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# Payment for Environmental Services and environmental tax under imperfect competition*

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**Abstract**

This paper designs the second-best Payment for Environmental Services (PES) when it interacts with a Pigouvian tax under imperfect competition. We consider farmers who face a choice between producing a conventional or an organic agriculture good. The regulator sets a Pigouvian tax on conventional agriculture as it generates environmental damages, as well as a PES on uncultivated land as buffer strips favor biodiversity. The conventional agriculture sector is perfectly competitive, unlike the organic agriculture sector, which is organized under an oligopoly. We show that the second-best level of the Pigouvian tax is higher than the marginal damage whereas the PES is lower than the marginal benefit. We then introduce the social marginal cost of public funds (MCF) and show that the Pigouvian tax increases with the MCF while the PES decreases with the MCF provided that demand for the conventional agriculture good is inelastic. We thus highlight a contributory component of the environmental incentive tax. This paper also identifies specific cases where the PES is ineffective in promoting biodiversity.

**Keywords**: Biodiversity Conservation; Payement for Environmental Services; Pigouvian Tax; the Social Marginal Social Cost of Public Funds; Market Power

**JEL Codes**: Q57, Q58

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# 1 Introduction

The collapse of biodiversity is a well-documented phenomenon, which is likely to worsen with climate change (Dasgupta, 2021; Díaz et al., 2019; Ruckelshaus et al., 2020). A leading cause of the decline in biodiversity is the loss of various habitats due to land use change (Lewis et al., 2011; Bamière et al., 2013). According to Dasgupta (2021), an estimated 20% of species could become extinct in the next several decades, perhaps twice as many by the end of the century. A way to take into account the many and varied benefits that humans derive from the natural environment and healthy ecosystems is to mobilize the concept of ecosystem services (Reid et al., 2005). According to Reid et al. (2005), they are categorized into the following four types: provisioning services such as food, water, timber, and fiber; regulating services that affect climate, floods, disease, wastes, and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as soil formation, photosynthesis, and nutrient cycling.

The economic literature distinguishes between ecosystem services and environmental services. While ecosystem services refer to the functioning of ecosystems, environmental services (ES) refer to the notion of externalities induced by human activities. In this case, mechanisms for internalizing externalities must be implemented, to encourage their optimal provision. Payments for environmental services (PES) are becoming a familiar tool for conserving and restoring ecosystems and the services they provide. They aim to finance the conservation and restoration of nature (Dasgupta, 2021).

One of the most widely cited definitions of PES comes from Wunder (2005). He defines PES as a voluntary transaction where a well-defined ES or a land-use that is likely to produce that service is bought by a (minimum one) ES buyer from a (minimum one) ES provider if and only if the ES provider secures ES provision. Other definitions as given by Muradian et al. (2010) include the possibility of in-kind payment. Wunder's definition is broad enough to include in particular a Coasean negotiation or a public buyer. For instance, if the PES involves private agents, this type of PES can be related to Coasean negotiations[1]. Others PES include certain types of government intervention that reflect a Pigouvian subsidy (Sattler & Matzdorf, 2013; Pigou, 1920). This type of PES is common in practice and is the focus of this article.

Some examples of PES funded by public authorities can be mentioned. Following France's National Biodiversity Plan of 2018 (MTES, 2021), French water agencies are experimenting with their own PES schemes. They have been allocated 150 million euros of the French national budget, with the objective to maintain or create good ecological practices, such as lowering pesticide use or planting cover crops (MTES, 2019). While both maintaining and creating good practices will be remunerated, creating good practices will receive much higher compensation (up to 676 euros/ha/year compared to up to 66 euros/ha/year for maintenance). A new program in Paris involves setting up a PES between the water agency Eau de Paris and farmers located in the water catchment area (CPES, 2020). Farmers will benefit from the PES if they commit to limiting the use of fertilizers and pesticides, or if they establish grasslands, which are considered a better filter for water than wheat or maize fields. A wheat farmer who converts to organic farming will be able to get €450 per year per hectare for the first five years and €220 for the next two years. Farmers will only receive the full payment if a target level for nitrate concentration in groundwater is reached. This PES was

[1] One example of a Coasean PES is the Vittel PES in north-eastern France, where Nestle reached an agreement with local farmers to prevent nitrate contamination in aquifers (Sattler & Matzdorf, 2013).

created thanks to the validation of a state aid scheme (n°SA.54810) by the European Commission. This type of PES is therefore considered as a public subsidy. Regarding the Pigouvian subsidy promoting positive externalities, it should correspond to the marginal environmental benefit.

The European agri-environmental programs are financed through public funds under the Common Agricultural Policy (CAP). They are one of the major advances in the PAC in recent years and are considered as PES programs. These agri-environmental measures consist of offering financial compensation to farmers for voluntary commitment on their part, over several years, to implement practices or production. Common management practices adopted under agri-environmental measures include reducing fertilizer and/or pesticide use, planting buffer crops near rivers, and adaptations to crop rotations. Indeed, long crop rotations improve ecosystem services such as support services through improved soil quality. The diversity of productive activities on a farm promotes beneficial interactions between crops and livestock and the management of landscape features such as grass strips, embankments, hedges or watercourses contribute to the ecological functioning of agroecosystems (Beesley & Ramsey, 2009; Wätzold et al., 2016; Princé & Jiguet, 2013).

While changing certain agricultural practices can help protect biodiversity, agricultural practices can also cause pollution. We can cite the use of chemical fertilizers and pesticides that pollute watersheds (Shortle & Abler, 2001). In order to internalize negative externalities, the regulator can set a Pigouvian tax (Pigou, 1920), equal to the marginal damage in a perfectly competitive market setting. However, this result is obtained by considering only the negative externality. In order to take into account the specificities of the agricultural domain, it would be necessary to consider a model that takes into account both positive and negative externalities.

Some work has looked at the interaction of different public policies (Howlett & Rayner, 2013). According to Bryan & Crossman (2013), interaction effects of multiple financial incentives may reduce policy efficiency wherever multiple incentives encourage the supply of services from agro-ecosystems. Agri-environmental measures must, however, take into account that policies are typically bundles of different policy tools arranged in policy mixes and that financial incentives for different ecosystem services interact (Huber et al., 2017). Lankoski & Ollikainen (2003) provide a framework for a theoretical analysis of several environmental policies in the agricultural sector. Assuming parcels of varying land quality, the authors study the optimal land allocation between two crops that are more or less intensive in fertilizer use and fallow buffer strips when facing negative externalities from nutrient runoff, and positive externalities from biodiversity and landscape diversity. They defined first-best environmental policies, involving a differentiated tax on fertilizer and a differentiated buffer strip subsidy. The crucial assumptions supporting these results are notably the absence of a distortion resulting from the contributory taxes and the absence of any market power in the agricultural sector.

The PES is based on the beneficiary pays principle. Its implementation requires raising public funds, which can cause economic distortions (Mirrlees, 1971). Increasing contributory taxes can change the allocation of resources in an economy through impacts on consumption, labor, and investment decisions (Dahlby, 2008). A simple way to take into account these distortions is to consider the marginal social cost of public funds (MCF). It is a measure of the welfare loss to society as a result of raising additional revenues to finance government spending (Browning, 1976; Dahlby, 2008). For example, Browning (1976) estimates the MCF of labor income taxes in the United States, finding a MCF of $1.09-$1.16 per dollar tax revenue raised. According to Beaud (2008), this cost is equal to 1.2 for France. So, when the regulator raises one euro in taxes, it costs the society 1.2 euros. This aspect should therefore not be neglected in the decision to set up a PES.

The relevance of competitive organic farming market can be questioned. According to Nguyen-Van et al. (2021), the development of organic agriculture can be very heterogeneous over a territory. For instance, out of 34259 municipalities in metropolitan France (excluding overseas territories) with at least one farmer, only 418 (1.2%) are 100% organic, and 52.4% of municipalities do not have an organic farmer.[2] The non-uniform distribution of organic farming across the country and transport constraints for organic products can limit competition in organic product market, resulting in local markets for organic farming where some producers have market power.

The economic literature has analyzed the effectiveness of agri-environmental programs in protecting biodiversity (Pe'er et al., 2014; Kleijn & Sutherland, 2003; Batáry et al., 2015) but neglected the possible interactions between the different environmental policies. On the one hand, if public PES are similar to Pigouvian subsidies, their analysis does not have to mirror Pigouvian taxes because they imply a necessary financing constraint. On the other hand, the economic literature is not well-developed concerning the design of a PES under imperfect competition, contrary to the Pigouvian tax. Indeed, a tax based only on marginal external damages ignores the social cost of further output contraction by a producer whose output already is below an optimal level. Under market power, the optimal second-best tax should actually be less than the marginal damage (Barnett, 1980; Ebert, 1991). Since then, the literature on environmental taxation has widely developed for numerous scenarios of imperfect competition.

The focus of our theoretical paper is to analyze the second-best PES design combined with environmental taxes under imperfect competition and taking into account distortions from contributory taxation. To do this, we assume a farmer chooses to produce a conventional or an organic good. Whereas the conventional agriculture good market is perfectly competitive, the organic good market is organized under an oligopoly. Farmers can produce conventional agriculture goods, which causes environmental damages, or an organic production which we are assuming will have a neutral impact on the environment. If the farmer leaves fallow buffer strips, this favors biodiversity. In order to simultaneously favor biodiversity and reduce environmental damages, the regulator sets a PES on fallow land and a Pigouvian tax on conventional agriculture production.

In our framework, the Pigouvian tax decreases the conventional good production level. The PES on the fallow land area reduces organic and conventional production levels. Under market power, we show that the second-best level of the Pigouvian tax is higher than the marginal damage - contrary to Barnett (1980) - and the PES is lower than the marginal benefit. The organic good production level is too low because of the market power and the PES further reduces this production level. In order to mitigate the reduction due to market power, the regulator sets a PES lower than the marginal benefit. The conventional good level is reduced with both the PES and the Pigouvian tax. As the PES is not high enough, the regulator sets a Pigouvian tax above the marginal damage in order to reach the correct level

[2] Spatial factors explain the gaps in organic development between territories, such as the quality of the soil (Wollni & Andersson, 2014; Lampach et al., 2020) as well as the geographical organisation of the activity and populations (Ben Arfa et al., 2009) and the presence of many other organic farmers in a geographical unit (Schmidtner et al., 2012; Bjørkhaug & Blekesaune, 2013).

of conventional agriculture. The environmental policies are used in a complementary way to take into account the distortion induced by the market power. We also analyze the particular case where farmers never choose buffer strips, which occurs when productions are profitable enough. In this case the PES is useless and the regulator can only regulate environmental damages. This time, market power in organic agriculture favors conventional agriculture production. So a way to reduce environmental damages is to set the Pigouvian tax above the marginal damage.

We then consider distortionary taxation in our economy. To do that, we introduce a marginal social cost of public funds (MCF). We show that the environmental tax increases with the MCF, whereas the PES decrease with the MCF under two assumptions: the demand for the conventional agriculture good is inelastic and environmental tools have to provide buffer strips efficiently. We thus highlight a *contributory component* of the environmental incentive tax under distortionary taxation. Indeed, the primary objective of a Pigouvian tax is to give the appropriate incentives to agents and not to raise a revenue for the regulator.

The assumption of a neutral impact of organic agriculture can be controversial. On the one hand, several empirical studies found a positive relationship between organic farming and biodiversity (Batáry et al., 2015; Freemark & Kirk, 2001; Marja et al., 2014; Hole et al., 2005). On the other hand, other studies found no or minor difference between conventional and organic farming (Hiron et al., 2013; Piha et al., 2007; Purtauf et al., 2005; Gerling et al., 2019) and in some cases conventional farming even supported a greater biodiversity than organic farming (Weibull et al., 2003; Rahmann, 2011). The reasons for these contradicting results are diverse. Fuller et al. (2005) found that some species benefit from organic farming, while others benefit from conventional farming. Tscharntke et al. (2021) highlight that what characterizes organic agriculture is the prohibition of synthetic agrochemicals, which results in limited benefits for biodiversity. Seriously estimating the impact of organic farming on biodiversity requires a well-defined benchmark. For example, according to Dasgupta (2021), one of the causes of biodiversity loss is the change in land use, especially conversion to agricultural use. In this case, organic agriculture would be considered always detrimental to biodiversity. If it had been assumed in this paper that organic farming also produces biodiversity, the effects of the single PES on grass strips and on organic farming would have been cancelled out making the PES still useless.

This paper is organized as follows. Section 2 presents our model. Section 3 examines second-best environmental policies and Section 4 introduces the MCF. Finally, Section 5 concludes.

# 2 The model

In this section, we present the assumptions used in our model, the farmers' production decision absent any policy and the first-best allocation.

## 2.1 Assumptions

We consider $n \geq 2$ identical farmers who each have three choices for how to manage his land: conventional agriculture ($x_{1i}$), organic agriculture ($x_{2i}$), and/or leaving the land uncultivated to act as a reserve for biodiversity ($y_i$). Each farmer $i$ produces $x_{1i}$, $x_{2i}$ and $y_i$, with total output for each good equal to $X_1 = \sum_{i=1}^{n} x_{1i}$, $X_2 = \sum_{i=1}^{n} x_{2i}$, and $Y = \sum_{i=1}^{n} y_i$, respectively. Each farmer decides how much of his land to allocate to each management option such that

$x_{1i} + x_{2i} + y_i = T_i$ where $T_i$ is his total area of land (with $T = \sum_{i=1}^{n} T_i$). We assume that producing $x_{1i}$ ($x_{2i}$) units requires $x_{1i}$ ($x_{2i}$) units of land $\forall i = 1, ..., n$ .

The cost of implementing organic agriculture is higher than that of conventional agriculture, $c_1(x_{1i}) < c_2(x_{2i})$. Both $c_1(x_{1i})$ and $c_2(x_{2i})$ are increasing and convex[3], $\forall i = 1, ..., n$. The quantity of land left uncultivated only incurs an opportunity cost of not producing. For simplicity, we set the cost of entry into the organic market at zero, which corresponds to an absence of barriers to entry[4]. We assume a linear demand for both agricultural goods. The inverse demand function for each agricultural product is given by $p_1(X_1)$ and $p_2(X_2)$ for conventional and organic agriculture, respectively.

The organic agricultural good can be considered as a good with few substitutes, contrary to the conventional agriculture good. For example, transport constraints for organic products can limit competition in the organic product market. So, we assume perfect competition on the conventional agriculture good market and imperfect competition on the organic agriculture good market, which is organized in the form of oligopoly.

Each of the land management choices has a different impact on the environment. Conventional agriculture causes pollution, represented by the damage function $D(X_1)$ which is increasing and convex, $D'(X_1) > 0, D''(X_1) > 0$. We assume that organic agriculture has a neutral impact on the environment. Finally, the uncultivated land leads to biodiversity benefits, and has a positive impact on the environment, represented by the increasing and concave benefit function, given by $B(Y)$.

## 2.2 The benchmark

In this subsection we look at the farmer's decision in the absence of any policy. He behaves as a price taker on the conventional product market and as a Cournot competitor on the organic product market. Farmer $i$ maximizes his profit by choosing $x_{1i}$ and $x_{2i}$ and by considering the physical constraint of his available land: $T_i$ has to be greater than or equal to $x_{1i} + x_{2i}$. Associating $\lambda$ to this constraint, the profit for farmer $i$ $\forall i = 1, 2, ..., n$ with $i \neq j$ is:

$$\pi_i(x_{1i}, x_{2i}) = p_1 x_{1i} + p_2\big(X_2\big)x_{2i} - c_1(x_{1i}) - c_2(x_{2i}) + \lambda(T_i - x_{1i} - x_{2i})$$

Maximizing profit yields the following conditions:

$$p_1 - c_1'(x_{1i}) - \lambda = 0 \tag{1}$$

$$p_2'\big(X_2\big)x_{2i} + p_2\big(X_2\big) - c_2'(x_{2i}) - \lambda = 0 \tag{2}$$

$$\lambda(T_i - x_{1i} - x_{2i}) = 0 \tag{3}$$

Whereas a farmer equalizes the marginal cost to the price when making his conventional agriculture production decision, he considers the marginal revenue when making his organic agriculture production decision. The production decision depends on whether the land constrains the farmer's decision, that is $\lambda > 0$, or whether the farmer will have some uncultivated land, that is $\lambda = 0$.

[3] Additionally, we assume that $c_1'''(x_{1i}) = 0$ and $c_2'''(x_{2i}) = 0, \forall i = 1, ..., n$.

[4] In reality, there are requirements for farmers producing conventional agriculture to make a transition to organic agriculture. For simplicity, we assume the corresponding costs equal zero

Farmer $i$ considers all other farmers' decisions in the organic product market in order to maximize his profit. To see how the production level of farmer $i$ responds to the production level of farmer $j$, we use Equation (2) and apply the implicit function theorem. When the farmer leaves uncultivated land ($\lambda = 0$), we find:

$$\frac{\partial x_{2i}}{\partial x_{2j}} = -\frac{\frac{\partial F}{\partial x_{2j}}}{\frac{\partial F}{\partial x_{2i}}} = -\frac{p_2''(X_2)x_{2i} + p_2'(X_2)}{p_2''(X_2)x_{2i} + 2p_2'(X_2) - c_2''(x_{2i})} < 0$$

An increase in farmer $j$'s production of the organic agriculture good will make farmer $i$ reduce his production of the organic agriculture good. Thus, goods produced from organic agriculture are strategic substitutes.

For the case where there is no uncultivated land ($\lambda > 0$), using equations (1), (2) and (3), we set $G(x_{2i}, x_{2j}) = p_1 - c_1'(T_i - x_{2i}) - p_2'(X_2)x_{2i} - p_2(X_2) + c_2'(x_{2i})$.

Applying the implicit function theorem we find:

$$\frac{\partial x_{2i}}{\partial x_{2j}} = -\frac{\frac{\partial G}{\partial x_{2j}}}{\frac{\partial G}{\partial x_{2i}}} = -\frac{-p_2''(X_2)x_{2i} - p_2'(X_2)}{c_1''(T_i - x_{2i}) - p_2''(X_2)x_{2i} - 2p_2'(X_2) + c_2''(x_{2i})} < 0$$

This shows that an increase in farmer $j$'s production of the organic agricultural good will lead to a decrease in farmer $i$'s production of the organic agricultural good. Organic agricultural goods are once again in this case, strategic substitutes.

Farmers make their decisions without taking into account environmental aspects – such as environmental damage and benefits – and in a world of imperfect competition. As a result, these production levels are not optimal. There is room for public intervention.

### 2.3 The first-best

In this subsection, we investigate the first-best outcome. The government regulator seeks to maximize welfare, which is composed of the consumer surplus, the farmer's profit, the environmental damage and benefit while taking into account the constraint on available land:

$$\begin{aligned}\underset{X_1,X_2,\lambda}{W} = &\int_0^{X_1} p_1(u)du + \int_0^{X_2} p_2(v)dv - nc_1\left(\frac{X_1}{n}\right) - nc_2\left(\frac{X_2}{n}\right) + B(T - X_1 - X_2) \\ &- D(X_1) + \lambda(T - X_1 - X_2)\end{aligned}$$

Maximizing welfare gives the conditions for the first best optimal solutions, $x_1^*$ and $x_2^*$:

$$p_1(X_1^*) - c_1'(\frac{X_1^*}{n}) - B_y - D'(\frac{X_1^*}{n}) - \lambda = 0 \tag{4}$$

$$p_2(\frac{X_2^*}{n}) - c_2'(\frac{X_2^*}{n}) - B_y - \lambda = 0 \tag{5}$$

$$\lambda(T - X_1^* - X_2^*) = 0 \tag{6}$$

There are two possible cases for $\lambda$. If $\lambda = 0$, then $y = T - X_1^* - X_2^*$ will either be zero or positive. If $\lambda > 0$, then $y = T - X_1^* - X_2^*$ will be zero, and no land will be left uncultivated. Taking into account the Kuhn-Tucker multiplier, the conventional and organic production levels are based on social marginal costs, i.e. marginal cost of production of each agriculture type, as well as biodiversity benefits from fallow land and the pollution damages from conventional agriculture.

Consider a first-best policy. In this case, the pigouvian tax must be equal to the marginal damage i.e. $t^* = D'(\frac{X_1^*}{n})$ and the PES must be set at the marginal environmental benefit level i.e. $s^* = B_y$ if $\lambda > 0$ and must be nonexistent if $\lambda = 0$. However, it is easy to see that these levels of environmental policy would not lead to the first-best (equations 1, 2, 3). Environmental policies would correct environmental externalities, but another distortion would remain: market power. The regulator must therefore designate second-best policies.

# 3 Second-best environmental policies

Although we cannot directly correct for market power, we can examine a second-best environmental policy to internalize the negative and positive externalities of pollution and biodiversity, respectively, and improve welfare. Here, we examine an environmental tax, $t$, on pollution related to the conventional agriculture good and a PES for biodiversity, $s$, which subsidizes uncultivated land in order to favor biodiversity. We first look at the farmer's behavior facing environmental policies and we then define the second best level of environmental tax and PES.

## 3.1 The farmer's behavior

We now introduce into the farmer's profit the environmental tax and the PES. The profit for farmer $i$, $\forall i$ and $i \neq j$, taking into account the constraint on his land is now:

$$\pi_i = p_1 x_{1i} + p_2\big(X_2\big)x_{2i} - c_1(x_{1i}) - c_2(x_{2i}) - t x_{1i} + s(T_i - x_{1i} - x_{2i}) + \lambda(T_i - x_{1i} - x_{2i})$$

Maximizing profit yields the following conditions:

$$p_1 - c_1'(x_{1i}) - t - s - \lambda = 0 \tag{7}$$

$$p_2'\big(X_2\big)x_{2i} + p_2\big(X_2\big) - c_2'(x_{2i}) - s - \lambda = 0 \tag{8}$$

$$\lambda(T_i - x_{1i} - x_{2i}) = 0 \tag{9}$$

We can see how production levels change with environmental policies. When the farmer leaves uncultivated land ($\lambda = 0$), we use Equations (7) and (8), and apply the implicit function theorem. We find:

$$\frac{\partial x_{1i}}{\partial s} = \frac{1}{-c_1''(x_{1i})} < 0$$

$$\frac{\partial x_{1i}}{\partial t} = \frac{1}{-c_1''(x_{1i})} < 0$$

$$\frac{dx_{2i}}{ds} = \frac{1}{2p_2'(X_2) + p_2''(X_2)x_{2i} - c_2''(x_{2i})} < 0$$

The PES decreases production levels of both agriculture goods while the environmental tax only decreases the production level of the conventional agriculture good. Thus, the PES and the environmental tax lead to an increase in uncultivated land and consequently favor biodiversity benefits.

If the farmer leaves no uncultivated land ($\lambda > 0$), we obtain, after using Equations (7), (8) and (9) and applying the implicit function theorem:

$$\frac{\partial x_{1i}}{\partial t} = \frac{1}{c_1''(x_{1i}) + c_2''(T_i - x_{1i}) - 2p_2'(T - X_1) - p_2''(T - X_1)(T_i - x_{1i}) - p_1'} < 0$$

Since $x_{2i} = T_i - x_{1i}(t)$, it is obvious that:

$$\frac{dx_{2i}}{dt} = -\frac{\partial x_{1i}}{\partial t} > 0$$

This implies that an increase in the environmental tax will lead to an increase in the production level of the organic agriculture good and a decrease in the production level of the conventional agriculture good, and in the same proportion. It is a zero-sum game. Here, the PES does not impact the farmer's production choices because the cost structure and market is such that it is not profitable to leave any land uncultivated. Hence, a PES is useless.

### 3.2 Second-best level of environmental tax and PES

We maximize the social welfare function to find the second-best levels of the environmental tax and of the PES. We first investigate the case where it is optimal to leave uncultivated land, and then when it is optimal to cultivate all the land. Starting with the first scenario ($\lambda = 0$), the social welfare function is:

$$\begin{aligned} \underset{s,t}{W(X_1(s,t), X_2(s))} = & \int_0^{X_1(s,t)} p_1(u)du + \int_0^{X_2(s)} p_2(v)dv - nc_1\left(\frac{X_1(s,t)}{n}\right) \\ & - nc_2\left(\frac{X_2(s)}{n}\right) + B(T - X_1(s,t) - X_2(s)) - D(X_1(s,t)) \end{aligned}$$

Maximizing this welfare function with respect to $s$ and $t$ leads to the following first order conditions:

$$\begin{aligned} & \frac{\partial X_1}{\partial s}[p_1(X_1(s)) - c_1'\left(\frac{X_1(s)}{n}\right) - B_y - D'(X_1(s))] \\ & + \frac{dX_2}{ds}[p_2(X_2(s)) - c_2'\left(\frac{X_2(s)}{n}\right) - B_y] = 0 \end{aligned} \tag{10}$$

$$\frac{\partial X_1}{\partial t}[p_1(X_1(t)) - c_1'\left(\frac{X_1(t)}{n}\right) - B_y - D'(X_1(t))] = 0 \tag{11}$$

with $\frac{\partial X_1}{\partial s} < 0$, $\frac{\partial X_1}{\partial t} < 0$, and $\frac{dX_2}{ds} < 0$ obtained in the previous section and $B_y = B'(y)$. Using equations (7) and (8), we rearrange the profit maximization conditions to obtain the following:

$$p_1 - c_1'\left(\frac{X_1}{n}\right) = t + s \tag{12}$$

$$p_2(X_2) - c_2'\left(\frac{X_2}{n}\right) = -p_2'(X_2)\frac{X_2}{n} + s \tag{13}$$

Next, we plug equations (12) and (13) into equations (10) and (11) to obtain the following equations:

$$\frac{\partial X_1}{\partial s}[t + s - B_y - D'(X_1(s))] + \frac{dX_2}{ds}[-p_2'(X_2(s))\frac{X_2}{n} + s - B_y] = 0 \tag{14}$$

$$\frac{\partial X_1}{\partial t}[t + s - B_y - D'(X_1(t))] = 0 \tag{15}$$

We can now solve (15) for $t$, and plug that into (14) to solve for $s$ and $t$. We find:

$$\begin{aligned} s &= B_y + p_2'(X_2)\frac{X_2}{n} \\ t &= D'(X_1) - p_2'(X_2)\frac{X_2}{n} \end{aligned} \tag{16}$$

It appears that the second-best PES is lower than the marginal benefit, whereas the second-best tax is higher than the marginal damage. This result differs from Barnett (1980) who shows that in the presence of market power, the Pigouvian tax must be lower than the marginal damage. In our study, production of the organic agriculture good is lower than its first best level because of market power. As the PES reduces the level of organic agriculture, a way to not further decrease this level is to set a lower PES. But this PES will not sufficiently reduce the production from conventional agriculture. Thus the environmental tax is higher than its first best level in order to get the right level of conventional agriculture. Replacing the value of environmental policy tools in (7) and (8), we find first-best quantities (given by (4) and (5)). Finally, we can see that if the number of firms increases and approaches infinity, both environmental policy tools reach their first best level: the marginal benefit for the PES and the marginal damage for the environmental tax.

We now investigate the second-best environmental policy tool level when it is profitable to leave no uncultivated land ($\lambda > 0$). So setting $X_1 = T - X_2$, the social welfare is now:

$$\begin{aligned} \underset{t}{W(X_1(t), X_2(t))} = &\int_0^{T-X_2(t)} p_1(u)du + \int_0^{X_2(t)} p_2(v)dv - nc_1\left(\frac{T - X_2(t)}{n}\right) \\ &- nc_2\left(\frac{X_2(t)}{n}\right) + B\Big(T - (T - X_2(t)) - X_2(t)\Big) \\ &- D(T - X_2(t)) \end{aligned}$$

Maximizing this welfare equation yields the following first order condition:

$$\frac{dX_2}{dt}[-p_1(T - X_2) + p_2(X_2) + c_1'\left(\frac{T - X_2}{n}\right) - c_2'\left(\frac{X_2}{n}\right) + D'(T - X_2)] = 0 \tag{17}$$

Using the profit first order conditions (7) and (8), we find that:

$$-p_1 + c_1'\left(\frac{T - X_2}{n}\right) + p_2(X_2) - c_2'\left(\frac{X_2}{n}\right) = -t - p_2'(X_2)\frac{X_2}{n} \tag{18}$$

Plugging (18) into (17) yields:

$$t = D'(T - X_2) - p_2'(X_2)\frac{X_2}{n} \tag{19}$$

In this case, the second-best environmental tax level is also higher than the marginal damage. As the PES cannot incentivize the uncultivated land, only the environmental tax will correct both the negative externality and market power in the organic market. Again, this second-best environmental tax can achieve the first-best levels of production. Our results are summed up in the following proposition:

**Proposition 1** *The second-best PES is lower than the marginal benefit, whereas the Pigouvian tax is higher than the marginal damage contrary to Barnett (1980). There are cases where PES are ineffective in protecting biodiversity.*

# 4 The social marginal cost of public funds

The public PES needs to be financed, which means taxing taxpayers in other ways. There are two ways to introduce the distortions induced by the tax system into our theoretical model. The first is to consider a general equilibrium model that explicitly introduces the tax system. The problem is the complexity of the model, making its results difficult to interpret. The second is to introduce into a partial equilibrium model the social marginal cost of public funds (MCF), which summarizes the fiscal distortions. In order to enrich our results, we choose this second path. We denote by $\epsilon$ the MCF. Each euro raised by the environmental tax will enable to reduce distortionary contributory taxes of $(1+\epsilon)$ euros. Conversely, implementing a PES means a requirement for additional government revenue through increased contributory taxes, which will come at a cost to society. So, each euro allocated to the PES costs $(1+\epsilon)$ euros to society.[5] We modify the welfare function given in Section 3 in order to take into account the taxation effects. In the case where the farmers leave uncultivated land, the welfare reads as:

$$\begin{aligned} \underset{s,t}{W(X_1(s,t), X_2(s))} = & \int_0^{X_1(s,t)} p_1(u)du + \int_0^{X_2(s)} p_2(v)dv - nc_1\left(\frac{X_1(s,t)}{n}\right) \\ & - nc_2\left(\frac{X_2(s)}{n}\right) + B(T - X_1(s,t) - X_2(s)) - D(X_1(s,t)) \\ & + \epsilon t X_1(s,t) - \epsilon s(T - X_1(s,t) - X_2(s)) \end{aligned}$$

Maximizing this welfare function with respect to $s$ and $t$ leads to the following first order conditions:

$$\begin{aligned} & \frac{\partial X_1}{\partial s}[p_1(X_1(s)) - c_1'\left(\frac{X_1(s)}{n}\right) - B_y - D'(X_1(s)) + \epsilon t + \epsilon s] \\ & + \frac{dX_2}{ds}[p_2(X_2(s)) - c_2'\left(\frac{X_2(s)}{n}\right) - B_y + \epsilon s] - \epsilon(T - X_1(s) - X_2(s)) = 0 \end{aligned} \tag{20}$$

$$\frac{\partial X_1(t,s)}{\partial t}[p_1(X_1(t,s)) - c_1'\left(\frac{X_1(t,s)}{n}\right) - B_y - D'(X_1(t,s)) + \epsilon t + \epsilon s] + \epsilon X_1(t,s) = 0 \tag{21}$$

[5]The model was extended by introducing a constraint to finance the PES by the environmental tax. However, the results were not tractable.

with $\frac{\partial X_1(t,s)}{\partial s} < 0$, $\frac{\partial X_1(t,s)}{\partial t} < 0$, and $\frac{dX_2(s)}{ds} < 0$. Using Equations (12) and (13), and solving for $s$ and $t$ we find:

$$\begin{aligned} s^{MCF} &= \frac{B_y + p_2'(X_2)\frac{X_2}{n}}{1+\epsilon} + \frac{\epsilon}{1+\epsilon}\left[\frac{T - X_1 - X_2}{\frac{dX_2}{ds}}\right] + \frac{\epsilon}{1+\epsilon} X_1 \left[\frac{\frac{\partial X_1}{\partial s}}{\frac{dX_2}{ds}\frac{\partial X_1}{\partial t}}\right] \\ t^{MCF} &= \frac{D'(X_1) - p_2'(X_2)\frac{X_2}{n}}{1+\epsilon} - \frac{\epsilon}{1+\epsilon}\left[\frac{\frac{\partial X_1}{\partial s}X_1}{\frac{dX_2}{ds}\frac{\partial X_1}{\partial t}} + \frac{T - X_1 - X_2}{\frac{dX_2}{ds}} + \frac{X_1}{\frac{\partial X_1}{\partial t}}\right] \end{aligned} \tag{22}$$

The second-best PES and environmental tax are now defined taking into account their costs as far as public finance is concerned. Environmental policy tool design combines the direct effect on the environment and market power and indirectly the induced changes in several land uses computed to the MCF. Comparing (16) and (22) shows that $PES^{MCF} < PES$ whereas the comparison is not simple for $t^{MCF}$ and $t$.

Contrary to the intuition, the effect of a change in $\epsilon$ in $t^{MCF}$ and $PES^{MCF}$ is not immediate (see Appendix C for full calculations). To investigate this point, we use (12) and (13) with $X_1(s(\epsilon), t(\epsilon))$ and $X_2(s(\epsilon))$. The variation of $t^{MCF}$ and $PES^{MCF}$ with respect to the MCF is mainly undetermined. Restricting conditions, we obtain:

$$\text{If } e_{X_1/t} > -1 : \frac{ds}{d\epsilon} < 0 \text{ and } \frac{dt}{d\epsilon} > 0 \text{ if } \frac{\partial X_1}{\partial t} / \frac{\partial X_2}{\partial s} > \varpi$$

If the elasticity of demand of the conventional agricultural good with respect to the environmental tax is low, the PES will always decrease and the environmental tax will increase with the MCF provided that both environmental prices favor uncultivated land in an efficient way. In the presence of distortionary taxation, the regulator exploits a contributory component of the environmental incentive tax .

Indeed if $e_{X_1/t} > -1$, the production level of conventional agriculture will not be significantly reduced after the implementation of the environmental tax. An increase in the marginal cost of public funds will increase the environmental tax, provided also that the impact of changes in production levels induced by the environmental tax and the PES are higher than a threshold given by $\varpi$. The environmental tax should reduce the level of conventional agricultural production more than the PES diminishes the level of organic production. In other words, the uncultivated land should be further to the detriment of conventional agriculture than to the detriment of organic agriculture. The introduction of the MCF leads the regulator to exploit a contributory component of the incentive tax while keeping in mind the objective of providing the right environmental incentives. Consequently, the environmental tax, which initially has an incentive objective, would also have a contributory outcome when the MCF is taken into account.

If the farmers cultivate the entire land ($\lambda > 0$), the introduction of the MCF modifies the welfare function as follows:

$$\begin{aligned} \underset{t}{W}(T - X_2(t), X_2(t)) = &\int_0^{T-X_2(t)} p_1(u)du + \int_0^{X_2(t)} p_2(v)dv - nc_1\left(\frac{T - X_2(t)}{n}\right) \\ &- nc_2\left(\frac{X_2(t)}{n}\right) + B\Big(T - (T - X_2(t)) - X_2(t)\Big) \\ &- D(T - X_2(t)) + \epsilon t X_1(t) - \epsilon s(T - (T - X_2(t)) - X_2(t)) \end{aligned}$$

Maximizing welfare yields this following first-order condition:

$$\frac{dX_2}{dt}[-p_1(T-X_2)+p_2(X_2)+c_1'(\frac{T-X_2}{n})-c_2'(\frac{X_2}{n})+D'(T-X_2)-\epsilon t]+\epsilon(T-X_2)=0 \quad (23)$$

Using equations (7) and (8) from the profit maximization gives:

$$-p_1+c_1'(X_1)+p_2(X_2)-c_2'(X_2)=-t-p_2'(X_2)\frac{X_2}{n} \quad (24)$$

We can then write equation (23) as:

$$\frac{dX_2}{dt}\left[-t-p_2'(X_2)\frac{X_2}{n}+D'(T-X_2)-\epsilon t\right]+\epsilon(T-X_2)=0 \quad (25)$$

Then, we solve equation (25) and we obtain the second-best environmental tax level:

$$t^{MCF}=\frac{D'(X_1)-p_2'(X_2)\frac{X_2}{n}}{1+\epsilon}+\frac{\epsilon}{1+\epsilon}\left(\frac{X_1}{\frac{dX_2}{dt}}\right) \quad (26)$$

We saw in Section 3 that the second-best environmental tax is the same, whether all the land is cultivated or not. This is not the case when including the MCF. Since there is no uncultivated land, the indirect effects are limited to organic and conventional agricultural production. This environmental tax is always lower than its design without the MCF. The regulator uses the contributory component of the incentive environmental tax in the presence of the MCF if the demand for the agricultural good is inelastic with respect to the environmental tax (see Appendix):

$$\text{If } e_{X_1/t}>-1,\ \frac{dt}{d\epsilon}>0$$

Proposition 2 summarizes our results:

**Proposition 2** *If the demand elasticity of the conventional agricultural food is inelastic with respect to the environmental tax, the MCF decreases the second-best PES but increases the environmental tax provided both environmental prices favor uncultivated land in an efficient way. The regulator exploits the contributory component of the environmental incentive tax.*

# 5 Conclusion

Pollution and biodiversity benefits are two externalities associated with agricultural land that lead to market failure. According to the Tinbergen rule, multiple market failures require multiple policies to address them. Here, we looked at the scenario where an environmental tax and a PES scheme are used to address pollution and biodiversity conservation, respectively. We added an additional market distortion in the form of an oligopoly in organic agriculture production. We found that the second-best tax on conventional agriculture production is higher than the marginal damage from pollution, and the second-best PES for biodiversity is lower than the marginal benefit. An important characteristic of a public PES scheme is the necessity to raise funds to finance it, which can also be at the origin of economic distortions. In order to account for this aspect, we then introduced the social marginal cost of public funds (MCF). The PES decreases with the MCF, whereas the Pigouvian tax increases with the MCF, provided that demand for the conventional agriculture good is inelastic and environmental policies provide buffer strips efficiently. This article highlights a contributory component of the environmental incentive tax. Indeed, the primary objective of a Pigouvian tax is to give the appropriate incentives to agents and not to raise a revenue for the regulator. This study also identifies cases where the PES is ineffective in promoting biodiversity.

This study was extended by considering other assumptions. First, we have challenged the assumption of a neutral impact of organic farming on biodiversity by assuming that fallow buffer strips produce more biodiversity than organic farming. In this case, we use two PES. The level of organic farming would be subject to two effects: a negative effect that favors buffer strips and a positive effect that favors biodiversity from organic farming. The first effect would therefore outweigh the second and the mechanisms highlighted in this paper would remain relevant. Second, under our assumptions, we have modified the environmental policy tools by considering two PES schemes, one on uncultivated land and the other on organic agriculture but no environmental tax. We found that the PES for organic agriculture takes the market power into account, and is higher than the marginal benefit of organic production, whereas the PES for uncultivated land is equal to the marginal benefit of biodiversity and no longer adjusts to incorporate the market power. Finally, we have challenged the assumption that there are no negative externalities of conventional agricultural production on the level of organic production. In this case, we found that the farmer will internalize this negative impact himself and the PES and environmental tax levels do not differ from those in the main scenario of this paper. However, the definition of PES when externalities between productions cannot be directly internalized should be further analyzed in another study. This is the case when farmers are different.

The issue of market power in the organic sector may be questionable. This market power can be justified by the non-uniform distribution of organic farming across the country and transport constraints for organic products. It is possible that for certain organic agricultural goods this assumption is not valid contrary to other organic agricultural goods. The objective of this theoretical article is to contribute to the economic literature by proposing a normative analysis of PES schemes while integrating different types of distortions. An amended version of this work could consider differentiated demands for organic agricultural goods that occur for some level of market power.

In this paper, PES remunerate environmental services provided by farmers. This article does not take into account the additionality issue under asymmetric information. Indeed, the farmer can leave some land uncultivated before any policy is introduced because it is not profitable for him to use all of his land in agricultural production. In this case, when a PES scheme is implemented, there is a windfall effect because the farmer will be subsidized for all uncultivated land, even the land he would have left uncultivated in the absence of any policy. The size of the windfall effect can be unknown to the regulator under asymmetric information. Further research is needed to investigate these different questions.

# Appendices

## A Welfare function concavity

- If $\lambda = 0$, we construct the Hessian matrix, $I(W)$:

$$I(W) = \begin{bmatrix} \frac{\partial^2 X_1}{\partial s^2}[F] + (\frac{\partial X_1}{\partial s})^2[F'] + \frac{d^2 X_2}{ds^2}[G] + (\frac{dX_2}{ds})^2[G'] & \frac{\partial^2 X_1}{\partial s \partial t}[F] + \frac{\partial X_1}{\partial s}\frac{\partial X_1}{\partial t}[F'] \\ \frac{\partial^2 X_1}{\partial s \partial t}[F] + \frac{\partial X_1}{\partial s}\frac{\partial X_1}{\partial t}[F'] & \frac{\partial^2 X_1}{\partial t^2}[F] + (\frac{\partial X_1}{\partial t})^2[F] \end{bmatrix}$$

where

$$\begin{aligned} F &= p_1(X_1) - c_1'(\frac{X_1}{n}) - B_y - D'(X_1) \\ F' &= p_1'(X_1) - \frac{1}{n}c_1''(\frac{X_1}{n}) + B_{yy} - D''(X_1) \\ G &= p_2(X_2) - c_2'(\frac{X_2}{n}) - B_y \\ G' &= p_2'(X_2) - \frac{1}{n}c_2''(\frac{X_2}{n}) + B_{yy} \end{aligned}$$

Following our assumptions about demand and cost structures, we can simplify the above matrix to

$$I(W) = \begin{bmatrix} (\frac{\partial X_1}{\partial s})^2[F'] + (\frac{dX_2}{ds})^2[G'] & \frac{\partial X_1}{\partial s}\frac{\partial X_1}{\partial t}[F'] \\ \frac{\partial X_1}{\partial s}\frac{\partial X_1}{\partial t}[F'] & (\frac{\partial X_1}{\partial t})^2[F'] \end{bmatrix}$$

Based on our assumptions, we know $F' < 0$ and $G' < 0$. Using this information, we calculate the determinant of $I$:

$$Det(I) = \left[\left[(\frac{\partial X_1}{\partial s})^2[F'] + (\frac{dX_2}{ds})^2[G']\right] * (\frac{\partial X_1}{\partial t})^2[F']\right] - \left[\frac{\partial X_1}{\partial s}\frac{\partial X_1}{\partial t}[F'] * \frac{\partial X_1}{\partial s}\frac{\partial X_1}{\partial t}[F']\right]$$

After simplification, we obtain:

$$Det(I) = (\frac{dX_2}{ds})^2[G'](\frac{\partial X_1}{\partial t})^2[F'] > 0$$

Thus, the welfare function is concave because the determinant is positive while $[\frac{dX_2}{ds}]^2[G'] + [\frac{\partial X_1}{\partial t}]^2[F'] < 0$.

- Next, we look at the case where $\lambda > 0$, referring to (17):

$$\begin{aligned} \frac{d^2W}{dt^2} &= \frac{d^2X_1}{dt^2}[p_1(X_1) - p_2(T - X_1) - c_1'(\frac{X_1}{n}) + c_2(\frac{T - X_1}{n}) - D'(X_1)] \\ &+ (\frac{dX_1}{dt})^2[p_1'(X_1) + p_2'(T - X_1) - \frac{1}{n}c_1''(\frac{X_1}{n}) - \frac{1}{n}c_2''(\frac{T - X_1}{n}) - D''(X_1)] \end{aligned}$$

Under our assumptions, we have:

$$(\frac{dX_1}{dt})^2\left[p_1'(X_1) + p_2'(T - X_1) - \frac{1}{n}c_1''(\frac{X_1}{n}) - \frac{1}{n}c_2''(\frac{T - X_1}{n}) - D''(X_1)\right] < 0$$

Therefore, the welfare function is still concave when $\lambda > 0$.

# B Welfare function concavity under the social marginal cost of public funds

- If $\lambda = 0$, we use (20) and (21) to create the Hessian matrix:

$$H = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

where

$$\begin{aligned}
a &= \frac{\partial^2 X_1}{\partial s^2}[A+\epsilon(t+s)] + (\frac{\partial X_1}{\partial s})^2[A'] + 2\epsilon\frac{\partial X_1}{\partial s} + \frac{d^2 X_2}{ds^2}[B+\epsilon s] + [\frac{dX_2}{ds}]^2[B'] + 2\epsilon\frac{dX_2}{ds} \\
b &= \frac{\partial^2 X_1}{\partial s \partial t}[A+\epsilon(t+s)] + \frac{\partial X_1}{\partial t}\frac{\partial X_1}{\partial s}[A'] + \epsilon[\frac{\partial X_1}{\partial s} + \frac{\partial X_1}{\partial t}] \\
c &= \frac{\partial^2 X_1}{\partial t \partial s}[A+\epsilon(t+s)] + \frac{\partial X_1}{\partial t}\frac{\partial X_1}{\partial s}[A'] + \epsilon[\frac{\partial X_1}{\partial s} + \frac{\partial X_1}{\partial t}] \\
d &= \frac{\partial^2 X_1}{\partial t^2}[A+\epsilon(t+s)] + (\frac{\partial X_1}{\partial t})^2[A'] + 2\epsilon\frac{\partial X_1}{\partial t}
\end{aligned}$$

and

$$\begin{aligned}
A &= p_1(X_1) - c_1'(\frac{X_1}{n}) - B_y - D'(X_1) \\
B &= p_2(X_2) - c_2'(\frac{X_2}{n}) - B_y \\
A' &= p_1'(X_1) - \frac{1}{n}c_1''(\frac{X_1}{n}) + B_{yy} - D''(X_1) \\
B' &= p_2'(X_2) - \frac{1}{n}c_2''(\frac{X_2}{n}) + B_{yy}
\end{aligned}$$

Thanks to our assumptions, we can simplify the Hessian to:

$$H = \begin{bmatrix} (\frac{\partial X_1}{\partial s})^2[A'] + [\frac{dX_2}{ds}]^2[B'] + 2\epsilon(\frac{\partial X_1}{\partial s} + \frac{dX_2}{ds}) & (\frac{\partial X_1}{\partial t})^2[A'] + 2\epsilon(\frac{\partial X_1}{\partial t}) \\ (\frac{\partial X_1}{\partial t})^2[A'] + 2\epsilon(\frac{\partial X_1}{\partial t}) & (\frac{\partial X_1}{\partial t})^2[A'] + 2\epsilon\frac{\partial X_1}{\partial t} \end{bmatrix}$$

So the determinant is:

$$\begin{aligned}
Det = &\left\{(\frac{\partial X_1}{\partial s})^2[A'] + [\frac{dX_2}{ds}]^2[B'] + 2\epsilon(\frac{\partial X_1}{\partial s} + \frac{dX_2}{ds}) * (\frac{\partial X_1}{\partial t})^2[A'] + 2\epsilon\frac{\partial X_1}{\partial t}\right\} \\
&- \left\{(\frac{\partial X_1}{\partial t})^2[A'] + 2\epsilon\frac{\partial X_1}{\partial t}\right\}^2
\end{aligned}$$

Simplifying, we find:

$$\begin{aligned}
Det = &(\frac{dX_2}{ds})^2(\frac{\partial X_1}{\partial t})^2[A'][B'] + 2\epsilon(\frac{\partial X_1}{\partial t}\frac{dX_2}{ds})(\frac{dX_2}{ds}[B'] + \frac{\partial X_1}{\partial t}[A']) \\
&+ 4\epsilon^2\frac{dX_2}{ds}\frac{\partial X_1}{\partial t} > 0
\end{aligned}$$

With $A' < 0$ and $B' < 0$, we find a positive determinant. And, because $(\frac{\partial X_1}{\partial s})^2[A'] + [\frac{dX_2}{ds}]^2[B'] + 2\epsilon(\frac{\partial X_1}{\partial s} + \frac{dX_2}{ds}) < 0$, we have a concave function.

- If $\lambda > 0$, we refer to (23):

$$\frac{d^2W}{dt^2} = \frac{d^2X_1}{dt^2}[E + \epsilon t] + \left(\frac{dX_1}{dt}\right)^2 [E'] + 2\epsilon\frac{dX_1}{dt}$$

where

$$\begin{aligned} E &= p_1(X_1) - p_2(T - X_1) - c_1'\left(\frac{X_1}{n}\right) + c_2'\left(\frac{T - X_1}{n}\right) - D'(X_1) \\ E' &= p_1'(X_1) + p_2'(T - X_1) - \frac{1}{n}c_1''\left(\frac{X_1}{n}\right) - \frac{1}{n}c_2''\left(\frac{T - X_1}{n}\right) - D''(X_1) < 0 \end{aligned}$$

With our assumptions we can simplify this to:

$$\frac{d^2W}{dt^2} = \left(\frac{dX_1}{dt}\right)^2 [E'] + 2\epsilon\frac{dX_1}{dt} < 0$$

Thus, our welfare function is still concave when $\lambda > 0$.

# C Tax and PES changes with the MCF if Y>0

According to (22), $t$ and $s$ depend on $\epsilon$. Moreover $t$ and $s$ must satisfy conditions (20) and (21). We set:

$$\begin{aligned} q &= p_1'(X_1(t(\epsilon), s(\epsilon))) - \frac{1}{n}c_1''\Big(\frac{X_1(t(\epsilon), s(\epsilon))}{n}\Big) - D''(X_1(t(\epsilon), s(\epsilon))) < 0 \\ z &= p_2'(X_2(s(\epsilon))) - \frac{1}{n}c_2''\Big(\frac{X_2(s(\epsilon))}{n}\Big) < 0 \end{aligned}$$

Additionally, we know: $\frac{\partial X_1}{\partial t} = \frac{\partial X_1}{\partial s} < 0$.

- We differentiate (20) and (21) with respect to $\epsilon$ and rearrange the equations into the following matrix form:

$$\begin{bmatrix} \frac{ds}{d\epsilon} \\ \frac{dt}{d\epsilon} \end{bmatrix} = K \begin{bmatrix} -\frac{\partial X_1}{\partial s}[t + s] - \frac{\partial X_2}{\partial s}s + (T - X_1 - X_2) \\ -\frac{\partial X_1}{\partial t}(t + s) - X_1 \end{bmatrix}$$

where $K = \begin{bmatrix} i & j \\ k & l \end{bmatrix}$, with:

$$\begin{aligned} i &= \frac{\partial X_1}{\partial s}[(q + B_{yy})\frac{\partial X_1}{\partial s} + 2\epsilon + B_{yy}\frac{\partial X_2}{\partial s}] + \frac{\partial X_2}{\partial s}[(z + B_{yy})\frac{\partial X_2}{\partial s} + B_{yy}\frac{\partial X_1}{\partial s} + 2\epsilon] \\ j &= \frac{\partial X_1}{\partial s}[(q + B_{yy})\frac{\partial X_1}{\partial t} + 2\epsilon + B_{yy}\frac{\partial X_2}{\partial s}] \\ k &= \frac{\partial X_1}{\partial t}[(q + B_{yy})\frac{\partial X_1}{\partial s} + B_{yy}\frac{\partial X_2}{\partial s} + 2\epsilon] \\ l &= \frac{\partial X_1}{\partial t}[(q + B_{yy})\frac{\partial X_1}{\partial t} + 2\epsilon] \end{aligned}$$

- We multiply each side of the equation by $K^{-1}$ to isolate $\frac{ds}{d\epsilon}$ and $\frac{dt}{d\epsilon}$:

$$\begin{bmatrix} \frac{ds}{d\epsilon} \\ \frac{dt}{d\epsilon} \end{bmatrix} = K^{-1} \begin{bmatrix} -\frac{\partial X_1}{\partial s}[t+s] - \frac{\partial X_2}{\partial s} s + (T - X_1 - X_2) \\ -\frac{\partial X_1}{\partial t}(t+s) - X_1 \end{bmatrix} \tag{27}$$

where

$$K^{-1} = \frac{1}{\det K} \begin{bmatrix} l & -j \\ -k & i \end{bmatrix}$$

- We calculate $\det K$ :

$$\begin{aligned} Det =& \Big\{ \frac{\partial X_1}{\partial t}[(q+B_{yy})\frac{\partial X_1}{\partial t} + 2\epsilon] \Big\} \Big\{ \frac{\partial X_1}{\partial s}[(q+B_{yy})\frac{\partial X_1}{\partial s} + 2\epsilon + B_{yy}\frac{\partial X_2}{\partial s}] \\ &+ \frac{\partial X_2}{\partial s}[(z+B_{yy})\frac{\partial X_2}{\partial s} + B_{yy}\frac{\partial X_1}{\partial s} + 2\epsilon] \Big\} - \Big[ \frac{\partial X_1}{\partial s}[(q+B_{yy})\frac{\partial X_1}{\partial t} + 2\epsilon + B_{yy}\frac{\partial X_2}{\partial s}] \Big]^2 \\ Det =& \frac{\partial X_1}{\partial t}^2 \frac{\partial X_2}{\partial s}^2 qz + \frac{\partial X_1}{\partial t}^2 \frac{\partial X_2}{\partial s}^2 qB_{yy} + \frac{\partial X_1}{\partial t}^2 \frac{\partial X_2}{\partial s}^2 zB_{yy} + 2\frac{\partial X_1}{\partial t}^2 \frac{\partial X_2}{\partial s} q\epsilon + 2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 z\epsilon \\ &+ 2\frac{\partial X_1}{\partial t}^2 \frac{\partial x_2}{\partial s} B_{yy}\epsilon + 2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 B_{yy}\epsilon + 4\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}\epsilon^2 > 0 \end{aligned}$$

because $q < 0$ and $z < 0$, $\frac{\partial X_1}{\partial t} = \frac{\partial X_1}{\partial s} < 0$ and $\frac{\partial X_2}{\partial s} < 0$.

- We calculate $\frac{ds}{d\epsilon}$, using (27):

$$\begin{aligned} \frac{\partial s}{\partial \epsilon} =& \frac{1}{\det} \Big\{ [\frac{\partial X_1}{\partial t}[(q+B_{yy})\frac{\partial X_1}{\partial t} + 2\epsilon] \Big\} \Big\{ -\frac{\partial X_1}{\partial s}[t+s] - \frac{\partial X_2}{\partial s} s + (T - X_1 - X_2) \Big\} \\ &+ \frac{1}{\det} \Big\{ -\frac{\partial X_1}{\partial s}[(q+B_{yy})\frac{\partial X_1}{\partial t} + 2\epsilon + B_{yy}\frac{\partial X_2}{\partial s}] \Big\} \Big\{ -\frac{\partial X_1}{\partial t}(t+s) - X_1 \Big\} \\ \frac{\partial s}{\partial \epsilon} =& \frac{1}{\det} \Big\{ -\frac{\partial X_1}{\partial t}^2 \frac{\partial X_2}{\partial s} qs + \frac{\partial X_1}{\partial t}^2 q(T - X_2) + \underbrace{\frac{\partial X_1}{\partial t}^2 \frac{\partial X_2}{\partial s} tB_{yy}}_{>0} + \frac{\partial X_1}{\partial t}^2 B_{yy}(T - X_2) \\ &+ \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s} X_1 B_{yy} - 2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s} s\epsilon + 2\frac{\partial X_1}{\partial t}\epsilon(T - X_2) \Big\} \end{aligned}$$

So $\dfrac{\partial s}{\partial \epsilon} < 0$ if $\dfrac{\partial X_1}{\partial t}^2 \dfrac{\partial X_2}{\partial s} tB_{yy} + \dfrac{\partial X_1}{\partial t}\dfrac{\partial X_2}{\partial s} X_1 B_{yy} < 0 \Leftrightarrow \dfrac{\partial X_1}{\partial t}\dfrac{\partial x_2}{\partial s} B_{yy}[\dfrac{\partial X_1}{\partial t} t + X_1] < 0$

i.e. if $\frac{\partial X_1}{\partial t} t + X_1 > 0 \Leftrightarrow \frac{\partial X_1}{\partial t}\frac{t}{X_1} + 1 > 0 \Leftrightarrow \underbrace{\dfrac{\partial X_1}{\partial t}\dfrac{t}{X_1}}_{e_{X_1/t}} > -1$

So $\frac{\partial s}{\partial \epsilon} < 0$ if $e_{X_1/t} > -1$.

- We calculate $\frac{dt}{d\epsilon}$, using (27):

$$\frac{\partial t}{\partial \epsilon} = \frac{1}{\det}\Big\{ -\frac{\partial X_1}{\partial t}\big[(q+B_{yy})\frac{\partial X_1}{\partial s} + B_{yy}\frac{\partial X_2}{\partial s} + 2\epsilon\big]\big[-\frac{\partial X_1}{\partial s}(t+s) - \frac{\partial X_2}{\partial s}s + (T - X_1 - X_2)\big]$$
$$+ \big[\frac{\partial X_1}{\partial s}[(q+B_{yy})\frac{\partial X_1}{\partial s} + 2\epsilon + B_{yy}\frac{\partial X_2}{\partial s}] + \frac{\partial X_2}{\partial s}[(z+B_{yy})\frac{\partial X_2}{\partial s} + B_{yy}\frac{\partial X_1}{\partial s} + 2\epsilon]\big]$$
$$\big[-\frac{\partial X_1}{\partial t}(t+s) - X_1\big]\Big\}$$

$$\frac{\partial t}{\partial \epsilon} = \frac{1}{\det}\Big\{ \frac{\partial X_1}{\partial t}^2 \frac{\partial X_2}{\partial s} qs - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 zs - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 zt - \frac{\partial X_1}{\partial t}^2 qT - \frac{\partial X_2}{\partial s}^2 zx_1 + \frac{\partial X_1}{\partial t}^2 qx_2$$
$$- \frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s} tB_{yy} - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 tB_{yy} - \frac{\partial X_1}{\partial t}^2 TB_{yy} - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s} TB_{yy} - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s} X_1 B_{yy}$$
$$- \frac{\partial X_2}{\partial s}^2 X_1 B_{yy} + \frac{\partial X_1}{\partial t}^2 X_2 B_{yy} + \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s} X_2 B_{yy} - 2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s} t\epsilon - 2\frac{\partial X_1}{\partial t} T\epsilon$$
$$- 2\frac{\partial X_2}{\partial s} X_1\epsilon + 2\frac{\partial X_1}{\partial t} X_2\epsilon\Big\}$$

$$\frac{\partial t}{\partial \epsilon} = \frac{1}{\det}\Big\{ \frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s} qs - \frac{\partial X_1}{\partial t}^2 q(T - X_2) - \frac{\partial X_1}{\partial t}^2 B_{yy}(T - X_2) - 2\frac{\partial X_1}{\partial t}\epsilon(T - X_2)$$
$$- \frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s} tB_{yy} - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s} X_1 B_{yy} - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 zs - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 zt$$
$$- \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s} B_{yy}(T - X_2) - \frac{\partial X_2}{\partial s}^2 X_1 B_{yy} - 2\frac{\partial X_2}{\partial s} X_1\epsilon - \frac{\partial X_2}{\partial s}^2 zX_1 - 2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s} t\epsilon$$
$$- \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 tB_{yy}\Big\}$$

We know that

- $-\frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s} tB_{yy} - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s} X_1 B_{yy} > 0 \Leftrightarrow -\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s} B_{yy}[\frac{\partial X_1}{\partial t} t - X_1] > 0 \Leftrightarrow \frac{\partial X_1}{\partial t}\frac{t}{X_1} > -1$
- $-2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s} t\epsilon - 2\frac{\partial X_2}{\partial s} X_1\epsilon > 0 \Leftrightarrow -2\frac{\partial X_2}{\partial s}\epsilon[\frac{\partial X_1}{\partial t} t + X_1] > 0 \Leftrightarrow \frac{\partial X_1}{\partial t}\frac{t}{X_1} > -1$
- $-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 zt - \frac{\partial X_2}{\partial s}^2 zX_1 > 0$ if $-\frac{\partial X_2}{\partial s}^2 z[\frac{\partial X_1}{\partial t} t + X_1] > 0 \Leftrightarrow \frac{\partial X_1}{\partial t}\frac{t}{X_1} > -1$
- $-\frac{\partial X_2}{\partial s}^2 X_1 B_{yy} - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 tB_{yy} > 0$ if $-\frac{\partial X_2}{\partial s}^2 B_{yy}[\frac{\partial X_1}{\partial t} t + X_1] > 0 \Leftrightarrow \frac{\partial X_1}{\partial t}\frac{t}{X_1} > -1$
- $-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 zs + \frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s} qs > 0 \Leftrightarrow \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s} s[\frac{\partial X_1}{\partial t} q - \frac{\partial X_2}{\partial s} z] > 0 \Leftrightarrow [\frac{\partial X_1}{\partial t} q - \frac{\partial X_2}{\partial s} z] > 0 \Leftrightarrow \frac{\partial X_1}{\partial t}/\frac{\partial X_2}{\partial s} > z/q \equiv \varpi$.

$\Rightarrow \frac{\partial t}{\partial \epsilon} > 0$ if $e_{X_1/t} > -1$ and $\frac{\partial X_1}{\partial t}/\frac{\partial X_2}{\partial s} > \varpi$.

# D Tax and PES changes with the MCF if Y=0

We use (23) and we set: $J(t,\epsilon) = \frac{dX_2}{dt}[-p_1(T - X_2) + p_2(X_2) + c_1'(\frac{T - X_2}{n}) - c_2'(\frac{X_2}{n}) + D'(T - X_2) - \epsilon t] + \epsilon(T - X_2)$. Applying the implicit function theorem we find:

$$\frac{dt}{d\epsilon} = -\frac{\frac{\partial J}{\partial \epsilon}}{\frac{\partial J}{\partial t}} = -\frac{\frac{dX_1}{dt} t + X_1}{\frac{dX_1}{dt}[p_1'(X_1) + p_2'(T - X_1) - \frac{1}{n}c_1''(\frac{X_1}{n}) - \frac{1}{n}c_2''(\frac{T - X_1}{n}) - D''(X_1)] + 2\frac{dX_1}{dt}\epsilon}$$

We know that the denominator of the above expression is negative. So we obtain $\frac{dt}{d\epsilon} > 0$ if $e_{X_1/t} > -1$.

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