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 Assumptions

We consider $n \geq 2$ 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). The farmers compete in a Cournot model of oligopoly for organic agriculture, with the assumption that all farmers are identical. 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, $\forall i = 1, ..., n$. Additionally, we assume that $c_1'''(x_{1i}) = 0$ and $c_2'''(x_{2i}) = 0, \forall i = 1, ..., n$. 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.

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 function $B(Y)$, which is given by $B(T - X_1 - X_2)$.

We consider that the conventional agriculture good experiences perfect competition whereas the organic agriculture good experiences imperfect competition in the form of oligopoly.

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_{1j} and x_{2j} are given.

The profit for farmer $i; \forall i = 1, 2, ..., n; i \neq j$ 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 will consider the marginal cost when making his conventional agriculture production decision, he will consider the marginal revenue rather than the marginal cost when making his organic agriculture production decision. Additionally, farmer i must consider all other farmers' decisions in order to maximize his profit. The production decision also 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 $\lambda = 0$, and use $F(x_{2i}, x_{2j}) = p_2'\big(X_2\big)x_{2i} + p_2\big(X_2\big) - c_2'(x_{2i})$.

$$\frac{\partial x_{2i}}{\partial x_{2j}} = -\frac{\frac{\partial F}{\partial x_{2j}}}{\frac{\partial F}{\partial x_{2i}}} = -\frac{p_2''(X_2)x_{2i} + p_2'(X_2)}{p_2''(X_2)x_{2i} + 2p_2'(X_2) - c_2''(x_{2i})} < 0 \tag{4}$$

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, the production of the organic agriculture good is a strategic substitute.

For the case where $\lambda > 0$, we apply the implict function theorem, using $x_{1i} = T_i - x_{2i}$ and $G = p_1 - c_1'(T_i - x_{2i}) - p_2'(X_2)x_{2i} - p_2(X_2) + c_2'(x_{2i})$

$$\frac{\partial x_{2i}}{\partial x_{2j}} = -\frac{\frac{\partial G}{\partial x_{2j}}}{\frac{\partial G}{\partial x_{2i}}} = -\frac{-p_2''(X_2)(n-1)x_{2i} - p_2'(X_2)(n-1)}{c_1''(T_i - x_{2i}) - p_2''(X_2)x_{2i} - 2p_2'(X_2) + c_2''(x_{2i})} < 0 \tag{5}$$

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, as it is once again in this case, a strategic substitute.

4 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.[1]

4.1 The farmer's behavior

When the tax and subsidy are implemented, the profit for farmer $i; \forall i = 1, 2, ..., n; i \neq j$ 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:

$$p_1 - c_1'(x_{1i}) - t - s - \lambda = 0 \tag{6}$$

$$p_2'\big(X_2\big)\frac{X_2}{n} + p_2\big(X_2\big) - c_2'(x_{2i}) - s - \lambda = 0 \tag{7}$$

$$\lambda(T_i - x_{1i} - x_{2i}) = 0 \tag{8}$$

Starting with the unbounded case ($\lambda = 0$), we can see how x_{1i} and x_{2i} change with changes in the values of s and t by applying the implicit function theorem on (6) and (7), using $F(x_{1i}, s, t) = p_1 - c_1'(x_{1i}) - t - s$ and $F(x_{2i}, s) = p_2'\big(X_2\big)x_{2i} + p_2\big(X_2\big) - c_2'(x_{2i}) - s$

$$\frac{\partial x_{1i}}{\partial s} = -\frac{\frac{\partial F}{\partial s}}{\frac{\partial F}{\partial x_{1i}}} = \frac{1}{p_1' - c_1''(x_{1i})} < 0$$

$$\frac{\partial x_{1i}}{\partial t} = -\frac{\frac{\partial F}{\partial t}}{\frac{\partial F}{\partial x_{1i}}} = \frac{1}{p_1' - c_1''(x_{1i})} < 0$$

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

[1] 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 subsidy equal to the marginal benefit of organic agriculture.

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

For the bounded case($\lambda > 0$), we set $x_{2i} = T_i - x_{1i}$ and we apply the implicit function theorem using $G(x_{1i}, t) = p_1 - c_1'(x_{1i}) - t - p_2'(T - X_1)(T_i - x_{1i}) - p_2(T - X_1) + c_2'(T_i - x_{1i})$.

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

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. Here, when $\lambda > 0$, 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.

4.2 Optimal tax and PES levels

We maximize the social welfare function to find the second-best levels of t and s for both the bounded and the unbounded scenarios. Starting with the unbounded scenario ($\lambda = 0$), the social welfare function is

$$\begin{aligned} \underset{s,t}{W}(X_1(s,t), X_2(s)) = &\int_0^{X_1(s,t)} p_1(u)du + \int_0^{X_2(s)} p_2(v)dv - nc_1\left(\frac{X_1(s,t)}{n}\right) \\ &- nc_2\left(\frac{X_2(s)}{n}\right) + B(T - X_1(s,t) - X_2(s)) - D(X_1(s,t)) \end{aligned} \tag{9}$$

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 $\frac{dX_2}{ds} < 0$, and $B_y = B'(y)$.

We can rearrange the profit maximization conditions, equations (6) and (7) 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 can 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:

$$s = B_y + p_2'(X_2)\frac{X_2}{n} \tag{16}$$

$$t = D'(X_1) - p_2'(X_2)\frac{X_2}{n} \tag{17}$$

We find that the second best subsidy is equal to the marginal benefit plus the marginal revenue, and since the marginal revenue is negative, the second best subsidy will have a value lower than the marginal benefit. Similarly, the second best tax will be equal to the marginal damage minus the marginal revenue, and thus will be higher than just the marginal damage alone. Production of the organic agriculture good is lower than optimal because of the market power involved. So, the tax becomes higher than the marginal damage and the subsidy lower than the marginal benefit in order to not further distort the level of organic agriculture that is produced.

As n increases and approaches infinity we approach the situation of perfect competition, since $\frac{X_2}{n}$ tends to zero as n tends to infinity. This then nullifies the additional component in the tax and the subsidy such that they are once again equal to the marginal damage and marginal benefit, respectively.

Next, we look at the bounded case ($\lambda > 0$), using $X_1 = T - X_2$ to account for the value of λ. The social welfare equation here is

$$\begin{aligned} \underset{t}{W(X_1(t), X_2(t))} = &\int_0^{T-X_2(t)} p_1(u)du + \int_0^{X_2(t)} p_2(v)dv - nc_1\left(\frac{T - X_2(t)}{n}\right) \\ &- nc_2\left(\frac{X_2(t)}{n}\right) + B\Big(T - (T - X_2(t)) - X_2(t)\Big) \\ &- D(T - X_2(t)) \end{aligned} \tag{18}$$

Maximizing this welfare equation yields the following first order condition:

$$\frac{dX_2}{dt}[-p_1(T - X_2) + p_2(X_2) + c_1'\left(\frac{T - X_2}{n}\right) - c_2'\left(\frac{X_2}{n}\right) + D'(T - X_2)] = 0 \tag{19}$$

Using the profit first order conditions (6) and (7), we find that

$$-p_1 + c_1'\left(\frac{T - X_2}{n}\right) + p_2(X_2) - c_2'\left(\frac{X_2}{n}\right) = -t - p_2'(X_2)\frac{X_2}{n} \tag{20}$$

Plugging (20) into (19) yields

$$t = D'(T - X_2) - p_2'(X_2)\frac{X_2}{n} \tag{21}$$

Similar to the unbounded case, the welfare-maximizing tax is equal to the marginal damage minus the marginal revenue. Since the marginal revenue is negative, the resulting tax is greater than the marginal damage. Depending on the value of λ, either a tax alone (when $\lambda > 0$), or a tax and a subsidy (when $\lambda = 0$) results in implementing the second best.

4.3 Marginal cost of public funds

The marginal 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). 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.

Laffont & Tirole (1986) and Caillaud et al. (1988) incorporate the social cost of public funds into their models investigating regulation in asymmetric information scenarios. More recently, Mougeot & Schwartz (2008) incorporate the MCF in their study of the optimal allocation of pollution quotas in an asymmetric information scenario. In their model, the regulator determines the pollution permit allocation, while taking into account a revenue target since each euro collected by the sale of permits results in $1 + \lambda$ euros in social benefit, where λ represents the MCF.

Brendemoen & Vennemo (1996) look at how the MCF changes in the presence of environmental externalities, and find that accounting for environmental externalities can alter the MCF of different taxes, and thus alter the ranking of efficiency of these taxes. If the MCF for an environmental taxes are in fact lower than the MCF of another tax, lowering the other tax will improve welfare (Brendemoen & Vennemo, 1996).

This improvement in welfare 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.

Below, we incorporate the MCF in both the tax on conventional agriculture and the PES for biodiversity. Using ϵ to represent the MCF, each euro in tax revenue will have $1 + \epsilon$ euros in social benefit, as the tax increases revenue and can replace other distortionary taxes. Conversely, the PES is funded by the government, and implementing a new subsidy means a requirement for additional government revenue through increased taxes, which will come at a cost to society. So, each euro allocated to the PES comes at a cost of $(1 + \epsilon)$ euros to society since it induces new distortionary taxes.

The welfare equation when $\lambda = 0$ and $y > 0$ now includes the terms $\epsilon t X_1$ and $\epsilon s(T - X_1 - X_2)$ to reflect the MCF:

$$
\begin{aligned}
W(X_1(s,t), X_2(s))_{s,t} = \int_0^{X_1(s,t)} p_1(u)du + \int_0^{X_2(s)} p_2(v)dv - nc_1\left(\frac{X_1(s,t)}{n}\right) \\
- nc_2\left(\frac{X_2(s)}{n}\right) + B(T - X_1(s,t) - X_2(s)) - D(X_1(s,t)) \\
+ \epsilon t X_1(s,t) - \epsilon s(T - X_1(s,t) - X_2(s))
\end{aligned} \tag{22}
$$

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

$$
\begin{aligned}
&\frac{\partial X_1}{\partial s}[p_1(X_1(s)) - c_1'\left(\frac{X_1(s)}{n}\right) - B_y - D'(X_1(s)) + \epsilon t + \epsilon s] \\
&+ \frac{dX_2}{ds}[p_2(X_2(s)) - c_2'\left(\frac{X_2(s)}{n}\right) - B_y + \epsilon s] - \epsilon(T - X_1(s) - X_2(s)) = 0
\end{aligned} \tag{23}
$$

$$
\frac{\partial X_1}{\partial t}[p_1(X_1(t)) - c_1'\left(\frac{X_1(t)}{n}\right) - B_y - D'(X_1(t)) + \epsilon t + \epsilon s] + \epsilon X_1(t) = 0 \tag{24}
$$

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

We can use (12) and (13) to obtain

$$
\begin{aligned}
&\frac{\partial X_1}{\partial s}[t(1+\epsilon) + s(1+\epsilon) - B_y - D'(X_1)] + \frac{dX_2}{ds}[-p_2'(X_2)\frac{X_2}{n} + s(1+\epsilon) - B_y] \\
&- \epsilon(T - X_1 - X_2) = 0
\end{aligned} \tag{25}
$$

$$
\frac{\partial X_1}{\partial t}[t(1+\epsilon) + s(1+\epsilon) - B_y - D'(X_1)] + \epsilon X_1 = 0 \tag{26}
$$

Solving (26) for t we find

$$
t = -s + \frac{B_y + D'(X_1)}{1+\epsilon} - \frac{\epsilon}{1+\epsilon}\frac{X_1}{\frac{\partial X_1}{\partial t}} \tag{27}
$$

Plugging (27) into (25)

$$
\frac{\partial X_1}{\partial s}\left[\frac{\epsilon X_1}{\frac{\partial X_1}{\partial t}}\right] + \frac{dX_2}{ds}\left[-p_2'(X_2)\frac{X_2}{n} + s(1+\epsilon) - B_y\right] - \epsilon(T - X_1 - X_2) = 0 \tag{28}
$$

Solving this equation for s we find:

$$
s = \frac{B_y + p_2'(X_2)\frac{X_2}{n}}{1+\epsilon} + \frac{\epsilon}{1+\epsilon}\left[\frac{T - X_1 - X_2}{\frac{dX_2}{ds}}\right] + \frac{\epsilon}{1+\epsilon}X_1\left[\frac{\frac{\partial X_1}{\partial s}}{\frac{dX_2}{ds}\frac{\partial X_1}{\partial t}}\right] \tag{29}
$$

Using this value of s we can solve (27) for t

$$
t = \frac{D'(X_1) - p_2'(X_2)\frac{X_2}{n}}{1+\epsilon} - \frac{\epsilon}{1+\epsilon}\left[\frac{\frac{\partial X_1}{\partial s}X_1}{\frac{dX_2}{ds}\frac{\partial X_1}{\partial t}} + \frac{T - X_1 - X_2}{\frac{dX_2}{ds}} + \frac{X_1}{\frac{\partial X_1}{\partial t}}\right] \tag{30}
$$

To see how the level of subsidy and tax change with changes in MCF, we solve (9) for first order conditions, using $X_1(s(\epsilon), t(\epsilon))$ and $X_2(s(\epsilon))$. We find the following (see Appendix B for full calculations):

$\frac{ds}{d\epsilon} < 0$ 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 $e_{X_1/t} > -1$. In other words, an increase in MCF will lead to a decrease in the second best PES if demand for X_1 is inelastic with respect to the tax. As the MCF increases, the PES becomes more expensive, which requires higher taxes to increase revenue to pay for it. With inelastic demand for the conventional agriculture good, the increased tax will not change conventional agriculture production by a large amount, which allows for the required increase in revenue. However, the amount of land available to set aside for biodiversity benefits is lower since the amount of land producing the conventional agriculture good will not change much with an increase in the tax due to its inelasticity of demand.

For the tax, we find that $\frac{dt}{d\epsilon} > 0$ if $e_{X_1/t} > -1$ and $\frac{\partial X_1}{\partial t}/\frac{\partial X_2}{\partial s} > z/q$ where

$$z = p_2'(X_2(s(\epsilon))) - \frac{1}{n}c_2''\Big(\frac{X_2(s(\epsilon))}{n}\Big)$$

$$q = p_1'(X_1(t(\epsilon), s(\epsilon))) - \frac{1}{n}c_1''\Big(\frac{X_1(t(\epsilon), s(\epsilon))}{n}\Big) - D''(X_1(t(\epsilon), s(\epsilon)))$$

So, an increase in MCF leads to an increase in the second best tax when demand for X_1 is inelastic and when $\frac{\partial X_1}{\partial t}/\frac{\partial X_2}{\partial s} > z/q$. In other words, the ratio of the change in conventional agriculture production with respect to the tax and the change in organic agriculture production in response to the PES must be above a certain threshold, represented by z/q.

The condition of having an inelastic demand in response to the tax means that instead of discouraging the polluting behavior, the tax functions to raise revenue, as an increase in the tax does not have a large impact on the amount of land a farmer puts into production of the polluting conventional agricultural good. Typically, we would prefer an environmental tax to discourage the damaging action and thus bring in less revenue but succeed in reducing pollution.

For the case where $\lambda > 0$, we have the following welfare function:

$$\begin{aligned} W(T - \underset{t}{X_2}(t), X_2(t)) = &\int_0^{T-X_2(t)} p_1(u)du + \int_0^{X_2(t)} p_2(v)dv - nc_1\left(\frac{T - X_2(t)}{n}\right) \\ &- nc_2\left(\frac{X_2(t)}{n}\right) + B\Big(T - (T - X_2(t)) - X_2(t)\Big) \\ &- D(T - X_2(t)) + \epsilon t X_1(t) - \epsilon s(T - (T - X_2(t)) - X_2(t)) \end{aligned} \tag{31}$$

Maximizing welfare yields the following first order condition:

$$\frac{dX_2}{dt}[-p_1(T - X_2) + p_2(X_2) + c_1'(\frac{T - X_2}{n}) - c_2'(\frac{X_2}{n}) + D'(T - X_2) - \epsilon t] + \epsilon(T - X_2) = 0 \tag{32}$$

Using equations (6) and (7) from the profit maximization, we have

$$-p_1 + c_1'(X_1) + p_2(X_2) - c_2'(X_2) = -t - p_2'(X_2)\frac{X_2}{n} \tag{33}$$

We can then write equation (32) as

$$\frac{dX_2}{dt}\Big[-t - p_2'(X_2)\frac{X_2}{n} + D'(T - X_2) - \epsilon t\Big] + \epsilon(T - X_2) = 0 \tag{34}$$

Then, we solve equation (34) and find

$$t = \frac{D'(T - X_2) - p_2'(X_2)\frac{X_2}{n}}{1+\epsilon} + \frac{\epsilon}{1+\epsilon}\left(\frac{T - X_2}{\frac{dX_2}{dt}}\right) \tag{35}$$

Without the MCF, the tax is the same in both scenarios, but once the MCF is introduced, the tax in the $\lambda = 0$ scenario is different from the tax in the $\lambda > 0$ scenario.

As in the preceding case, here the tax is affected by the MCF. To see how t changes with a change in ϵ, we apply the implicit function theorem on (32), which we will call J:

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

We know that the denominator of the above expression is negative. If $\frac{dt}{d\epsilon} > 0$, then

$$\frac{dX_1}{dt}t + X_1 > 0$$

$$\frac{dX_1}{dt}\frac{t}{X_1} + 1 > 0$$

$$\frac{dX_1}{dt}\frac{t}{X_1} > -1$$

Here, the relationship between the tax and MCF is positive when the demand for the conventional agriculture good is inelastic, just as in the case where $\lambda = 0$.

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.

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

We construct the Hessian matrix, $I(W)$:

$$I(W) = \begin{bmatrix} \frac{\partial^2 X_1}{\partial s^2}[F] + (\frac{\partial X_1}{\partial s})^2[F'] + \frac{d^2 X_2}{ds^2}[G] + (\frac{dX_2}{ds})^2[G'] & \frac{\partial^2 X_1}{\partial s \partial t}[F] + \frac{\partial X_1}{\partial s}\frac{\partial X_1}{\partial t}[F'] \\ \frac{\partial^2 X_1}{\partial s \partial t}[F] + \frac{\partial X_1}{\partial s}\frac{\partial X_1}{\partial t}[F'] & \frac{\partial^2 X_1}{\partial t^2}[F] + (\frac{\partial X_1}{\partial t})^2[F] \end{bmatrix} \tag{36}$$

where

$$F = p_1(X_1) - c_1'(\frac{X_1}{n}) - B_y - D'(X_1)$$

$$F' = p_1'(X_1) - \frac{1}{n}c_1''(\frac{X_1}{n}) + B_{yy} - D''(X_1)$$

$$G = p_2(X_2) - c_2'(\frac{X_2}{n}) - B_y$$

$$G' = p_2'(X_2) - \frac{1}{n}c_2''(\frac{X_2}{n}) + B_{yy}$$

Following our assumptions about demand and cost structures, we can simplify (36) to

$$I(W) = \begin{bmatrix} (\frac{\partial X_1}{\partial s})^2[F'] + (\frac{dX_2}{ds})^2[G'] & \frac{\partial X_1}{\partial s}\frac{\partial X_1}{\partial t}[F'] \\ \frac{\partial X_1}{\partial s}\frac{\partial X_1}{\partial t}[F'] & (\frac{\partial X_1}{\partial t})^2[F'] \end{bmatrix} \tag{37}$$

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

$$Det(I) = \left[\left[(\frac{\partial X_1}{\partial s})^2[F'] + (\frac{dX_2}{ds})^2[G']\right] * (\frac{\partial X_1}{\partial t})^2[F']\right] - \left[\frac{\partial X_1}{\partial s}\frac{\partial X_1}{\partial t}[F'] * \frac{\partial X_1}{\partial s}\frac{\partial X_1}{\partial t}[F']\right] \tag{38}$$

We can simplify (38) to:

$$Det(I) = (\frac{dX_2}{ds})^2[G'](\frac{\partial X_1}{\partial t})^2[F'] > 0 \tag{39}$$

Thus, we have a concave welfare function for oligopoly, 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 (19):

$$\begin{aligned} \frac{d^2 W}{dt^2} &= \frac{d^2 X_1}{dt^2}[p_1(X_1) - p_2(T - X_1) - c_1'(\frac{X_1}{n}) + c_2(\frac{T - X_1}{n}) - D'(X_1)] \\ &+ (\frac{dX_1}{dt})^2[p_1'(X_1) + p_2'(T - X_1) - \frac{1}{n}c_1''(\frac{X_1}{n}) - \frac{1}{n}c_2''(\frac{T - X_1}{n}) - D''(X_1)] \end{aligned} \tag{40}$$

We assume $\frac{d^2 X_1}{dt^2} = 0$ and $c_i''' = 0$, such that we now have

$$(\frac{dX_1}{dt})^2\left[p_1'(X_1) + p_2'(T - X_1) - \frac{1}{n}c_1''(\frac{X_1}{n}) - \frac{1}{n}c_2''(\frac{T - X_1}{n}) - D''(X_1)\right] < 0 \tag{41}$$

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

A.1 Marginal cost of public funds

Starting with the case where $\lambda = 0$, we use (23) and (24) to create the Hessian:

$$H = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \tag{42}$$

Where

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

$$b = \frac{\partial^2 X_1}{\partial s \partial t}[A + \epsilon(t+s)] + \frac{\partial X_1}{\partial t}\frac{\partial X_1}{\partial s}[A'] + \epsilon[\frac{\partial X_1}{\partial s} + \frac{\partial X_1}{\partial t}]$$

$$c = \frac{\partial^2 X_1}{\partial t \partial s}[A + \epsilon(t+s)] + \frac{\partial X_1}{\partial t}\frac{\partial X_1}{\partial s}[A'] + \epsilon[\frac{\partial X_1}{\partial s} + \frac{\partial X_1}{\partial t}]$$

$$d = \frac{\partial^2 X_1}{\partial t^2}[A + \epsilon(t+s)] + (\frac{\partial X_1}{\partial t})^2[A'] + 2\epsilon\frac{\partial X_1}{\partial t}$$

and

$$A = p_1(X_1) - c_1'(\frac{X_1}{n}) - B_y - D'(X_1)$$

$$B = p_2(X_2) - c_2'(\frac{X_2}{n}) - B_y$$

$$A' = p_1'(X_1) - \frac{1}{n}c_1''(\frac{X_1}{n}) + B_{yy} - D''(X_1)$$

$$B' = p_2'(X_2) - \frac{1}{n}c_2''(\frac{X_2}{n}) + B_{yy}$$

Thanks to our assumptions, we can simplify the Hessian to

$$H = \begin{bmatrix} (\frac{\partial X_1}{\partial s})^2[A'] + [\frac{dX_2}{ds}]^2[B'] + 2\epsilon(\frac{\partial X_1}{\partial s} + \frac{dX_2}{ds}) & (\frac{\partial X_1}{\partial t})^2[A'] + 2\epsilon(\frac{\partial X_1}{\partial t}) \\ (\frac{\partial X_1}{\partial t})^2[A'] + 2\epsilon(\frac{\partial X_1}{\partial t}) & (\frac{\partial X_1}{\partial t})^2[A'] + 2\epsilon\frac{\partial X_1}{\partial t} \end{bmatrix} \tag{43}$$

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

simplifying:

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

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.

For the case where $\lambda > 0$, we refer to (32):

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

where

$$E = p_1(X_1) - p_2(T - X_1) - c_1'\left(\frac{X_1}{n}\right) + c_2'\left(\frac{T - X_1}{n}\right) - D'(X_1)$$

and

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

With our assumptions we can simplify this to:

$$\frac{d^2W}{dt^2} = \left(\frac{dX_1}{dt}\right)^2 [E'] + 2\epsilon\frac{dX_1}{dt} < 0 \tag{44}$$

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

B How the tax and PES change with the MCF

We know from section 4.3 that the levels of tax and PES depend on the marginal cost of public funds, ϵ, so the tax and PES must satisfy conditions (23) and (24).

We set:

$$q = p_1'(X_1(t(\epsilon), s(\epsilon))) - \frac{1}{n}c_1''\Big(\frac{X_1(t(\epsilon), s(\epsilon))}{n}\Big) - D''(X_1(t(\epsilon), s(\epsilon))) < 0$$

$$z = p_2'(X_2(s(\epsilon))) - \frac{1}{n}c_2''\Big(\frac{X_2(s(\epsilon))}{n}\Big) < 0$$

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

Next, we differentiate (23) and (24) by ϵ and rearrange the equations into matrix form:

$$\begin{bmatrix} i & j \\ k & l \end{bmatrix} \begin{bmatrix} \frac{ds}{d\epsilon} \\ \frac{dt}{d\epsilon} \end{bmatrix} = \begin{bmatrix} -\frac{\partial X_1}{\partial s}[t + s] - \frac{\partial X_2}{\partial s}s + (T - X1 - X2) \\ -\frac{\partial X_1}{\partial t}(t + s) - X_1 \end{bmatrix} \tag{45}$$

where

$$i = \frac{\partial X_1}{\partial s}[(q + B_{yy})\frac{\partial X_1}{\partial s} + 2\epsilon + B_{yy}\frac{\partial X_2}{\partial s}] + \frac{\partial X_2}{\partial s}[(z + B_{yy})\frac{\partial X_2}{\partial s} + B_{yy}\frac{\partial X_1}{\partial s} + 2\epsilon]$$

$$j = \frac{\partial X_1}{\partial s}[(q + B_{yy})\frac{\partial X_1}{\partial t} + 2\epsilon + B_{yy}\frac{\partial X_2}{\partial s}]$$

$$k = \frac{\partial X_1}{\partial t}[(q + B_{yy})\frac{\partial X_1}{\partial s} + B_{yy}\frac{\partial X_2}{\partial s} + 2\epsilon]$$

$$l = \frac{\partial X_1}{\partial t}[(q + B_{yy})\frac{\partial X_1}{\partial t} + 2\epsilon]$$

Next, we multiply each side of the equation by the inverse of $\begin{bmatrix} i & j \\ k & l \end{bmatrix}$ to find $\frac{ds}{d\epsilon}$ and $\frac{dt}{d\epsilon}$

$$\begin{bmatrix} \frac{ds}{d\epsilon} \\ \frac{dt}{d\epsilon} \end{bmatrix} = \begin{bmatrix} i & j \\ k & l \end{bmatrix}^{-1} \begin{bmatrix} -\frac{\partial X_1}{\partial s}[t+s] - \frac{\partial X_2}{\partial s}s + (T - X_1 - X_2) \\ -\frac{\partial X_1}{\partial t}(t+s) - X_1 \end{bmatrix} \tag{46}$$

where

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

Calculating the determinant of $\begin{bmatrix} i & j \\ k & l \end{bmatrix}$ we find:

$$\begin{aligned} Det =& \Big\{ \frac{\partial X_1}{\partial t}[(q + B_{yy})\frac{\partial X_1}{\partial t} + 2\epsilon] \Big\} \Big\{ \frac{\partial X_1}{\partial s}[(q + B_{yy})\frac{\partial X_1}{\partial s} + 2\epsilon + B_{yy}\frac{\partial X_2}{\partial s}] \\ &+ \frac{\partial X_2}{\partial s}[(z + B_{yy})\frac{\partial X_2}{\partial s} + B_{yy}\frac{\partial X_1}{\partial s} + 2\epsilon] \Big\} - \Big[- \frac{\partial X_1}{\partial s}[(q + B_{yy})\frac{\partial X_1}{\partial t} + 2\epsilon + B_{yy}\frac{\partial X_2}{\partial s}] \Big]^2 \end{aligned} \tag{47}$$

$$\begin{aligned} Det =& \frac{\partial X_1}{\partial t}^2 \frac{\partial X_2}{\partial s}^2 qz + \frac{\partial X_1}{\partial t}^2 \frac{\partial X_2}{\partial s}^2 qB_{yy} + \frac{\partial X_1}{\partial t}^2 \frac{\partial X_2}{\partial s}^2 zB_{yy} + 2\frac{\partial X_1}{\partial t}^2 \frac{\partial X_2}{\partial s} q\epsilon + 2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 z\epsilon \\ &+ 2\frac{\partial X_1}{\partial t}^2 \frac{\partial x_2}{\partial s} B_{yy}\epsilon + 2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2 B_{yy}\epsilon + 4\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}\epsilon^2 > 0 \end{aligned} \tag{48}$$

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 can now calculate $\frac{ds}{d\epsilon}$ using (46):

$$\begin{aligned} \frac{\partial s}{\partial \epsilon} =& \frac{1}{\det}\Big\{ [\frac{\partial X_1}{\partial t}[(q + B_{yy})\frac{\partial X_1}{\partial t} + 2\epsilon] \Big\} \Big\{ - \frac{\partial X_1}{\partial s}[t+s] - \frac{\partial X_2}{\partial s}s + (T - X_1 - X_2) \Big\} \\ &+ \frac{1}{\det}\Big\{ - \frac{\partial X_1}{\partial s}[(q + B_{yy})\frac{\partial X_1}{\partial t} + 2\epsilon + B_{yy}\frac{\partial X_2}{\partial s}] \Big\} \Big\{ - \frac{\partial X_1}{\partial t}(t+s) - X_1 \Big\} \end{aligned} \tag{49}$$

$$\begin{aligned} \frac{\partial s}{\partial \epsilon} =& \frac{1}{\det}\Big\{ - \frac{\partial X_1}{\partial t}^2 \frac{\partial X_2}{\partial s} qs + \frac{\partial X_1}{\partial t}^2 q(T - X_2) + \underbrace{\frac{\partial X_1}{\partial t}^2 \frac{\partial X_2}{\partial s} tB_{yy}}_{>0} + \frac{\partial X_1}{\partial t}^2 B_{yy}(T - X_2) \\ &+ \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s} X_1 B_{yy} - 2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s} s\epsilon + 2\frac{\partial X_1}{\partial t}\epsilon(T - X_2) \Big\} \end{aligned} \tag{50}$$

$\frac{\partial s}{\partial \epsilon} < 0$ if

$$\frac{\partial X_1}{\partial t}^2 \frac{\partial X_2}{\partial s} tB_{yy} + \frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s} X_1 B_{yy} < 0 \Leftrightarrow \frac{\partial X_1}{\partial t}\frac{\partial x_2}{\partial s} B_{yy}[\frac{\partial X_1}{\partial t}t + X_1] < 0 \tag{51}$$

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 $e_{X_1/t} > -1$.

Next, looking at the tax we find:

$$
\begin{aligned}
\frac{\partial t}{\partial \epsilon} =& \frac{1}{\det}\Big\{\frac{\partial X_1}{\partial t}\big[(q+B_{yy})\frac{\partial X_1}{\partial s}+B_{yy}\frac{\partial X_2}{\partial s}+2\epsilon\big]\big[-\frac{\partial X_1}{\partial s}(t+s)-\frac{\partial X_2}{\partial s}s+(T-X_1-X_2)\big] \\
&+\big[\frac{\partial X_1}{\partial s}[(q+B_{yy})\frac{\partial X_1}{\partial s}+2\epsilon+B_{yy}\frac{\partial X_2}{\partial s}]+\frac{\partial X_2}{\partial s}[(z+B_{yy})\frac{\partial X_2}{\partial s}+B_{yy}\frac{\partial X_1}{\partial s}+2\epsilon]\big] \\
&\big[-\frac{\partial X_1}{\partial t}(t+s)-X_1\big]\Big\}
\end{aligned}
\tag{52}
$$

$$
\begin{aligned}
\frac{\partial t}{\partial \epsilon} =& \frac{1}{\det}\Big\{\frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s}qs-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2zs-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2zt-\frac{\partial X_1}{\partial t}^2qT-\frac{\partial X_2}{\partial s}^2zx_1+\frac{\partial X_1}{\partial t}^2qx_2 \\
&-\frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s}tB_{yy}-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2tB_{yy}-\frac{\partial X_1}{\partial t}^2TB_{yy}-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}TB_{yy}-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}X_1B_{yy} \\
&-\frac{\partial X_2}{\partial s}^2X_1B_{yy}+\frac{\partial X_1}{\partial t}^2X_2B_{yy}+\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}X_2B_{yy}-2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}t\epsilon-2\frac{\partial X_1}{\partial t}T\epsilon \\
&-2\frac{\partial X_2}{\partial s}X_1\epsilon+2\frac{\partial X_1}{\partial t}X_2\epsilon\Big\}
\end{aligned}
\tag{53}
$$

$$
\begin{aligned}
\frac{\partial t}{\partial \epsilon} =& \frac{1}{\det}\Big\{\frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s}qs-\frac{\partial X_1}{\partial t}^2q(T-X_2)-\frac{\partial X_1}{\partial t}^2B_{yy}(T-X_2)-2\frac{\partial X_1}{\partial t}\epsilon(T-X_2) \\
&-\frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s}tB_{yy}-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}X_1B_{yy}-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2zs-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2zt \\
&-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}B_{yy}(T-X_2)-\frac{\partial X_2}{\partial s}^2X_1B_{yy}-2\frac{\partial X_2}{\partial s}X_1\epsilon-\frac{\partial X_2}{\partial s}^2zX_1-2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}t\epsilon \\
&-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}^2tB_{yy}\Big\}
\end{aligned}
\tag{54}
$$

We know that

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

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

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