Payment for Environmental Services and pollution tax under imperfect competition

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Abstract

In this paper, we analyse the second best Payment for Environmental Services (PES) design 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 whereas the organic good sector is 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 marginal social 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.

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1 Introduction

Environmental services (ES) are the benefits we obtain from nature, and they are generally 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" (Reid et al., 2005). Many of these services have been in decline or are currently less than optimally provided. Although provisioning services are generally included in markets, the other three types of ES are positive externalities that are not accounted for in markets, which leaves room for policy intervention to encourage their optimal provision.

Payments for Environmental Services (PES) is one policy tool that has been implemented to try to increase the provision of environmental services. One of the most widely cited definitions of PES comes from Wunder (2005), who 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 (conditionality)." Conditionality can be difficult to evaluate in results-based PES schemes, as some ES are difficult to measure. In practice, it is much more common to see PES schemes conditional on land use or specific management practices.

The above definition exemplifies the Coase theorem (Coase, 1960), which states that an externalitiy can be resolved through private negotiation, and the socially optimal allocation of ES can be achieved, regardless of the initial property allocation and assuming sufficiently low transaction costs. 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).

The definition of PES can be widened to include certain types of government intervention that reflect a Pigouvian subsidy (Sattler & Matzdorf, 2013; Pigou, 1920). This type of PES is far more common in practice than a Coasean PES. For example, the European agri-environmental programs are financed through public funds, and the government acts as an intermediary between ES buyers (the public) and ES sellers (farmers who receive PES subsidies) (Sattler & Matzdorf, 2013). Both the Coasean and Pigouvian PES schemes follow the beneficiary pays principle rather than the polluter pays principle.

Muradian et al. (2010) provide yet another alternative definition, describing PES as "a transfer of resources between social actors, which aims to create incentives to align individual and/or collective land use decisions with the social interest in the management of natural resources." This definition is more flexible than that of Wunder (2005), and better reflects what occurs in actual PES schemes rather than what should occur in theory. This definition also reflects that payments may not necessarily be monetary, but they may be in-kind transfers as well.

There have been a variety of PES schemes, and classifying them is not a straightforward task. As Sattler et al. (2013) point out, "PES schemes draw on a multitude of approaches that highly differ in terms of addressed ES, mechanisms for price formation, payment origins and levels, buyer and seller characteristics, rules governing the contract among involved parties, level of complexity and so forth." One example of different approaches is that payments can be increasing, decreasing, or stable over time, though this is outside of the scope of this paper. According to Wunder (2005), the main ES involved in PES are carbon sequestration and storage, biodiversity protection, watershed protection, and landscape beauty.

Biodiversity protection in particular has been getting more attention in recent years as we learn more about the extent of the decline of global biodiversity and its consequences. It has been shown that land use change is the leading driver of biodiversity loss in terrestrial ecosystems and voluntary incentives are the most common mechanism to encourage conservation on privately owned land (Lewis et al., 2011).

Agricultural lands are often home to a significant share of biodiversity, but over the past several decades, as a result of farm intensification and increase in farm size, "natural habitats have been transformed and fragmented, leading to many species' decline" (Bamière et al., 2013). Accordingly, one of the more common forms of PES targeting biodiversity conservation are Agro-Environmental Schemes (AES), which are incentive-based instruments that provide payments to farmers for voluntary actions taken to preserve and enhance the environment (Uthes & Matzdorf, 2013). In fact, "in the EU, the largest source of funding for practical nature conservation is delivered through agri-environment-climate schemes (AES) implemented under the Common Agricultural Policy (CAP)" (Herzon et al., 2018). Common management practices adopted under AESs include reducing fertilizer and/or pesticide use, planting buffer crops near rivers, and adaptations to crop rotations. More recently, following France's National Biodiversity Plan of 2018, French water agencies are experimenting with their own PES schemes that are separate from the AES under the CAP. They have been allocated 150 million euros of the French national budget, which they will mobilize by 2021, with the objective to maintain or create good ecological practices, such as lowering pesticide use, planting cover crops, etc. 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.

Agricultural lands are also sometimes associated with pollution; for example, the use of chemical fertilizers and pesticides that pollute watersheds. The standard economic solution to pollution is a Pigouvian tax, which addresses the negative externality of pollution by charging polluters the price of the damage caused by the pollution. In a perfectly competitive market setting, placing a tax on pollution equal to its marginal damage internalizes the damage into the production decision, and the polluter will reduce pollution to the socially optimal level. Alternatively, a subsidy can be implemented to incentivize farmers to use less fertilizers and pesticides, which is essentially a PES.

However, in situations with imperfect competition, "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" (Barnett, 1980). Indeed, Buchanan (1969) showed graphically that a Pigouvian tax that works under perfect competition could lead to a welfare loss under a monopoly. After Buchanan, Barnett (1980) demonstrated mathematically that, under a monopoly, the optimal second best tax should actually be less than the marginal damage and that the price elasticity of demand affects the optimal tax rate. Ebert (1991) follows Barnett (1980) in analyzing Pigouvian taxes under imperfect competition, but focusing on the case of an oligopoly rather than a monopoly. Ebert finds once again that the optimal Pigouvian tax rate will depend on the marginal damage as well as the market structure. Since then, the literature on taxation has widely developed for numerous scenarios of imperfect competition.

Most PES policy evaluations focus on a single policy's impact, but in reality there may be multiple policies interacting to provide the outcomes we observe. Lankoski & Ollikainen (2003) is one paper that looks at both a tax and a subsidy in an agricultural setting. They use a production function approach and augment Lichtenberg's model of agricultural production

(Lichtenberg, 1989) to study the optimal land allocation between two crops and fallow buffer strips when facing negative externalities from nutrient runoff, and positive externalities from biodiversity and landscape diversity. Their model involves land parcels of varying land quality (though with uniform quality within a given parcel) adjacent to a water body such as a stream or river. Their socially optimal policy involves a differentiated tax on fertilizer and a differentiated buffer strip subsidy.

The aim of our paper differs from Lankoski & Ollikainen (2003), which considers a perfectly competitive world. In this article, 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 leave uncultivated land as buffer strips which favor biodiversity whereas conventional agriculture creates environmental damages. In order to favor biodiversity and reduce environmental damages, the regulator sets a PES and a Pigouvian tax. If the farmer chooses to leave buffer strips, the Pigouvian tax decreases the conventional good production level and the PES reduces both production levels (organic and conventional). We show that the second best level of the Pigouvian tax is higher than the marginal damage 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 of conventional agriculture. If productions are profitable enough, farmers never choose buffer strips and the PES is useless. In this case 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 introduce a marginal social cost of public funds (MCF) and find that the tax will increase with the MCF, whereas the PES will decrease with the MCF.

This paper is organized as follows: Section 2 sets forth the assumptions used in our model; Section 3 presents the farmer's production decision absent of any policy; Section 4 examines second best policies, looking at the farmer's behavior, the optimal tax and PES, and the marginal cost of public funds. Finally, Section 5 concludes and presents policy recommendations.

2 The model

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. 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[1], $\forall i = 1, ..., n$. The quantity of land left uncultivated only incurs an opportunity cost of not producing. Finally, 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. Demand is linear for both agricultural goods.

The good resulting from organic agriculture can be considered as a good with few substitutes contrary to the conventional agriculture good. We consider that the conventional agriculture good experiences perfect competition whereas the organic agriculture good experiences imperfect competition in the form of oligopoly.

Each of the land management choices also 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 does not lead to pollution, but also does not increase biodiversity, thus it 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 function $B(Y)$.

2.2 The first-best

In this subsection, we investigate the first-best outcome where there is no market power and both agriculture markets are perfectly competitive. The government regulator seeks to maximize welfare, which is composed of the consumer surplus, the firm's profit, the environmental damage and benefit while taking into account the constraint on available land:

$$\begin{aligned} \underset{x_1,x_2,\lambda}{W} = & \int_0^{x_1} p_1(u)du + \int_0^{x_2} p_2(v)dv - c_1(x_1) - c_2(x_2) + B(T - x_1 - x_2) \\ & - D(x_1) + \lambda(T - x_1 - x_2) \end{aligned}$$

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

$$p_1(x_1^*) - c_1'(x_1^*) - B_y - D'(x_1^*) - \lambda = 0$$

$$p_2(x_2^*) - c_2'(x_2^*) - B_y - \lambda = 0$$

$$\lambda(T - x_1^* - x_2^*) = 0$$

The optimal land allocation will depend on the prices and marginal costs of each agriculture type, as well as biodiversity benefits from fallow land and the pollution damages from conventional agriculture.

There are two possible cases for λ. 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 such that the price is now equal to marginal social costs.

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

2.3 No regulation

In this section we look at the farmer's decision in the absence of any policy. Farmer i maximizes his profit by choosing x_{1i} and x_{2i}, assuming x_{2j} are given.

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:

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

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

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

Whereas a farmer equalizes the marginal cost to the price when making his conventional agriculture production decision, he will consider the marginal revenue rather than the price when making his organic agriculture production decision. Additionally, farmer i must consider all other farmers' decisions in order to maximize his profit. Environmental aspects are not taken into account. 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 $\lambda = 0$.

To see how x_{2i} responds to the choices of farmer j, we apply the implicit function theorem. We start with the case where the farmer leaves uncultivated land ($\lambda = 0$). We set from Equation (1) $F(x_{2i}, x_{2j}) = p_2'\big(X_2\big)x_{2i} + p_2\big(X_2\big) - c_2'(x_{2i})$. 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 $G(x_{2i}, x_{2j} = p_1 - c_1'(T_i - x_{2i}) - p_2'(X_2)x_{2i} - p_2(X_2) + c_2'(x_{2i})$, and we find:

$$\frac{\partial x_{2i}}{\partial x_{2j}} = -\frac{\frac{\partial G}{\partial x_{2j}}}{\frac{\partial G}{2i}} = -\frac{-p_2''(X_2)(n-1)x_{2i} - p_2'(X_2)(n-1)}{c_1''(T_i - x_{2i}) - p_2''(X_2)x_{2i} - 2p_2'(X_2) + c_2''(x_{2i})} < 0$$

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

3 Second best policies

Although we cannot directly correct for the oligopoly, we can examine a second best policy to correct for the negative and positive externalities of pollution and biodiversity, respectively, and improve welfare. Here, we examine a 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.[2]

3.1 The farmer's behavior

When the tax and subsidy are implemented, the profit for farmer i, $\forall i$ and $i \neq j$, taking into account the constraint on its land is:

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

Maximizing profit yields the following conditions:

$$p_1 - c_1'(x_{1i}) - t - s - \lambda = 0 \tag{4}$$

$$p_2'\big(X_2\big)\frac{X_2}{n} + p_2\big(X_2\big) - c_2'(x_{2i}) - s - \lambda = 0 \tag{5}$$

$$\lambda(T_i - x_{1i} - x_{2i}) = 0 \tag{6}$$

We can see how x_{1i} and x_{2i} change in the values of s and t by applying the implicit function theorem. Starting with the case where the farmer leaves uncultivated land ($\lambda = 0$) and using Equations (4) and (5), we set: $F(x_{1i}, s, t) = p_1 - c_1'(x_{1i}) - t - s$ and $G(x_{2i}, s) = p_2'\big(X_2\big)x_{2i} + p_2\big(X_2\big) - c_2'(x_{2i}) - s$, and we find:

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

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

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

An increase in subsidy level will lead to a decrease in both agriculture goods, and thus an increase in uncultivated land and consequently biodiversity benefits. Additionally, an increase in the tax t will also lead to a decrease in the conventional agriculture good.

If the farmer leaves no uncultivated land ($\lambda > 0$), using Equations (4), (5) and (6) and setting $H(x_{1i}, t) = p_1 - c_1'(x_{1i}) - t - p_2'(T - X_1)(T_i - x_{1i}) - p_2(T - X_1) + c_2'(T_i - x_{1i})$, we obtain:

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

[2] We also analysed a scenario with two PES: one for biodiversity and one for organic agriculture, which replaces the tax. We find in this case that the PES for organic agriculture takes the market power into account and the result is a PES equal to the marginal benefit of organic agriculture.

Since $x_{2i} = T_i - x_{1i}(t)$,

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

This implies that an increase in tax t will lead to an increase in production of the organic agriculture good, and a decrease in production of the conventional agriculture good in the same proportion. It is a zero-sum game. Here, the subsidy 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.

3.2 Optimal tax and PES levels

We maximize the social welfare function to find the second-best levels of t and s. We first investigate the case where it is optimal to leave uncultivated land and then when it is optimal 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:

$$\begin{aligned} &\frac{\partial X_1}{\partial s}[p_1(X_1(s)) - c_1'\left(\frac{X_1(s)}{n}\right) - B_y - D'(X_1(s))] \\ &+ \frac{dX_2}{ds}[p_2(X_2(s)) - c_2'\left(\frac{X_2(s)}{n}\right) - B_y] = 0 \end{aligned} \tag{7}$$

$$\frac{\partial X_1}{\partial t}[p_1(X_1(t)) - c_1'\left(\frac{X_1(t)}{n}\right) - B_y - D'(X_1(t))] = 0 \tag{8}$$

with $\frac{\partial X_1}{\partial s} < 0$, $\frac{\partial X_1}{\partial t} < 0$, and $\frac{dX_2}{ds} < 0$, and $B_y = B'(y)$.

We can rearrange the profit maximization conditions, equations (4) and (5) to obtain the following:

$$p_1 - c_1'\left(\frac{X_1}{n}\right) = t + s \tag{9}$$

$$p_2(X_2) - c_2'\left(\frac{X_2}{n}\right) = -p_2'(X_2)\frac{X_2}{n} + s \tag{10}$$

Next, we can plug equations (9) and (10) into equations (7) and (8) to obtain the following equations:

$$\frac{\partial X_1}{\partial s}[t + s - B_y - D'(X_1(s))] + \frac{dX_2}{ds}[-p_2'(X_2(s))\frac{X_2}{n} + s - B_y] = 0 \tag{11}$$

$$\frac{\partial X_1}{\partial t}[t + s - B_y - D'(X_1(t))] = 0 \tag{12}$$

We can now solve (12) for t, and plug that into (11) to solve for s and t. We find:

$$s = B_y + p_2'(X_2)\frac{X_2}{n} \tag{13}$$

$$t = D'(X_1) - p_2'(X_2)\frac{X_2}{n} \tag{14}$$

It appears that the second best PES is lower than the marginal benefit whereas the the second best tax is higher than the marginal damage. Production of the organic agriculture good is lower than its first best level because of market power. As the PES reduces the level of the 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 (4) and (5), we find that first-best quantities (given by (**??**) and (**??**)). 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.

Next, we 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:

$$\frac{dX_2}{dt}[-p_1(T - X_2) + p_2(X_2) + c_1'\left(\frac{T - X_2}{n}\right) - c_2'\left(\frac{X_2}{n}\right) + D'(T - X_2)] = 0 \tag{15}$$

Using the profit first order conditions (4) and (5), we find that

$$-p_1 + c_1'\left(\frac{T - X_2}{n}\right) + p_2(X_2) - c_2'\left(\frac{X_2}{n}\right) = -t - p_2'(X_2)\frac{X_2}{n} \tag{16}$$

Plugging (16) into (15) yields

$$t = D'(T - X_2) - p_2'(X_2)\frac{X_2}{n} \tag{17}$$

In this case, the second-best environmental tax level is also higher than the marginal damage. As the PES cannot promote the uncultivated land, only the environmental tax will correct both the negative externality and market power in the organic market. Again, this second best tax can achieve the first-best.

4 Marginal social cost of public funds

The marginal social cost of public funds (MCF) is a measure of the welfare loss to society as a result of raising additional revenues to finance government spending (Browning, 1976; Dahlby, 2008). Increasing taxes or implementing a new subsidy can change the allocation of resources in an economy through impacts on consumption, labor, and investment decisions (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. In this article, the introduction of a PES needs to be financed and maybe environmental taxes can reduce another distortionary contributory tax.[3] So we will design in this section the second-best level of the environmental tax and PES taking into account the MCF.

We use ϵ to denote the MCF. Each euro raised by the environmental tax will enable to reduce distortionary contributive taxes of $(1+\epsilon)$ euros. Conversely, implementing a PES means a requirement for additional government revenue through increased contributive taxes, which will come at a cost to society. So, each euro allocated to the PES costs $(1+\epsilon)$ euros to society. So, we modify the welfare function given in Section 3 in order to take into account the taxation effects.

In the case where the farms leaves uncultivated land, the welfare reads:

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

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

$$\begin{aligned}&\frac{\partial X_1}{\partial s}[p_1(X_1(s)) - c_1'\left(\frac{X_1(s)}{n}\right) - B_y - D'(X_1(s)) + \epsilon t + \epsilon s] \\ &+ \frac{dX_2}{ds}[p_2(X_2(s)) - c_2'\left(\frac{X_2(s)}{n}\right) - B_y + \epsilon s] - \epsilon(T - X_1(s) - X_2(s)) = 0\end{aligned} \tag{18}$$

$$\frac{\partial X_1}{\partial t}[p_1(X_1(t)) - c_1'\left(\frac{X_1(t)}{n}\right) - B_y - D'(X_1(t)) + \epsilon t + \epsilon s] + \epsilon X_1(t) = 0 \tag{19}$$

with $\frac{\partial X_1}{\partial s} < 0$, $\frac{\partial X_1}{\partial t} < 0$, and $\frac{dX_2}{ds} < 0$.

Using Equations (9) and (10), and solving for s and t we find:

[3] This latter point relates to the concept of the "double dividend" which supposes that levying a revenue-neutral Pigouvian tax can reduce market distortions in two ways: internalizing a negative externality, and reducing distortionary taxes while maintaining the same governmental revenue level. Essentially, this idea supposes that the MCFs for environmental taxes are lower than the MCFs for other sources of tax revenue (Dahlby, 2008). Several papers investigate the theoretical and empirical merit of the idea of the double dividend under different conditions, such as different labor supply curves (Goulder, 1995; Bovenberg, 1999; Carraro et al., 1996; Ploeg & Bovenberg, 1994; Ligthart & Van Der Ploeg, 1999). Finally, Chiroleu-Assouline (2001) provides a literature review of the different studies of the double dividend. We do not examine this point in this article.

$$s = \frac{B_y + p_2'(X_2)\frac{X_2}{n}}{1+\epsilon} + \frac{\epsilon}{1+\epsilon}\left[\frac{T - X_1 - X_2}{\frac{dX_2}{ds}}\right] + \frac{\epsilon}{1+\epsilon}X_1\left[\frac{\frac{\partial X_1}{\partial s}}{\frac{dX_2}{ds}\frac{\partial X_1}{\partial t}}\right] \tag{20}$$

$$t = \frac{D'(X_1) - p_2'(X_2)\frac{X_2}{n}}{1+\epsilon} - \frac{\epsilon}{1+\epsilon}\left[\frac{\frac{\partial X_1}{\partial s}X_1}{\frac{dX_2}{ds}\frac{\partial X_1}{\partial t}} + \frac{T - X_1 - X_2}{\frac{dX_2}{ds}} + \frac{X_1}{\frac{\partial X_1}{\partial t}}\right]$$

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. The MCF increases the value of the environmental tax and reduces the value of the PES:

$$t^{MCF} > t \text{ and } PES^{MCF} < PES$$

Finally, the level of conventional agriculture will be lower than its first-best level while the level of organic agriculture will be higher than its first-best level. However, the impact on the uncultivated area is not clear. The uncultivated area increases with the MCF if the effect of the environmental tax is higher than the effect on the PES on land use, i.e:

$$-\frac{\epsilon}{1+\epsilon}\frac{X_1}{dX_1/dt} > \frac{\epsilon}{1+\epsilon}\left(\frac{T - X_2}{dX_2/ds}\right)$$

Surprisingly, the effect of a change in ϵ in t^{MCF} and PES^{MCF} is not very immediate. To investigate this point, we use (9) and (10) with $X_1(s(\epsilon), t(\epsilon))$ and $X_2(s(\epsilon))$. We examine a very specific case where the elasticity of the conventional agriculture good with respect to the environmental tax is low. We find (see Appendix C for full calculations):

$$\begin{aligned}
\text{If } e_{X_1/t} &> -1, \ \frac{ds}{d\epsilon} < 0 \text{ and } \frac{dt}{d\epsilon} > 0 \text{ if } \frac{\partial X_1}{\partial t} / \frac{\partial X_2}{\partial s} > z/q \\
\text{with } z &= p_2'(X_2(s(\epsilon))) - \frac{1}{n}c_2''\left(\frac{X_2(s(\epsilon))}{n}\right) \\
q &= p_1'(X_1(t(\epsilon), s(\epsilon))) - \frac{1}{n}c_1''\left(\frac{X_1(t(\epsilon), s(\epsilon))}{n}\right) - D''(X_1(t(\epsilon), s(\epsilon)))
\end{aligned}$$

Under the adopted assumption, conventional agricultural production will not be significantly reduced after the implementation of the environmental tax. Consequently, the environmental tax, which initially has an incentive objective, would have a contributory outcome. Thus an increase in the marginal cost of public funds will further increase the environmental tax, provided also that the impact of changes in environmental policy is above a certain threshold. More specifically, the change in the marginal benefit from conventional agriculture as a result of a tax change must be greater than the change induced by the PES on the marginal benefit from organic agriculture. In other words the environmental tax becomes a contributory tax provided that the elasticity is low but also that this policy further disincentivizes the conventional agricultural sector more than the organic agricultural sector. As far as the PES is concerned, the higher the MCF, the lower it is.

If the farmers cultivate the entire land ($\lambda > 0$), taking the MCF into account leads to the following welfare function:

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

Maximizing welfare yields this following first-order condition:

$$\frac{dX_2}{dt}[-p_1(T - X_2) + p_2(X_2) + c_1'(\frac{T - X_2}{n}) - c_2'(\frac{X_2}{n}) + D'(T - X_2) - \epsilon t] + \epsilon(T - X_2) = 0 \quad (21)$$

Using equations (4) and (5) from the profit maximization gives:

$$-p_1 + c_1'(X_1) + p_2(X_2) - c_2'(X_2) = -t - p_2'(X_2)\frac{X_2}{n} \quad (22)$$

We can then write equation (21) as

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

Then, we solve equation (23) and we obtain the second-best environmental tax level:

$$t = \frac{D'(X_1) - p_2'(X_2)\frac{X_2}{n}}{1 + \epsilon} + \frac{\epsilon}{1 + \epsilon}\left(\frac{X_1}{\frac{dX_2}{dt}}\right) \quad (24)$$

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. Again, this environmental tax is lower than its design without the MCF. Again, we find that the incentive tax can be used as a contributory tax if the demand for the agricultural good is inelastic with respect to the environmental tax (see Appendix):

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

5 Conclusion and recommendations

Pollution and biodiversity benefits are two externalities associated with agricultural land that lead to market failure. Multiple market failures require multiple policies to address them. Here, we looked at the scenario where a 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. We then introduce the marginal cost of public funds in order to investigate how the PES and the Pigouvian tax are modified. The PES decreases with the MCF whereas the Pigouvian tax increases with the MCF, provided that demand for the conventional agriculture good is inelastic.

We further explored some alternative scenarios. First, we looked at a scenario with a PES for organic agriculture in addition to the PES for biodiversity and the Pigouvian tax, which resulted in an over-determined system of equations due to the organic PES and the tax essentially having the same function of reducing conventional agriculture. Next, we looked at a scenario with the two PES schemes but no tax, and found that the organic PES takes the market power into account, and is higher than the marginal benefit of organic production, whereas the biodiversity PES is equal to the marginal benefit of biodiversity and no longer adjusts to incorporate the market power. Finally, we examined a scenario with the biodiversity PES and the Pigouvian tax where the conventional production negatively impacts the organic production, reflected in its cost function, $c_2(x_1, x_2)$, and found that the farmer will internalize this negative impact and the PES and tax levels do not differ from those in the main scenario of this paper.

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. One proposed solution to the asymmetric information problem that has been widely explored in the literature is to use reverse auctions to allocate PES contracts.

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 (15):

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

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 (18) and (19) 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 (21):

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

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 (20), t and s depend on ϵ. Moreover t and s must satisfy conditions (18) and (19). We set:

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

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

- We differentiate (18) and (19) with respect to ϵ and rearrange the equations into the following matrix form:

$$\begin{bmatrix} \frac{ds}{d\epsilon} \\ \frac{dt}{d\epsilon} \end{bmatrix} = K \begin{bmatrix} -\frac{\partial X_1}{\partial s}[t + s] - \frac{\partial X_2}{\partial s} s + (T - X1 - X2) \\ -\frac{\partial X_1}{\partial t}(t + s) - X_1 \end{bmatrix}$$

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 byK^{-1} to isolate $\frac{ds}{d\epsilon}$ and $\frac{dt}{d\epsilon}$:

$$\begin{bmatrix} \frac{ds}{d\epsilon} \\ \frac{dt}{d\epsilon} \end{bmatrix} = K^{-1} \begin{bmatrix} -\frac{\partial X_1}{\partial s}[t+s] - \frac{\partial X_2}{\partial s}s + (T - X_1 - X_2) \\ -\frac{\partial X_1}{\partial t}(t+s) - X_1 \end{bmatrix} \tag{25}$$

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 (25):

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

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

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

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

- We calculate $\frac{dt}{d\epsilon}$, using (25):

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

$$\frac{\partial t}{\partial \epsilon} = \frac{1}{\det}\Big\{\frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s}qs - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 zs - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 zt - \frac{\partial X_1}{\partial t}^2 qT - \frac{\partial X_2}{\partial s}^2 zx_1 + \frac{\partial X_1}{\partial t}^2 qx_2$$
$$- \frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s}tB_{yy} - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 tB_{yy} - \frac{\partial X_1}{\partial t}^2 TB_{yy} - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}TB_{yy} - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}X_1B_{yy}$$
$$- \frac{\partial X_2}{\partial s}^2 X_1B_{yy} + \frac{\partial X_1}{\partial t}^2 X_2B_{yy} + \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}X_2B_{yy} - 2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}t\epsilon - 2\frac{\partial X_1}{\partial t}T\epsilon$$
$$- 2\frac{\partial X_2}{\partial s}X_1\epsilon + 2\frac{\partial X_1}{\partial t}X_2\epsilon\Big\}$$

$$\frac{\partial t}{\partial \epsilon} = \frac{1}{\det}\Big\{\frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s}qs - \frac{\partial X_1}{\partial t}^2 q(T - X_2) - \frac{\partial X_1}{\partial t}^2 B_{yy}(T - X_2) - 2\frac{\partial X_1}{\partial t}\epsilon(T - X_2)$$
$$- \frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s}tB_{yy} - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}X_1B_{yy} - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 zs - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 zt$$
$$- \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}B_{yy}(T - X_2) - \frac{\partial X_2}{\partial s}^2 X_1B_{yy} - 2\frac{\partial X_2}{\partial s}X_1\epsilon - \frac{\partial X_2}{\partial s}^2 zX_1 - 2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}t\epsilon$$
$$- \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 tB_{yy}\Big\}$$

We know that

- $-\frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s}tB_{yy} - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}X_1B_{yy} > 0 \Leftrightarrow -\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}B_{yy}[\frac{\partial X_1}{\partial t}t - X_1] > 0 \Leftrightarrow \frac{\partial X_1}{\partial t}\frac{t}{X_1} > -1$
- $-2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}t\epsilon - 2\frac{\partial X_2}{\partial s}X_1\epsilon > 0 \Leftrightarrow -2\frac{\partial X_2}{\partial s}\epsilon[\frac{\partial X_1}{\partial t}t + X_1] > 0 \Leftrightarrow \frac{\partial X_1}{\partial t}\frac{t}{X_1} > -1$
- $-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 zt - \frac{\partial X_2}{\partial s}^2 zX_1 > 0$ if $-\frac{\partial X_2}{\partial s}^2 z[\frac{\partial X_1}{\partial t}t + X_1] > 0 \Leftrightarrow \frac{\partial X_1}{\partial t}\frac{t}{X_1} > -1$
- $-\frac{\partial X_2}{\partial s}^2 X_1B_{yy} - \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 tB_{yy} > 0$ if $-\frac{\partial X_2}{\partial s}^2 B_{yy}[\frac{\partial X_1}{\partial t}t + X_1] > 0 \Leftrightarrow \frac{\partial X_1}{\partial t}\frac{t}{X_1} > -1$
- $-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 zs + \frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s}qs > 0 \Leftrightarrow \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}s[\frac{\partial X_1}{\partial t}q - \frac{\partial X_2}{\partial s}z] > 0 \Leftrightarrow [\frac{\partial X_1}{\partial t}q - \frac{\partial X_2}{\partial s}z] > 0 \Leftrightarrow \frac{\partial X_1}{\partial t}q > \frac{\partial X_2}{\partial s}z$

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

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

We use (21) and we set: $J(t,\epsilon) = \frac{dX_2}{dt}[-p_1(T - X_2) + p_2(X_2) + c_1'(\frac{T-X_2}{n}) - c_2'(\frac{X_2}{n}) + D'(T - X_2) - \epsilon t] + \epsilon(T - X_2)$. Apllying 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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