag{5}$$

Similarly, the optimisation problem of each ECSR firm E is given by

$$\begin{aligned} \max_{q_E, z_E}\ O_E = {} & \left(a - q_P - \sum_{i=0}^{m-1} q_i - q_E - \sum_{j=0}^{N-m-1} q_j - c\right) q_E \\ & - \frac{\theta}{2} z_E^2 - (q_E - z_E)(\tau + \alpha) \\ & + \frac{\beta}{2}\left(q_P + \sum_{i=0}^{m-1} q_i + q_E + \sum_{j=0}^{N-m-1} q_j\right)^2, \\ & \text{s.t. } q_E \geq 0,\ z_E \geq 0,\ q_E - z_E \geq 0. \end{aligned} \tag{6}$$

For notational simplicity, we set $\mu = a - c$, where μ measures market size. We assume $\mu > \tau + \alpha$, implying that the market size is sufficiently large so that PS and ECSR firms are both able to bear the cost of emissions and the internalisation of pollution. The complete solution to the constrained maximisation problem is developed in the appendix (see "Proof of Proposition 1"). The following proposition summarises the equilibrium of the static game.

Proposition 1. *The equilibrium quantities and abatement of PS and ECSR firms are:*

$$\begin{aligned} q_P^* &= \frac{\mu - \tau + (N - m)\alpha - (\mu - \tau)(N - m)\beta}{N + 1 - (N - m)\beta}, \\ q_E^* &= \frac{\mu - \tau - (m + 1)\alpha + (\mu - \tau)\beta m}{N + 1 - (N - m)\beta}, \\ z_P^* &= \frac{\tau}{\theta}, \\ z_E^* &= \frac{\tau + \alpha}{\theta}. \end{aligned} \tag{7}$$

Proposition 1 provides some insights into the nature of the equilibrium. First, the sensitivity of social concern (represented by β) is negatively related with the production of each firm P, while positively related with the production of each E firm. This is a standard result in a mixed market with CSR and ECSR firms (Gioffré et al., 2021; Kopel and Lamantia, 2018; Lambertini and Tampieri, 2015; and Kopel et al., 2014, among others). Intuitively, by taking into account consumer surplus, ECSR firms put a greater weight on output than PS rivals, who are strategically induced to reduce their output. Second, the investment in emissions reduction technology is strictly dependent on the tax on emissions: without the tax, a PS firm does not invest at all (Mc Donald and Poyago-Theotoky, 2017) because the regulatory pressure is what provides the incentive to reduce emissions. But for the ECSR firm the investment in abatement depends on the tax *and* the environmental concern. In practice, the environmental concern acts as if an ECSR firm taxes itself at a tax rate α, irrespective of the presence of the emission tax.

Using Proposition 1, we can rewrite profits for each firm P and each firm E as follows:

$$\begin{aligned} \pi_P^*(m) &= [q_P^*(m)]^2 + \frac{\tau^2}{2\theta}, \\ \pi_E^*(m) &= \{[1 + \alpha - (N - m)\beta] q_E^*(m) - \beta m q_P^*(m)\} q_E^*(m) + \frac{\tau^2 - \alpha^2}{2\theta}. \end{aligned} \tag{8}$$

The conditions in the following corollary ensure the existence of interior solutions in Eq. (7).

Corollary 2. *$\theta > \underline{\theta}$ and $\beta \in (\underline{\beta}, \overline{\beta})$ ensure positive quantities, abatement and emissions for each PS and ECSR firms, where*

$$\begin{aligned} \underline{\theta} &= \max\left\{\frac{[(1 - \beta)N + 1]\tau}{\alpha - (\mu - \tau)(\beta N - 1)}, \frac{(N + 1)(\tau + \alpha)}{(\mu - \tau)(\beta N + 1) - (N + 1)\alpha}\right\}, \\ \underline{\beta} &= \max\left\{0, \frac{(N + 1)\alpha - (\mu - \tau)}{(\mu - \tau)N}\right\}, \\ \overline{\beta} &= \min\left\{\frac{\mu - \tau + \alpha}{(\mu - \tau)N}, 1\right\}. \end{aligned}$$

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[2] Inverse demand p has no subscript because the good is homogeneous and thus it is the same for all firms.

[3] Note that one firm can control its polluting emissions by reducing production or investing in emission reduction technology, but it has no control over the environmental damage caused by the emissions (defined in Section 5.2). This assumption seems natural, considering that a firm may influence only its production process.

Corollary 2 ensures positive quantities, abatement, emissions and ECSR-firm's profits. Specifically, $\theta > \underline{\theta}$ ensures positive emissions for any nonnegative level of investment in emission abatement, $\beta < \overline{\beta}$ ensures positive quantities for PS firms for every $m \in \{0, 1, \dots, N\}$, while $\beta > \underline{\beta}$ ensures positive quantities for ECSR firms for every $m \in \{0, 1, \dots, N\}$.

We now offer an intuitive explanation behind these conditions. A low enough cost of investment in emissions reduction technology, θ, would give the incentive to invest enough to reduce emissions completely. This situation is unrealistic and it is cast aside by the restriction $\theta > \underline{\theta}$. Further, a low enough social concern, β, would not be enough to offset the negative effect on output due to the inclusion of environmental concern. But, if the ECSR's social concern is too high, PS firms have no incentives to produce at all. This is because of the very aggressive production by each ECSR firm. Similar restrictions are typical in static mixed markets with CSR and ECSR firms and appear to be qualitatively similar. See Gioffré et al. (2021) and Lambertini and Tampieri (2015) for CSR and ECSR oligopolies, respectively.

4. Evolutionary duopoly

We are now in a position to endogenise a firm's choice of being of PS or ECSR type according to expected profits. In every time period, firms first select simultaneously whether to become an ECSR or PS type by comparing the expected profits obtained by the two objectives; then, they choose their output and emissions reduction technology to maximise the chosen objective function.

As a preliminary analysis, we develop a duopoly setting *àla* (Droste et al., 2002). A recent paper that applies this framework to strategic interaction between PS and CSR firms is Kopel et al. (2014). This approach allows us to obtain an analytical characterisation of the equilibrium by restricting the analysis to only two firms.

Suppose there exists a large number of firms and, at time t, a fraction $x \in [0, 1]$ of the population is of type PS, while a fraction $1-x$ is of ECSR type. In each time period, $N = 2$ firms are drawn from the population, forming a duopoly. We denote $\pi^*_{kk'}$ as firm $k \in \{P, E\}$ profits when k is matched with firm $k' \in \{P, E\}$. In practice, the random match implies that the duopoly may be between two PS firms, two ECSR firms or mixed. If firm k is of type P, it will get profits π^*_{PP} if matched with another type PS, and profits π^*_{PE} if the competitor is of type ECSR. Analogously, if firm k is of type E, it will get profits π^*_{EP} or π^*_{EE} if matched with a competitor of type PS or ECSR, respectively. Using the results from Proposition 1 when $N = 2$ and $m = 0$ (match between two PS), $m = 1$ (mixed match) or $m = 2$ (match between two ECSR, the optimal profits for each market composition are:

$$\pi^*_{PP} = \frac{(\mu-\tau)^2}{9} - \frac{\tau^2}{2\theta},$$

$$\pi^*_{PE} = \frac{(\alpha+\mu-\tau-\beta\mu+\beta\tau)^2}{(\beta-3)^2} + \frac{\tau^2}{2\theta},$$

$$\pi^*_{EP} = \frac{(2\alpha-\mu+\tau-\beta\mu+\beta\tau)(2\alpha-\mu+\tau-\alpha\beta+\beta\mu-\beta\tau)}{(\beta-3)^2} + \frac{(\tau+\alpha)^2}{2\theta},$$

$$\pi^*_{EE} = -\frac{(2\beta-1)(\alpha-\mu+\tau)^2}{(2\beta-3)^2} + \frac{(\tau+\alpha)^2}{2\theta}.$$

Given the population state at time t, each (PS or ECSR) firm is randomly paired with a competitor of type PS with probability $x(t)$ and of type ECSR with probability $1-x(t)$. Then the probability $x(t)$ to meet a competitor of type PS amounts to the share of firms adopting strategy PS in the population of firms at time t. Similarly, the probability $1-x(t)$ to meet a competitor of type ECSR corresponds to the share of firms of type ECSR in the population. If the population of firms is large enough, then by the law of large numbers we can take the expected profits to be a close approximation of realised profits (Weibull, 1995, p. 71–72).

Firm 2

Firm 1	*PS*	*ECSR*
PS	π^*_{PP}, π^*_{PP}	π^*_{PE}, π^*_{EP}
ECSR	π^*_{EP}, π^*_{PE}	π^*_{EE}, π^*_{EE}

The payoff matrix shows the stage game on the firm's type between the two firms drawn to play in the duopoly. At any time period t, the expected profits of a firm who chooses to adopt a PS and ECSR strategy are, respectively,

$$\begin{aligned} \mathbb{E}_d\left(\pi^*_P(x)\right) &= x\pi^*_{PP} + (1-x)\pi^*_{PE}, \\ \mathbb{E}_d\left(\pi^*_E(x)\right) &= x\pi^*_{EP} + (1-x)\pi^*_{EE}, \end{aligned} \tag{9}$$

where subscript d stands for "duopoly" and we omit the time argument for simplicity. The increase or decrease in the number of a certain type of firm in the population depends on the comparison between expected profits in (9), according to the following replicator dynamics in continuous time (Weibull, 1995; Antoci et al., 2021; Tang et al., 2021, among others):

$$\dot{x} = x(1-x)[\mathbb{E}\left(\pi^*_P(x)\right) - \mathbb{E}\left(\pi^*_E(x)\right)]. \tag{10}$$

Eq. (10) admits three types of stable steady states:[4] two corner equilibria with homogeneous populations of either "All ECSR" or "All PS" firms ($x \in \{0, 1\}$), or one interior "Mixed" equilibrium in which ECSR and PS types coexist ($x \in (0, 1)$). We denote x^* as a stable steady state.

According to (9), a corner steady state such that the industry is composed only by PS firms ($x^* = 1$) emerges if $\pi^*_{PE} - \pi^*_{EE} > 0$ and $\pi^*_{PP} - \pi^*_{EP} > 0$ then $\mathbb{E}\pi^*_P(x) > \mathbb{E}\pi^*_E(x)$ for every x. By contrast, a corner steady state such that the industry is composed only of ECSR firms ($x^* = 0$) requires the dominance of the ECSR strategy, that is, whenever $\pi^*_{PE} - \pi^*_{EE} < 0$ and $\pi^*_{PP} - \pi^*_{EP} < 0$ then $\mathbb{E}\pi^*_P(x) < \mathbb{E}\pi^*_E(x)$ for every x. Finally, the market configuration is mixed ($x^* \in (0, 1)$) for $\mathbb{E}\pi^*_P(x) = \mathbb{E}\pi^*_E(x)$.

The thresholds $\widehat{\theta}$ and $\widetilde{\theta}$ are consistent with $\pi^*_{PE} = \pi^*_{EE}$ and $\pi^*_{PP} = \pi^*_{EP}$, respectively, from which we can define each steady state configuration (see in the appendix the Proof of Proposition 3). Fig. 1 illustrates these conditions for each stable steady state (see Section "Industry configuration in a duopoly" in the Appendix for a derivation).

A high environmental concern α generally makes the ECSR strategy too costly to compete with a strategy oriented to profit maximisation, leading to an industry composed of only PS firms. In contrast, a relatively small α combined with a relatively small β dominates profits maximisation, leading to an industry configuration with *All ECSR*. Finally, higher levels of β yield a strategic advantage only when the competitor is PS, but not against ECSR firms, which brings about the coexistence of both types in the population of firms.

5. Evolutionary oligopoly

The analysis developed in Section 4 allows us to obtain a tractable configuration of the steady state. However, by construction, the duopoly framework *à la* (Droste et al., 2002) prevents an investigation of industries where more than two firms operate, as well as the related policy analysis. This section develops the steady state configuration of the industry in an oligopoly setting. In this case, the computational complexity of the model precludes an analytical characterisation of the steady states. Yet, we can show that some steady states in an oligopoly may behave similarly to those in duopoly.

We adopt the evolutionary setting developed by De Giovanni and Lamantia (2016), Hommes et al. (2018), Kopel and Lamantia (2018), Lamantia et al. (2018), and Tichý et al. (2020), among others. The

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[4] It also admits an unstable steady state, which for completeness is derived in the "Proof of Proposition 3" in Appendix.

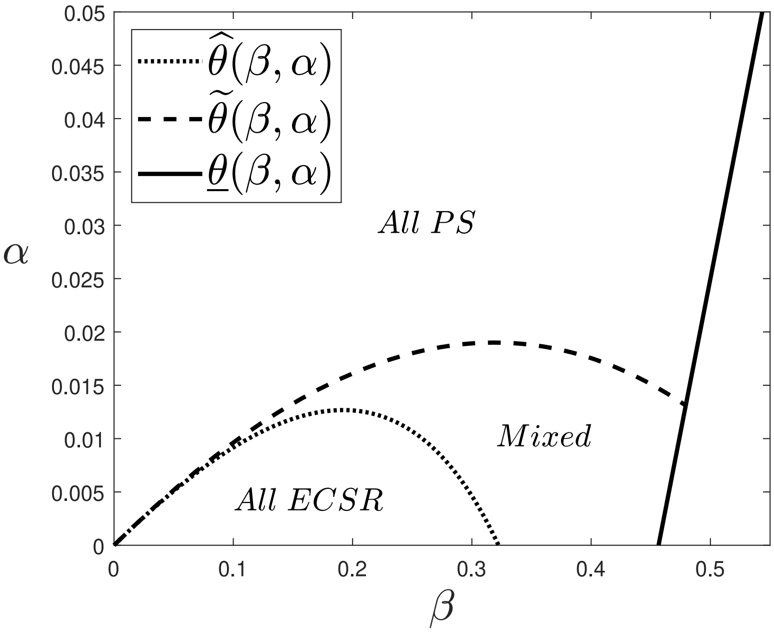

Fig. 1. Industry configurations. Level curves $\widehat{\theta}(\beta,\alpha)$ and $\widetilde{\theta}(\beta,\alpha)$ in the plane (β,α).

approach is the following. In each time period, $N > 2$ firms are randomly selected from a large population of firms to play the one-shot game described in Section 3. Firms are Nash players in the sense that, before choosing quantities, they observe the real composition of the $N-1$ rivals. This means that each firm computes the value of the expected profits for every possible combination of PS and ECSR firms in the industry. Therefore, compared to the framework developed in Section 4, this one allows to study the strategic interaction among $N > 2$ firms.

Again, we denote $x \in [0,1]$ as the probability that one firm adopts the profit-seeking strategy. For the same reasons outlined in Section 4, the probability x can be interpreted as the share of PS firms on the market and $1-x$ as the share of ECSR firms.

In an oligopoly setting, the expected profits are a function of all the possible combinations of the production strategy of all $N-1$ competitors. Specifically, we denote as h the number of competitors who are PS in any possible industry configuration. For each PS firm, expected profits are given by

$$\mathbb{E}_o[\pi_P(x)] = \sum_{h=0}^{N-1} \binom{N-1}{h} x^h (1-x)^{N-1-h} \pi^*_P(h+1), \tag{11}$$

where subscript o stands for "oligopoly", and equilibrium profits for each firm P are given by

$$\pi^*_P(h+1) = [\mu - (h+1)q^*_P(h+1) - (N-1-h)q^*_E(h+1)]q^*_P(h+1) - \frac{\theta}{2}(z^*_P)^2 - (q^*_P(h+1) - z^*_E)\tau. \tag{12}$$

In equation Eq. (12), argument $(h+1)$ refers to the fact that, if the firm chooses a PS profile, it increases the number of PS firms in the industry by one unit.

Analogously, the expected profit of an ECSR firm is given by

$$\mathbb{E}[\pi_E(x)] = \sum_{h=0}^{N-1} \binom{N-1}{h} x^h (1-x)^{N-1-h} \pi^*_E(h), \tag{13}$$

where

$$\pi^*_E(h) = [\mu - kq^*_P(h) - (N-h)q^*_E(h)]q^*_E(h) - \frac{\theta}{2}(z^*_E)^2 - (q^*_E(h) - z^*_E)\tau. \tag{14}$$

In equation Eq. (14), argument h refers to the fact that, if the firm chooses an ECSR profile, it leaves the number of PS firms by the same amount h.[5] Expected profits Eq. (11) and Eq. (13) constitute a generalisation of the duopoly scenario, where expected profits Eq. (9) were specific to that case. These expressions are binomial distribution functions that describe all possible rivals' strategies, spanning from $m \in \{0,1,2,\ldots,N-1\}$.

Conversely, in a duopoly, only two firms compete in the industry, resulting in expected profits being contingent upon the single rival. In this context, expected profits Eq. (9) follow a Bernoulli distribution, which is essentially a binomial distribution with just one trial, since in that case $N-1 = 2-1$.

Equations Eqs. (11) and (13) imply that at time $t+1$ each firm figures out the expected profits of a PS or ECSR type, respectively, for any possible industry configuration that may occur, i.e., all possible combinations between PS and ECSR firms. The time evolution of the share x is given by the same replicator dynamics similar to that adopted in Section 4:

$$\dot{x} = x(1-x)[\mathbb{E}_o\left(\pi^*_P(x)\right) - \mathbb{E}_o\left(\pi^*_E(x)\right)]. \tag{15}$$

Whenever $\mathbb{E}_o\left(\pi^*_P(x)\right) > \mathbb{E}_o\left(\pi^*_E(x)\right)$, the industry exhibits an *All PS* configuration ($x^* = 1$), while $\mathbb{E}_o\left(\pi^*_P(x)\right) < \mathbb{E}_o\left(\pi^*_E(x)\right)$ implies an *All ECSR* industry configuration ($x^* = 0$) and naturally, for $\mathbb{E}_o\left(\pi^*_P(x)\right) = \mathbb{E}_o\left(\pi^*_E(x)\right)$, the industry configuration will be *Mixed*.

In what follows we illustrate our main results. Given the analytical complexity of the problem at hand, we base our discussion on numerical examples. To overcome this limitation, we look for consistency with the duopoly setting. In the appendix, we verify the global stability of our equilibrium configuration.

5.1. Industry configuration and competition

We begin by showing the steady state market configuration x based on different levels of sensitivity to social and environmental concern, for given numbers of firms $N > 2$. That is, we examine how the equilibrium share of PS firms x^* changes with respect to the level of

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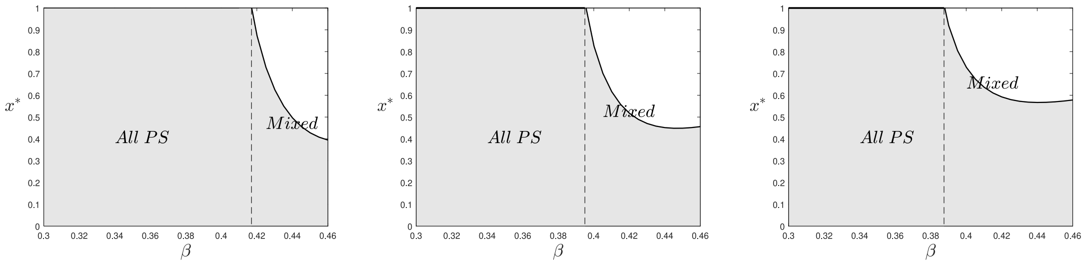
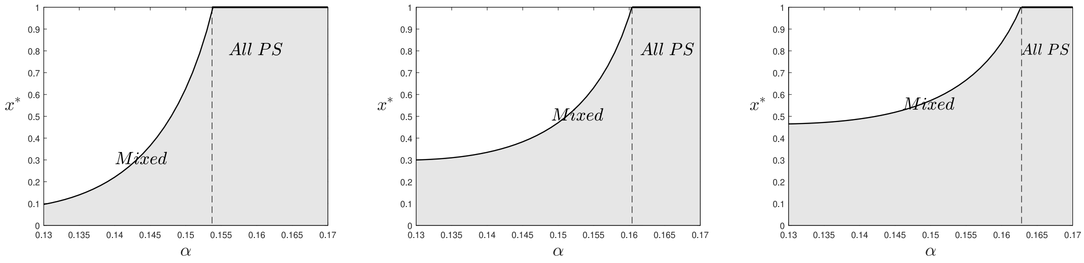
[5] To fix ideas, suppose a firm faces 9 competitors, 5 of which are PS and 4 are ECSR. If this firm chooses to be PS, then the number of PS firms becomes $h+1 = 6$, while if it chooses to become ECSR, the number of PS firms remain $h = 5$.



(a) $N = 3$. **(b)** $N = 4$. **(c)** $N = 5$.

Fig. 2. Industry configuration with respect to β, $\mu = 0.7$, $\alpha = 0.15$, $\tau = 0.1$, $\theta = 4$.



(a) $N = 3$. **(b)** $N = 4$. **(c)** $N = 5$.

Fig. 3. Industry configuration with respect to α, $\mu = 0.7$, $\beta = 0.43$, $\tau = 0.1$, $\theta = 4$.

social concern, β, and environmental concern α, based on the replicator dynamics (15).

We first make connection with the steady state results analytically obtained in the duopoly case. Notice that the thresholds in Fig. 1 are obtained analytically from the strategic interaction of two firms and thus cannot be replicated in this setting. Therefore, we consider the change in the industry configuration for β and α separately in Figs. 2 and 3, respectively. The bold line represents the level of x^* according to replicator dynamics (15). These figures allow us to evaluate how the industry configuration changes with respect to the degree of social or environmental concern and in the number of firms in the industry. In addition, this exercise allows us to compare our results with the literature.

Figs. 2(a)–2(c) show the different industry configurations for various levels of β for $N = 3$, $N = 4$ and $N = 5$, respectively. The share of ECSR firms $(1 - x^*(\beta))$ under evolutionary competition is represented in the non-shaded area for each value of β, while the dashed line separates the equilibrium types. The interval of β in the horizontal axis, as well as the choice of parameter values, takes into account the restrictions in Corollary 2 and the vertical dashed line separates the different industry configurations.

Compared to the duopoly case, these results correspond to the configurations in Fig. 1 for α in the range $(0.13, 0.17)$,[6] where an increase in β results in an industry configuration that passes from *All PS* to *Mixed*. Our results show that PS firms are generally dominant. In particular, the relation between competition and the long-run existence of a share of ECSR firms is curvilinear, and the level of β such that the industry configuration passes from *All PS* to *Mixed* decreases with the number of firms. Given that the number of firms represents the level of competition, Fig. 2 suggests that an industry with a higher level of competition requires a higher level of social concern in the ECSR statute to allow ECSR firms to stay in the industry. Finally, a market configuration *All ECSR* never appears (i.e., x^* is always greater than zero). These considerations are robust to extensive robustness checks, namely, to different parameter values α, τ, θ and μ, which can be found in the Appendix (see section "Robustness checks", Figs. 9–11).

In the analysis of the industry configuration with respect to β, our results are qualitatively similar to the findings of Kopel and Lamantia (2018). Compared to our results, they find larger regions in which socially concerned firms are present. Thus the presence of environmental concern in the CSR statute, as well as emissions regulation and innovation abatement reinforce the persistence of firms focused only on profits.

Figs. 3(a)–3(c) show the different industry configurations to changes in α for $N = 3$, $N = 4$ and $N = 5$, respectively. Similar to Fig. 2, the share of ECSR firms $(1 - x(\alpha))$ is represented in the non-shaded area above the curve. The interval of α in the horizontal axis takes into account the restrictions imposed by Corollary 2. Comparing again with the duopoly case, these results correspond to the configurations in Fig. 1 for β in the range $(0.3, 0.46)$: the increase in environmental concern, α, makes the ECSR production strategy less and less competitive, leading to a homogeneous configuration of the industry with only PS firms. An increase from 3 to 4 firms in the industry, and thus a higher level of competition, brings about a *Mixed* configuration for higher levels of environmental concern.

5.2. The interaction between the emission tax and ECSR practices

This section develops the main results of the paper. By relying on the steady-state industry configuration developed in the oligopoly setting, we show the effects of variations in the emission tax τ and ECSR internalisation of emissions α on the long-run equilibrium features: the market configuration, the level of polluting emissions and social welfare. From this analysis, we are able to illustrate the interaction between ECSR practices and the introduction of an emission tax and explain why both must be present to reach the welfare-maximising outcome for the environment and social welfare. For completeness, in the Appendix we evaluate how the steady state equilibrium changes due to variations in the cost of technology θ (see Fig. 8).

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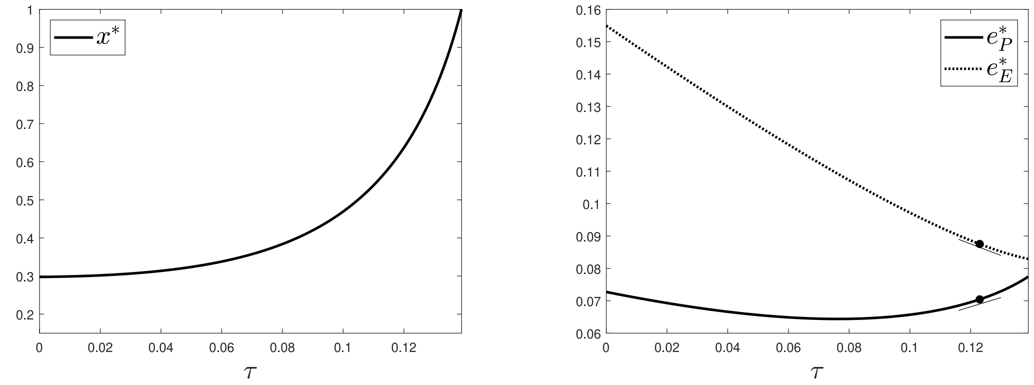
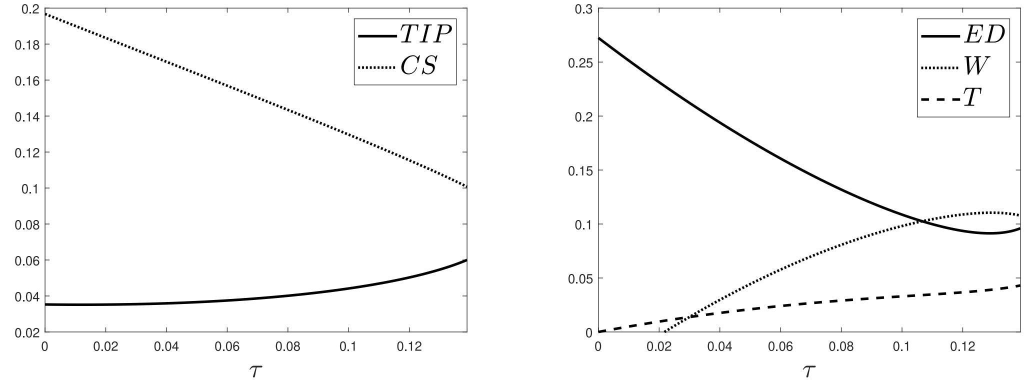
[6] Given the different framework adopted and the different number of firms considered, it is not possible to provide a qualitative comparison for the same numerical values, because the parameter range of admissibility changes according to the framework and as a function of the number of firms N.



(a) Long-run share of profit-seeking firms. **(b)** Emissions of PS and ECSR firms.



(c) Total Industry Profits and Consumer Surplus. **(d)** Environmental Damage and Welfare.

Fig. 4. Variation in the emission tax, $N = 4$, $\mu = 0.7$, $\beta = 0.43$, $\alpha = 0.15$ and $\theta = 4$.

Social welfare is defined as the sum of industry profits, consumer surplus and tax revenue T minus environmental damages, ED:

$$W = m\pi_P^*(x^*) + (N-m)\pi_E^*(x^*) + CS + T - ED \tag{16}$$

In (16), the tax revenue amounts to

$$T = \tau\left[m(q_P^*(x^*) - z_P^*) + (N-m)(q_E^*(x^*) - z_E^*)\right] \tag{17}$$

while environmental damage is a quadratic function of polluting emissions,

$$ED = \left[m(q_P^*(x^*) - z_P^*) + (N-m)(q_E^*(x^*) - z_E^*)\right]^2 \tag{18}$$

In what follows, we describe the effects of a variation in τ and α on overall social welfare and its components separately, namely, consumer surplus, total industry profits, environmental damage and tax revenue. Finally, note that changes in emissions and welfare may be appreciated together with changes in the market configuration, which may provide an intuition for some of the results.

5.2.1. Variation of the emission tax

Fig. 4 shows the results of changes in the emission tax. The panels may be read starting from the situation in which no tax is implemented ($\tau = 0$), and then see how its introduction affects the steady state.

Panel 4(a) shows that an increase in τ decreases the share of ESCR firms. This result may be explained by the fact that ECSR firms bear an extra cost compared to PS firms, namely, the internalisation of pollution with unit cost α. We further explore this result in Section 5.2.2, Fig. 6(a). The increase in τ makes ESCR firms less and less competitive. The tax rate increase brings about an increase in costs for both types of firms. First, it increases production costs; and second, it increases the investment in emissions reduction. The resulting outcome is a reduction in the equilibrium quantity. For ECSR firms, this reduction in equilibrium quantity reduces the positive effect of social concern β on production, in turn making the ECSR expected profits to be lower than PS's. Therefore, ESCR practices and environmental regulation appear to be alternative components of the long-run equilibrium.

Turning to Panel 4(b), we find that the increase in the tax pushes ESCR firms to invest more in emissions reduction technology, which leads to a greater reduction in emissions. In contrast, for the PS firm emissions are U-shaped with respect to the tax on emissions. With an increase in the tax rate, two effects are at play. First, the higher investment in abatement technology reduces emissions. Second, a decrease in the share of ECSR firms induces PS firms to increase their equilibrium quantities, and in turn their emissions. The first effect more than offsets the second one when the share of ECSR firms remains large in the industry, while the second effect prevails with a small share of ECSR firms.

Panel 4(c) shows the variation in consumer surplus CS and total industry profits, TIP. Consumer surplus decreases with τ, because of the reduction in production by both types of firms, but also the decrease in the share of ESCR firms, which promote it in their objective function.

An interesting result is that the increase in the tax rate may prompt an increase in total industry profits. This does not depend on the reduction in the share of ECSR firms. We show analytically that the same outcome applies in an industry with all PS firms.[7] Instead, the result may be explained by relying on the so-called "Porter Hypothesis", which claims that environmental regulation may push pollution control investment to the point where it counterbalances the cost of compliance.[8] This finding becomes evident when one observes that,

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[7] Computations are available upon request.

[8] Similar results related to the Porter Hypothesis may be found in Lambertini et al. (2020), in a static setting.

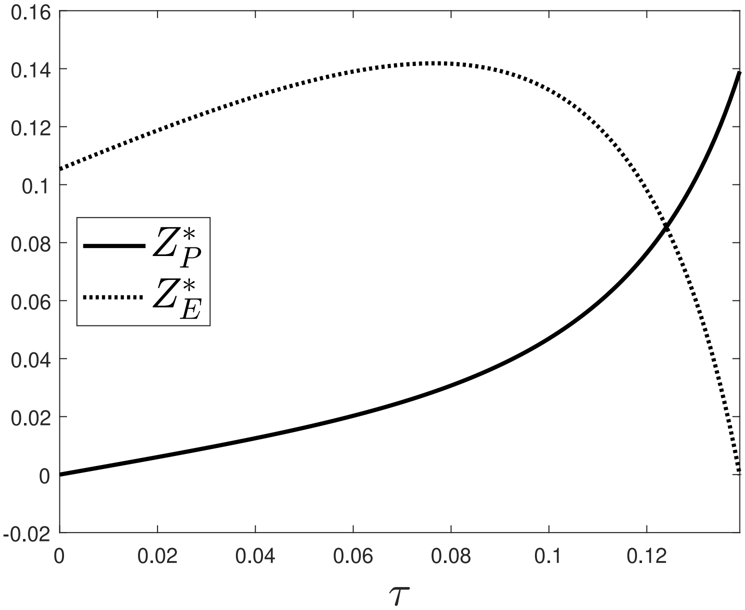


Fig. 5. Variation in the emission tax and total emission abatement by firm types, $N = 4$, $\mu = 0.7$, $\beta = 0.43$, $\alpha = 0.15$ and $\theta = 4$.

according to Proposition 1, the equilibrium investment in emissions reduction technology increases with τ for both types of firms. Importantly, this relationship holds regardless of the industry configuration, as the equilibrium investment is not a function of m.

Next, we turn to tax revenue, environmental damage and social welfare, illustrated in Panel 4(d). Tax revenue increases with the tax rate, suggesting that the increase in unit tax compensates for the decrease in output. Social welfare exhibits a maximum at the tax level in which environmental damage reaches a minimum. Also notice that, at this level of tax revenue, a small share of ECSR firm is active in the industry.

The most counterintuitive result is the fact that ESCR firms' emissions are higher than PS firms' for all values in the simulation. This comes not as a surprise: Fukuda and Ouchida (2020) has shown this potential effect of ECSR practices in a static monopoly. This finding is explained by the social concern component of ESCR firms, which pushes their production at a higher level than that of PS firms in their competitive interaction and more than counterbalances the ECSR commitment towards abatement emissions (Lambertini and Tampieri, 2015, Lambertini et al., 2016). It is important to note that, without social concern, an ECSR firm may not survive the competitive pressure against PS firms. Nonetheless, a higher level of emissions of ECSR compared to PS firms induces us to question their very scope.

This result may be particularly appreciated when $\tau = 0$, which implies no abatement investment from PS firms, $z_P^* = 0$ (see Proposition 1): social concern pushes the production of ECSR firms, resulting in the highest level of consumer surplus, ECSR emissions and overall environmental damage. In addition, ECSR firms grab a consistently higher share of the industry. However, in the presence of an emission tax, PS firms' abatement investment becomes positive which turns into a competitive instrument by pushing ECSR firms to invest more.

With this in mind, the number of ECSR firms is reduced, but the minimisation of environmental damage, as well as the maximisation of social welfare, requires that a relatively small (but not irrelevant) share of them remains in the industry, despite their relatively high level of emissions.

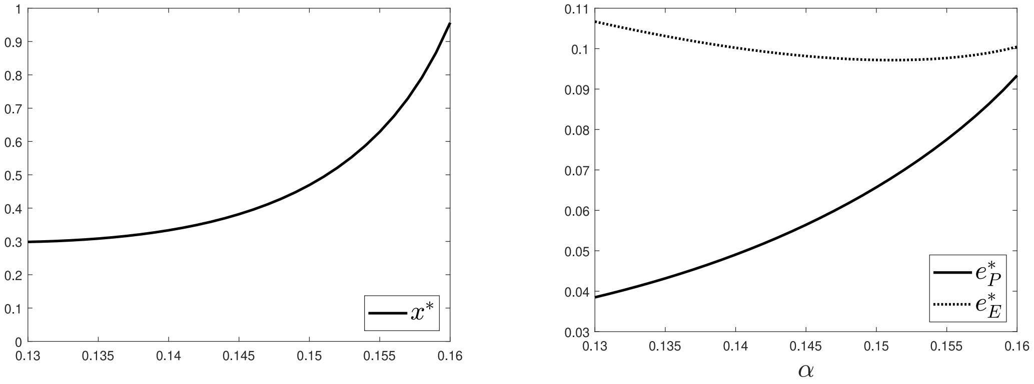
Our numerical exercise also shows that the maximum of social welfare can be reached to a point in which the market configuration exhibits a prevalence of PS firms, about 80% share of the industry. Interestingly, the maximum point of social welfare corresponds to the minimum point of environmental damage, showing its relevance among the welfare components.

To get further insight into the results of Panel 4(d), Fig. 5 shows how the overall investments of PS (Z_P^*) and ECSR (Z_E^*) firms change with the emission tax. Compared to Panel 4(d), the minimum level of environmental damage (i.e., maximum level of social welfare) corresponds here to the intersection point between Z_P^* and Z_E^*. This is consistent with what happens to individual emissions. Looking at the two dots in Panel 4(b), in the neighbourhood of the maximum the individual emissions of ECSR firms are decreasing while the individual emissions of PS firms are increasing. At the welfare-maximising level, the slope (in absolute value) of the emissions of ECSR firms is the same as that of emissions of PS firms. In other words, welfare-maximum corresponds to the industry configuration in which the social marginal benefit of a decrease in emission from an ECSR firm is equal to the social marginal cost given by the increase in emissions of a PS firm.

5.2.2. *Internalisation of emissions*

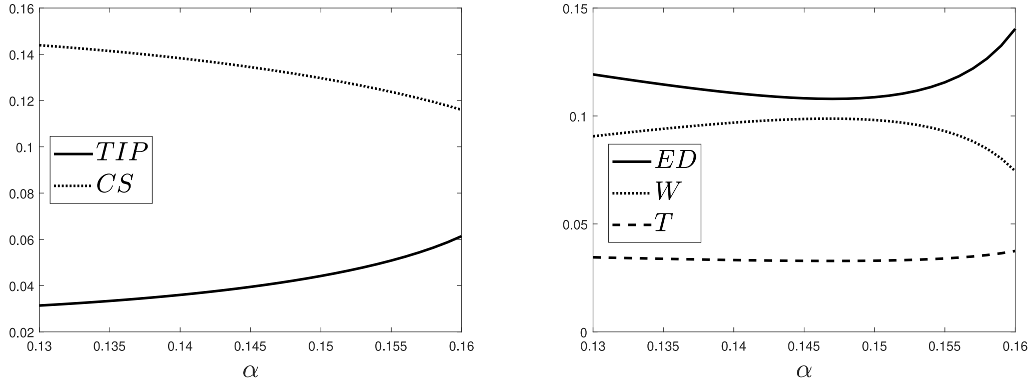
Here we investigate how a variation of the voluntary internalisation of polluting emissions by ECSR firms α affects the features of the steady-state equilibrium. This analysis is helpful to understand how the introduction of the emission tax influences the strategic interaction between ECSR and PS firms, as it modifies the relative incentives to undertake investments in emission abatement.

Fig. 6 illustrates. Begin by noting that α may be interpreted as a further unit tax on emissions that a ECSR firm freely chooses to bear to reduce its environmental impact. Hence, it comes at no surprise that the results in Panel 6(a) are qualitatively similar to those in Panel 4(a). An increase in the internalisation of emissions makes it increasingly costly to sustain ECSR practices, with the effect of reducing their competitiveness against PS firms and in turn their share in the market. In addition, the lower competitiveness of ECSR firms due to the increase in α reduces the strategic incentive of PS firms to invest in emission abatement. This point explains the importance of the presence of ECSR firms for the effectiveness of environmental regulation. ECSR firms pollute more but also induce PS firms to abate more through competition.



(a) Long-run share of profit-seeking firms.

(b) Emissions of PS and ECSR firms.



(c) Total Industry Profits and Consumer Surplus.

(d) Environmental Damage and Welfare.

Fig. 6. CSR internalisation of emissions, $N = 4$, $\mu = 0.7$, $\beta = 0.43$, $\theta = 4$, $\tau = 0.1$.

Paradoxically, this is particularly true when the commitment towards the internalisation of emissions is not too high. The results in Panel 6(d) in terms of environmental damage and social welfare confirm this intuition.

6. Concluding remarks

We have examined the long-run equilibrium configuration of a mixed oligopoly composed of PS and ECSR firms, when an emission tax is in place and firms may invest in emissions reduction technology. We have shown that ECSR firms may pollute more than their PS counterparts, despite their environmental concern. Yet, provided the adoption of the emission tax, their presence in the industry spurs competition through emission abatement, resulting in the minimisation of the environmental damage and maximisation of social welfare when a small but relevant share of ECSR is active in the industry.

An interesting side result is the support for the Porter Hypothesis: the adoption of an environmental policy may increase firms' profits. This is particularly true when the tax burden is sufficiently high, so that emission reduction investment is relatively more convenient. Related to the industry configuration, the increase in profits due to an increase in the emission tax goes along with a decrease in the share of ECSR firms.

Some features of the framework deserve discussion. First, given the growing environmental concern among consumers, it could be argued that the assumption of homogeneity between goods produced by PS and ECSR firms is too strong. In particular, one might expect a different willingness to pay for goods processed by firms of a different type. The assumption indeed aims at simplifying the framework, which is already rich in the number of parameters. Yet, by relaxing it we would just reinforce the existing results, so that our analysis can be thought of as a restrictive case that embodies all degrees of environmental concern among consumers. Second, our findings are completely developed through numerical simulations. Yet, the results are robust to several numerical checks.

Third, unlike other contributions in the literature (Fukuda and Ouchida, 2020; Xu et al., 2022; Xu and Lee, 2022), we have focused on exogenous rather than optimal taxation. Treating the tax as a parameter allows us to evaluate the effects of its changes over the equilibrium configuration and compare them in different scenarios.

An interesting avenue for future research may be the analysis of how variations in the degree of competition influence the degree of investment in emissions reduction technology in the presence of ECSR firms. Lambertini et al. (2017) explores this question in an oligopoly of profit-seeking firms. They find an inverted U relationship between the number of firms in the industry and the total investment in green technology. Given the worldwide diffusion of ECSR practices, the same investigation seems relevant to mixed markets composed of PS and ECSR firms.

To conclude, the main message to regulators is that social welfare is increased by a combination of emission tax and the presence of a small share of ECSR firms. Environmental regulation and voluntary emission abatement practices seem complement features to reach the environmental optimum.

CRediT authorship contribution statement

Gianluca Iannucci: Conceptualization, Formal analysis, Methodology, Writing – original draft, Revision. **Alessandro Tampieri:** Conceptualization, Formal analysis, Methodology, Writing – original draft, Revision.

Appendix

Proof of Proposition 1

The Lagrangian function associated with problem Eq. (5) is the following:

$$\mathcal{L}_P = \pi_P + \lambda_1 q_P + \lambda_2 z_P + \lambda_3 (q_P - z_P), \tag{19}$$

where λ_1, λ_2, and λ_3 are the Khun–Tucker multipliers associated with the positivity constraint of quantity, emission reduction abatement and emissions, respectively. The Lagrangian function associated with Eq. (6) is the following:

$$\mathcal{L}_E = O_E + \lambda_4 q_E + \lambda_5 z_E + \lambda_6 (q_E - z_E), \tag{20}$$

where λ_4, λ_5, and λ_6 are the associated Khun–Tucker multipliers.

The first order conditions with respect to q_k and z_k are, respectively,

$$\begin{aligned}
\frac{\partial \mathcal{L}_P}{\partial q_P} &= a - 2q_P - \textstyle\sum_{i=0}^{m-1} q_i - q_E - \sum_{j=0}^{N-m-1} q_j - c - \tau + \lambda_1 + \lambda_3 = 0,\\
\frac{\partial \mathcal{L}_P}{\partial z_P} &= -\theta z_P + \tau + \lambda_2 - \lambda_3 = 0,\\
\frac{\partial \mathcal{L}_E}{\partial q_E} &= a - 2q_E - q_P - \textstyle\sum_{i=0}^{m-1} q_i - \sum_{j=0}^{N-m-1} q_j - c - \tau - \alpha\\
&\quad + \beta \left(q_P + \textstyle\sum_{i=0}^{m-1} q_i + \sum_{j=0}^{N-m-1} q_j + q_E \right) + \lambda_4 + \lambda_6 = 0,\\
\frac{\partial \mathcal{L}_E}{\partial z_E} &= -\theta z_E + \tau + \alpha + \lambda_5 - \lambda_6 = 0.
\end{aligned} \tag{21}$$

From (19), we obtain the optimality conditions:

$$\begin{cases}
a - 2q_P - \sum_{i=0}^{m-1} q_i - q_E - \sum_{j=0}^{N-m-1} q_j - c - \tau + \lambda_1 + \lambda_3 = 0,\\
-\theta z_P + \tau + \lambda_2 - \lambda_3 = 0,\\
\lambda_1 q_P = 0,\ \lambda_1 \geq 0,\\
\lambda_2 z_P = 0,\ \lambda_2 \geq 0,\\
\lambda_3 (q_P - z_P) = 0,\ \lambda_3 \geq 0,\\
q_P \geq 0,\ z_P \geq 0,\ q_P - z_P \geq 0.
\end{cases} \tag{22}$$

Invoking symmetry and plugging $\mu = a - c$, system (22) amounts to

$$\begin{cases}
\mu - (m+1) q_P - (N-m) q_E - \tau + \lambda_1 + \lambda_3 = 0,\\
-\theta z_P + \tau + \lambda_2 - \lambda_3 = 0,\\
\lambda_1 q_P = 0,\ \lambda_1 \geq 0,\\
\lambda_2 z_P = 0,\ \lambda_2 \geq 0,\\
\lambda_3 (q_P - z_P) = 0,\ \lambda_3 \geq 0,\\
q_P \geq 0,\ z_P \geq 0,\ q_P - z_P \geq 0.
\end{cases} \tag{23}$$

Similarly, from (20), we obtain the optimality conditions:

$$\begin{cases}
a - 2q_E - q_P - \sum_{i=0}^{m-1} q_i - \sum_{j=0}^{N-m-1} q_j - c - \tau - \alpha\\
\quad + \beta \left(q_P + \sum_{i=0}^{m-1} q_i + q_E + \sum_{j=0}^{N-m-1} q_j \right) + \lambda_4 + \lambda_6 = 0,\\
-\theta z_E + \tau + \alpha + \lambda_5 - \lambda_6 = 0,\\
\lambda_4 q_E = 0,\ \lambda_4 \geq 0,\\
\lambda_5 z_E = 0,\ \lambda_5 \geq 0,\\
\lambda_6 (q_E - z_j) = 0,\ \lambda_6 \geq 0,\\
q_E \geq 0,\ z_E \geq 0,\ q_E - z_E \geq 0.
\end{cases} \tag{24}$$

Invoking symmetry and substituting $\mu = a - c$, system (24) turns into

$$\begin{cases}
\mu - (N - m + 1) q_E - m q_P - \tau - \alpha + \beta [m q_P + (N-m) q_E] + \lambda_4 + \lambda_6 = 0,\\
-\theta z_E + \tau + \alpha + \lambda_5 - \lambda_6 = 0,\\
\lambda_4 q_E = 0,\ \lambda_4 \geq 0,\\
\lambda_5 z_E = 0,\ \lambda_5 \geq 0,\\
\lambda_6 (q_E - z_E),\ \lambda_6 \geq 0,\\
q_E \geq 0,\ z_E \geq 0,\ q_E - z_E \geq 0.
\end{cases} \tag{25}$$

Solving the system composed of the two optimality conditions we obtain:

$$q_P = \begin{cases}
\frac{\mu - \tau + (N-m)\alpha - (\mu-\tau)(N-m)\beta}{N - (N-m)\beta + 1}, \text{ if } \theta > \frac{[N - (N-m)\beta + 1]\tau}{\mu - \tau + (N-m)\alpha - (\mu-\tau)(N-m)\beta},\\
\frac{\mu[1 - (N-m)\beta]}{N - (N-m)(\beta - \theta + \beta\theta) + 1 + \theta}, \text{ if } \theta \leq \frac{[N - (N-m)\beta + 1]\tau}{\mu - \tau + (N-m)\alpha - (\mu-\tau)(N-m)\beta};
\end{cases}$$

$$z_P = \begin{cases}
\frac{\tau}{\theta}, \text{ if } \theta > \frac{[N - (N-m)\beta + 1]\tau}{\mu - \tau + (N-m)\alpha - (\mu-\tau)(N-m)\beta},\\
\frac{\mu[1 - (N-m)\beta]}{N - (N-m)(\beta - \theta + \beta\theta) + 1 + \theta}, \text{ if } \theta \leq \frac{[N - (N-m)\beta + 1]\tau}{\mu - \tau + (N-m)\alpha - (\mu-\tau)(N-m)\beta};
\end{cases}$$

$$q_E = \begin{cases}
\frac{\mu - \tau - (m+1)\alpha + (\mu-\tau)\beta m}{N + 1 - (N-m)\beta}, \text{ if } \theta > \frac{[N - (N-m)\beta + 1](\tau + \alpha)}{\mu - \tau - (m+1)\alpha + (\mu-\tau)\beta m},\\
\frac{\mu[\beta m + \theta + 1]}{N - (N-m)(\beta - \theta + \beta\theta) + 1 + \theta}, \text{ if } \theta \leq \frac{[N - (N-m)\beta + 1](\tau + \alpha)}{\mu - \tau - (m+1)\alpha + (\mu-\tau)\beta m};
\end{cases}$$

$$z_E = \begin{cases}
\frac{\tau + \alpha}{\theta}, \text{ if } \theta > \frac{[N - (N-m)\beta + 1](\tau + \alpha)}{\mu - \tau - (m+1)\alpha + (\mu-\tau)\beta m},\\
\frac{\mu[\beta m + \theta + 1]}{N - (N-m)(\beta - \theta + \beta\theta) + 1 + \theta}, \text{ if } \theta \leq \frac{[N - (N-m)\beta + 1](\tau + \alpha)}{\mu - \tau - (m+1)\alpha + (\mu-\tau)\beta m}.
\end{cases}$$

The condition

$$\theta > \max \left\{ \frac{[N - (N-m)\beta + 1]\tau}{\mu - \tau + (N-m)\alpha - (\mu-\tau)(N-m)\beta}, \frac{[N - (N-m)\beta + 1](\tau + \alpha)}{\mu - \tau - (m+1)\alpha + (\mu-\tau)\beta m} \right\}, \tag{26}$$

ensures interior solutions.

Proof of Corollary 2

From Eq. (26), we derive the sufficient condition such that quantities, investments and emissions are positive for any $m \in \{0, 1, \dots, N\}$. First, note that

$$\frac{[N - (N-m)\beta + 1]\tau}{\mu - \tau + (N-m)\alpha - (\mu-\tau)(N-m)\beta} > 0, \tag{27}$$

for

$$\beta < \frac{\mu - \tau + (N-m)\alpha}{(\mu - \tau)(N-m)}. \tag{28}$$

Therefore, the condition

$$\beta < \overline{\beta} \equiv \min \left\{ \frac{\mu - \tau + \alpha}{(\mu - \tau)N}, 1 \right\}, \tag{29}$$

is sufficient for any industry configuration.

Analogously,

$$\frac{[N - (N-m)\beta + 1](\tau + \alpha)}{\mu - \tau - (m+1)\alpha + (\mu-\tau)\beta m} > 0, \tag{30}$$

for

$$\beta > \frac{(m+1)\alpha - (\mu - \tau)}{(\mu - \tau)m}. \tag{31}$$

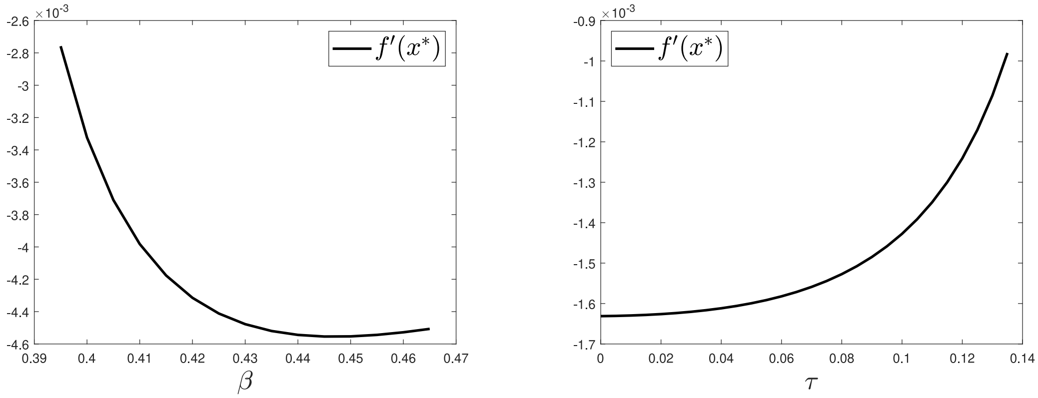
Therefore, the condition

$$\beta > \underline{\beta} \equiv \max \left\{ 0, \frac{(N+1)\alpha - (\mu - \tau)}{(\mu - \tau)N} \right\}, \tag{32}$$

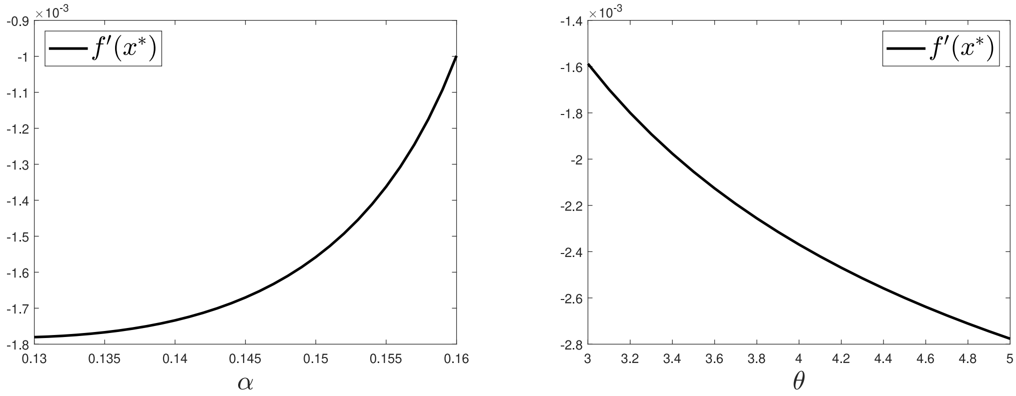
is sufficient for any industry configuration. Moreover, note that

$$\frac{(N+1)\alpha - (\mu - \tau)}{(\mu - \tau)N} < 1, \tag{33}$$

if $\alpha < \mu - \tau$, which we assume. □



(a) $\alpha = 0.15$, $\tau = 0.1$, $\theta = 4$. **(b)** $\alpha = 0.15$, $\beta = 0.43$, $\theta = 4$.



(c) $\beta = 0.43$, $\tau = 0.1$, $\theta = 4$. **(d)** $\beta = 0.43$, $\tau = 0.1$, $\alpha = 0.15$.

Fig. 7. Market configuration stability, $N = 4$, $\mu = 0.7$.

Industry configuration in a duopoly

The following proposition summarises the possible industry configurations in a duopoly setting.

Proposition 3. *The possible industry configurations are*

1. *"All ECSR" ($x^* = 0$) for $\theta \in (\underline{\theta}, \widehat{\theta})$;*
2. *"All PS" ($x^* = 1$) for $\theta \in (\widetilde{\theta}, +\infty)$;*
3. *"Mixed" ($x^* \in (0,1)$) for $\theta \in (\widehat{\theta}, \widetilde{\theta})$.*

Proof. Equation $\pi^*_{PE} - \pi^*_{EE} = 0$ can be written as

$$2\{(2\beta-3)^2[\alpha-(\beta-1)(\mu-\tau)]^2+ (2\beta-1)(\beta-3)^2(\alpha-\mu+\tau)^2\}\theta- (\alpha+2\tau)(\beta-3)^2(2\beta-3)^2\alpha = 0. \tag{34}$$

Eq. (34) can be rewritten with respect to θ as a level curve in the plane (β, α), that is

$$\widehat{\theta}(\beta,\alpha) = \frac{(\alpha+2\tau)(\beta-3)^2(2\beta-3)^2\alpha}{2\{(2\beta-3)^2[\alpha-(\beta-1)(\mu-\tau)]^2+(2\beta-1)(\beta-3)^2(\alpha-\mu+\tau)^2\}}. \tag{35}$$

Similarly, equation $\pi^*_{PE} - \pi^*_{EE} = 0$ can be written as

$$2\{(\beta-3)^2(\mu-\tau)^2- 9[2\alpha-(\beta+1)(\mu-\tau)][(\beta-1)(\mu-\tau)-(\beta-2)\alpha]\}\theta- 9(\alpha+2\tau)(\beta-3)^2 = 0. \tag{36}$$

Solving (36) with respect to θ, we can rewrite it as a level curve in the plane (β, α):

$$\widetilde{\theta}(\beta,\alpha) = \frac{9(\alpha+2\tau)(\beta-3)^2}{2\{(\beta-3)^2(\mu-\tau)^2-9[2\alpha-(\beta+1)(\mu-\tau)][(\beta-1)(\mu-\tau)-(\beta-2)\alpha]\}}. \tag{37}$$

Denoting x^* as a stable steady state, we have that:

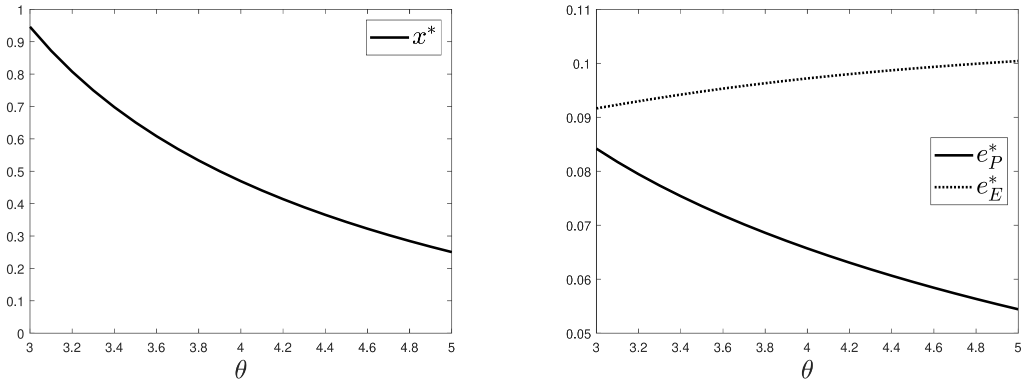
- for $\theta \in (\widetilde{\theta}, +\infty)$, $\pi^*_{PE} - \pi^*_{EE} > 0$ and $\pi^*_{PP} - \pi^*_{EP} > 0$, namely $\mathbb{E}(\pi^*_P) - \mathbb{E}(\pi^*_E) > 0 \; \forall x$ and $x^* = 1$;
- for $\theta \in (\underline{\theta}, \widehat{\theta})$, $\pi^*_{PE} - \pi^*_{EE} < 0$ and $\pi^*_{PP} - \pi^*_{EP} < 0$, namely $\mathbb{E}(\pi^*_P) - \mathbb{E}(\pi^*_E) < 0 \; \forall x$ and $x^* = 0$;
- for $\theta \in (\widehat{\theta}, \widetilde{\theta})$, $\pi^*_{PE} - \pi^*_{EE} > 0$ and $\pi^*_{PP} - \pi^*_{EP} < 0$, namely $\exists x \in (0,1) : \mathbb{E}(\pi^*_P) - \mathbb{E}(\pi^*_E) = 0$ and $x^* \in (0,1)$;
- for $\theta \in (\widetilde{\theta}, \widehat{\theta})$, $\pi^*_{PE} - \pi^*_{EE} < 0$ and $\pi^*_{PP} - \pi^*_{EP} > 0$, namely $\exists x \in (0,1) : \mathbb{E}(\pi^*_P) - \mathbb{E}(\pi^*_E) = 0$ and $x^* \in \{0,1\}$.

Eq. (10) also admits an unstable mixed equilibrium, which occurs whenever $\pi^*_{PE} - \pi^*_{EE} < 0$ and $\pi^*_{PP} - \pi^*_{EP} > 0$, implying $\widehat{\theta} > \tilde{\theta}$. An internal unstable steady state means that only one type of firms will remain on the market depending on the initial condition of the share x. ☐

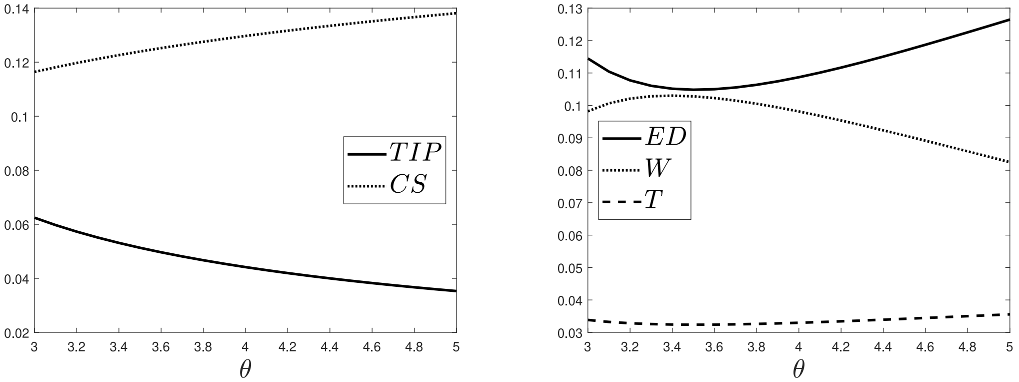
Fig. 1 illustrates the regions of the stable equilibria by Proposition 3 in the plane (β, α) based on the level curves $\widehat{\theta}(\beta, \alpha)$, $\tilde{\theta}(\beta, \alpha)$, while $\underline{\theta}(\beta, \alpha)$ circumscribes the admissible area by Corollary 2 when $\mu = 0.7, \theta = 4$ and $\tau = 0.1$.

Stability of the oligopoly equilibrium

In this Appendix, we check for the stability properties of the oligopoly configuration. In the present dynamical system, the stability properties of its stationary states are simple: in one-dimensional autonomous system, an equilibrium is stable if the derivative of the differential equation, evaluated at the equilibrium point, with respect

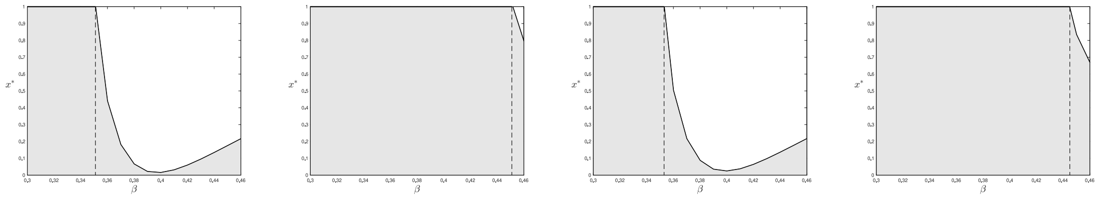


(a) Long-run share of profit-seeking firms. **(b)** Emissions of profit-seeking and CSR firms.

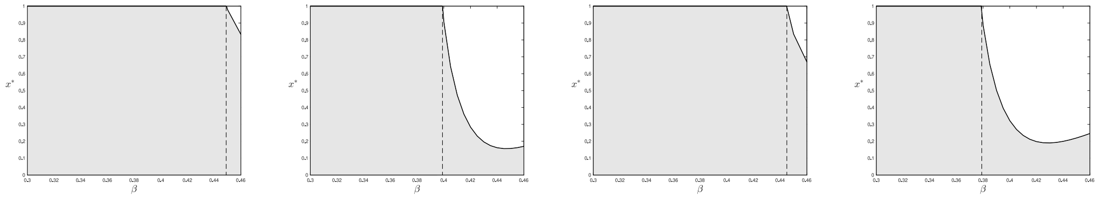


(c) Total Industry Profits and Consumer Surplus. **(d)** Environmental Damage and Welfare.

Fig. 8. The cost of innovation, $N = 4$, $\mu = 0.7$, $\alpha = 0.15$, $\beta = 0.43$, $\tau = 0.1$.



(a) $\alpha = 0.13$. **(b)** $\alpha = 0.16$. **(c)** $\tau = 0.01$. **(d)** $\tau = 0.13$.



(e) $\theta = 3$. **(f)** $\theta = 5$. **(g)** $\mu = 0.67$. **(h)** $\mu = 0.75$.

Fig. 9. $N = 3$.

to the variable itself is negative. Denoting $\dot{x} = f(x)$, in our case the equilibrium $x^* \in (0, 1)$ is stable if

$$f'(x^*) < 0. \tag{38}$$

If condition Eq. (38) is satisfied, then the equilibrium point $x^* \in (0, 1)$ is globally attractive. This means that, whatever the initial conditions, all the trajectories converge to x^*.

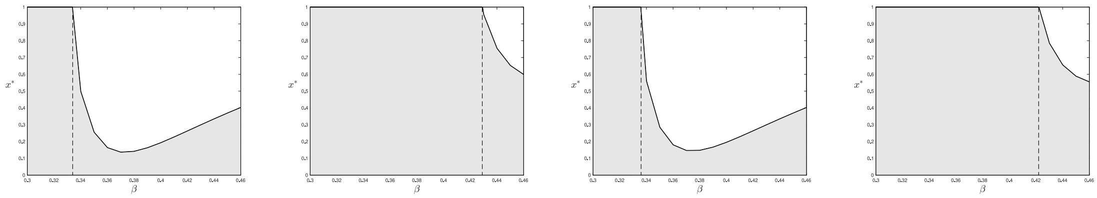
In Fig. 7, we check the negativity of condition (38) with respect to variations to different parameters in an oligopoly with $N = 4$ firms. The results are robust to all the parameter values considered.

Cost of innovation

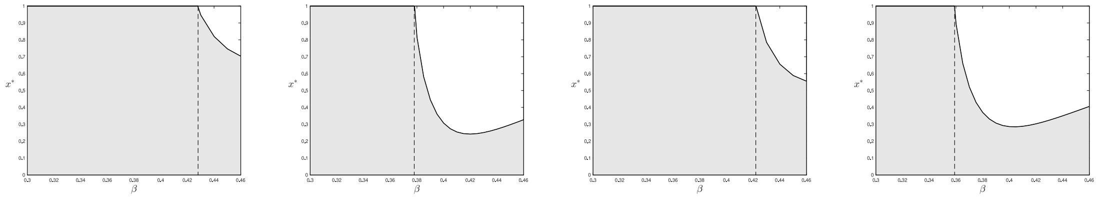
In this appendix, we show the changes in equilibrium following a variation in the cost of innovation. See Fig. 8.

Robustness checks

Figs. 9–11 illustrate the different industry configurations for various levels of β for $N = 3$, $N = 4$ and $N = 5$ by changing the basic parameter values ($\alpha = 0.15$, $\tau = 0.1$, $\theta = 4$, $\mu = 0.7$). The results are consistent with the baseline results.

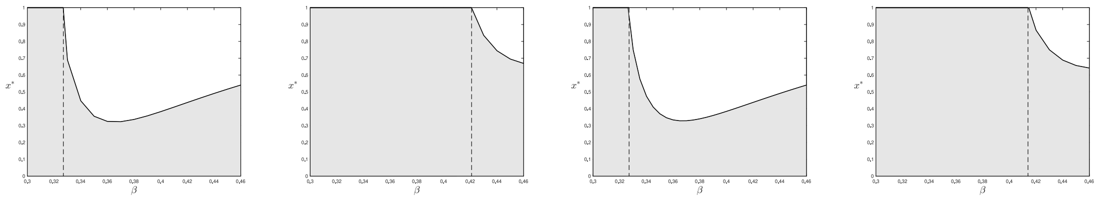


(a) $\alpha = 0.13$. **(b)** $\alpha = 0.16$. **(c)** $\tau = 0.01$. **(d)** $\tau = 0.13$.

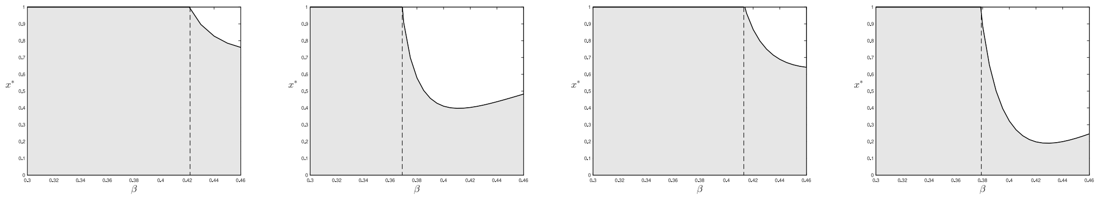


(e) $\theta = 3$. **(f)** $\theta = 5$. **(g)** $\mu = 0.67$. **(h)** $\mu = 0.75$.

Fig. 10. $N = 4$.



(a) $\alpha = 0.13$. **(b)** $\alpha = 0.16$. **(c)** $\tau = 0.01$. **(d)** $\tau = 0.13$.



(e) $\theta = 3$. **(f)** $\theta = 5$. **(g)** $\mu = 0.67$. **(h)** $\mu = 0.75$.

Fig. 11. $N = 5$.

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