Are Additional Payments for Environmental Services Efficient?*

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Abstract

The implementation of PES may face a financing constraint, especially when the buyer is a public regulator. An additional PES can address this problem. The objective of this paper is to study the efficiency of additional PES. To do so, we consider a farmer who has to choose to allocate his land between organic production, conventional production, or biodiversity-generating grass strips. Using a two-period model, we introduce a PES in the final period, remunerating the additional grass strips provided by the farmer. We show that the additional PES distorts the behavior in the initial period, in order to obtain more payment in the final period. The second-order PES to limit this behavior is equal to the discounted difference of the marginal environmental benefits obtained in each period. We also establish the value of environmental taxes in the presence of the additionality-based PES. They are no longer equal to the marginal damage and are amended to take into account the distortions caused by the additionality-based PES. The analysis is then extended by taking into account market power in the organic market. It turns out that this market power reduces the distortion due to the additionality-based PES in the initial period.

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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). 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 action-based PES schemes conditional on land use or specific management practices.

One major factor in the economic efficiency of PES programs is whether or not they are 'additional'; that is, they lead to the provision of an environmental service that would not have occurred in the absence of any payment. Early on in PES development, a majority of programs had no additionality requirement, possibly due to the idea that monitoring additionality would prove to be too costly (Bennett, 2010). Or, as in the case of the national program in Costa Rica, the aim may be to recognize and remunerate any environmental service provision regardless of its additionality (Bennett, 2010). It is only more recently that evaluating the additionality of PES programs has become a concern, even though doing so is essential for a PES scheme to achieve its environmental target with economic efficiency while maintaining investor confidence (Bennett, 2010).

Wunder (2005) explains that establishing a baseline level of ES is essential in order to assess the additionality of a PES program and thus to avoid paying for ES that would have been provided without the program, leading to windfall gains for the ES seller, and a lost opportunity to pay for environmental services where they would be additional. However, since establishing the baseline level of ES can be be costly, a regulator or other ES buyer may rely on the ES seller to report this information. When payments are based on additionality, this gives the ES seller incentive to under-report their current level of ES provision in order to earn payments for more units of ES provision, which is an example of moral hazard.

When the purchaser of a PES is a public regulator, the issue of additionality is even more important as it prevents wasting public funds. The objective of this paper is to analyze the effectiveness of additional PES in achieving optimal levels of environmental benefits. To do so, we consider a farmer who has to choose to allocate his land between organic production, conventional production, or biodiversity-generating grass strips. Using a two-period model, we introduce a PES in the final period remunerating the grass strips chosen by the farmer. We show that the PES based on additionality distorts the behavior in the initial period, in order to obtain more payment in the final period. The second-order PES that takes into account the distortion due to the additionality condition has to be based on the discounted difference of the marginal environmental benefits obtained in each period. We also establish the second-best level of environmental taxes in the presence of the additionality-based PES.

They are no longer equal to the marginal damage and are amended to take into account the distortions caused by the additionality-based PES. The analysis is then extended by taking into account market power in the organic market. In fact, data about the distribution of organic farming in France has shown that the development of organic agriculture can be very heterogeneous across a territory (Nguyen-Van et al., 2021). For instance, out of 34259 municipalities in metropolitan France (excluding overseas territories) with at least one farmer, only 418 (1.2%) are 100% organic, and 52.4% of municipalities do not have an organic farmer.[1] The non-uniform distribution of organic farming across the country and transport constraints for organic products can limit competition in the organic product market, resulting in local markets for organic farming where some producers have market power. It turns out that this market power reduces the distortion due to the additionality-based PES in the initial period.

This article is structured as follows. Section 2 provides a review of the literature on additionality in PES schemes. In Section 3 we specify the assumptions of our model and analyze a benchmark and first-best scenario. Next, Section 4 examines the policy levels of a PES and tax and their resulting production levels, assuming perfect competition. In Section 5 we introduce imperfect competition in the organic sector. Finally, Section 6 concludes.

2 Literature review

Sills et al. (2008) describe four challenges to achieving additionality, namely adverse selection, spillovers or leakage, moral hazard, and the possibility that even if there is additionality of a certain land use that is thought to provide certain services, these services may not be additional. Adverse selection occurs when there is hidden information, i.e. the costs that an ES seller faces. Because the ES buyer does not have this information, the ES seller has incentive to say they have higher costs in order to receive a larger payment. Spillover effects or leakage may occur when preserving some plots of forest leads to increased timber prices, which may incentivize the deforestation of other plots not subject to a PES scheme. Moral hazard, or hidden behavior, occurs when the prospect of a PES scheme getting implemented leads to an ES seller altering their baseline behavior in order to get a higher payment when the PES is in place.

Determining the baseline ES provision for many individual sellers can be quite costly, and Kaczan et al. (2017) look at the possibility of using collective PES schemes to lower this cost. They use a framed field-laboratory experiment with participants from a PES scheme in Mexico and study the impact of conditioning PES payments on an aggregate outcome on group participation and coordination. They found that it was easier to determine baseline and program outcomes for a collective group than for an individual and thus easier to write contracts with additional outcomes. Furthermore, when the PES payments are conditioned on a group's additionality they find that lower contributors raised their contributions.

Additionality is of utmost importance in carbon offset markets and other carbon sequestration PES schemes. Those paying for carbon offset credits risk paying forest managers to protect forest area that would have remained intact in absence of their payments. Moreover, leakage of the deforestation activities may occur if a forest PES leads to market conditions making it more profitable for forest managers in other regions to cut down more trees, thus

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

leading to a displacement of carbon emissions rather than a net increase in carbon sequestration. Since the objective behind carbon offsets is generally to achieve net zero carbon emissions in order to limit global climate change, the additionality of such a program is crucial.

Mason & Plantinga (2013) look into the additionality of conservation contracts, by examining contracts for carbon sequestration from land placed in forest use that serve as offsets to meet emissions reduction goals. In this case, additionality is key to ensuring a reduction in carbon emissions. A government or business seeking to purchase offsets to reduce their emissions will want to minimize expenditures, so paying for forests that would remain without a payment would be wasteful. The authors argue there is an adverse selection problem, as only the agent knows how much land would be placed in forest absent any payment. They propose offering a menu of contracts to induce agents to reveal their type (in terms of high vs. low opportunity cost of placing land in forest). While not a perfect solution, the menu of contracts allows for a reduction in government expenditure compared to a uniform payment. Similarly, Chiroleu-Assouline et al. (2018) undertake a theoretical analysis of additionality of REDD+ contracts, which are made between developed and developing countries with the aim of reducing carbon emissions from deforestation and degradation. Using a principal-agent model, they show that dividing developing countries into two groups based on two different policy instruments can help the developed country obtain efficient deforestation and avoided deforestation levels from their payments.

Pates & Hendricks (2020) frame non-additionality as a moral hazard problem in a technology diffusion context. They look at the case where a new and more environmentally friendly technology becomes less expensive to adopt over time, and whose adoption might be subsidized. They argue that an agent may delay adoption of the technology in order to earn a payment for adoption in a future time period, which is an example of moral hazard since the agent changes his behavior in response to the policy. After developing a conceptual model, the authors run numerical simulations and find that the moral hazard results in a non-monotonic relationship between different policy parameters (e.g. budget or payment size) and the change in technology adoption rates linked to the PES policy (Pates & Hendricks, 2020). Furthermore, they find that the cost-effectiveness of such a policy is lower when the policy is introduced at a time of rapid technology adoption.

Others have investigated the empirical evidence of additionality in PES schemes with mixed results. For example, Chabé-Ferret & Subervie (2013) study five agro-environment schemes (AES) implemented in France to estimate their additional and windfall effects. They find different levels of additionality for the different AES, with the more stringent requirements leading to higher additionality. Mezzatesta et al. (2013) use propensity score matching to evaluate the additionality of the Conservation Reserve Program in the US in regard to six conservation practices: conservation tillage, cover crops, hayfield establishment, grid sampling, grass waterways, and filter strips. Based on survey data of farmers in the state of Ohio, they calculate the average treatment effect on the treated (ATT), which they define as the average increase in the proportion of the land adopted in a conservation practice for enrolled farmers relative to their counterfactual proportion of the land in this practice that they would have adopted without funding (Mezzatesta et al., 2013). The authors find that while the overall ATT of the program is positive and statistically significant for each of the conservation practices, the degree of additionality varies across the practices, with hayfield establishment having the highest additionality and conservation tillage the lowest. Jones et al. (2020) look at the additionality of a PES in terms of forest cover and subsequent effects on hydrological services and find that the PES reduces losses but does not provide many gains in forest cover. Furthermore, they find that a lack of additionality in forest cover due to the PES results in economic loss. Finally, Mohebalian & Aguilar (2016) use GIS data to investigate the additionality of a forest PES program in Ecuador and their findings suggest that the PES program has provided little additionality in terms of preventing deforestation.

3 The model

In this section, we start by stating the assumptions of our model. Next, we analyze the benchmark situation with no regulation in place. Finally, we investigate the first best regulation.

3.1 Assumptions

In order to analyze the additionality issue, we construct a model with two periods, $t = 0, 1$. We use β to denote the discount factor. In each period, a representative farmer has three choices for how to manage his land: a conventional crop (x_1^t), an organic crop (x_2^t), and leaving grass strips (y^t), for $t = 1, 2$. He decides how much of his land to allocate to each management option such that $x_1^t + x_2^t + y^t = T$ where T is the total area of land in each period. We assume that producing x_i^t units requires x_i^t units of land, $\forall i, \forall t$.

Each farmer behaves as a price taker in both markets in each time period but we relax this assumption in Section 5, where we will consider market power on the organic crop market. The farmer faces production costs, which are assumed to be higher for the organic crop than the conventional crop, $c_1(x_1^t) < c_2(x_2^t)$. Both cost functions, $c_1(x_1^t)$ and $c_2(x_2^t)$, are increasing, convex and quadratic in form, with $c_i'(x_i^t) > 0$ and $c_i''(x_i^t) > 0$, $\forall i = 1, 2$. Regarding the grass strips, y^t, the only costs incurred are the foregone profits from not producing. Finally, the inverse demand function for each agricultural product is given by $p_1^t(x_1^t)$ and $p_2^t(x_2^t)$ for conventional and organic agriculture, respectively. Demand is linear for both agricultural goods, $p_i^{t\prime}(x_i^t) < 0$, $p_i^{t\prime\prime}(x_i^t) = 0$, $\forall i, \forall t$.

The different land management options all have different environmental impacts. Conventional agriculture causes pollution, represented by the damage function $D(x_1^t)$ which is increasing and convex, $D'(x_1^t) > 0, D''(x_1^t) > 0$. We assume that organic agriculture does not lead to pollution, nor does it increase biodiversity, so it has a neutral impact on the environment. Finally, the grass strips lead to biodiversity benefits, and thus has a positive impact on the environment. The benefit function is represented by $BF^1(y^0, y^1) = \psi(y^0)^t B(y^1)$, with $B'(y^t) > 0$ and $B''(y^t) < 0$, and $\psi'(y^0) > 0$. This function means that the environmental benefit in the final period depends on the biodiversity level obtained in initial period. We normalize $BF^0(y^0) = B(y^0)$. We assume that the farmer always chooses a positive level of grass strips, i.e., $y^t > 0$.

3.2 The benchmark: No regulation

In this section, we analyze the laissez-faire situation, i.e., when there is no environmental policy. As there are two periods with no link between them, we can directly maximize the intertemporal profit:

$$\pi(\bar{x}_1^0, \bar{x}_2^0, \bar{x}_1^1, \bar{x}_2^1) = p_1^0\bar{x}_1^0 + p_2^0\bar{x}_2^0 - c_1(\bar{x}_1^0) - c_2(\bar{x}_2^0) + \beta\{p_1^1\bar{x}_1^1 + p_2^1\bar{x}_2^1 - c_1(\bar{x}_1^1) - c_2(\bar{x}_2^1)\} \quad (1)$$

Maximizing this function yields typical first order conditions that price should equal marginal cost for $x_i^t, \forall i, \forall t$:

$$p_i^t - c_i'(\bar{x_i^t}) = 0 \; \forall i, \forall t$$

In each case the quantities of conventional and organic agriculture production are such that the price is equal to the private marginal costs. This equilibrium is not efficient because environmental externalities are not taken into account.

3.3 First-best regulation

In this section, we consider a social planner who decides on first-best quantities for each production. He maximizes social welfare, taking into account the farmer's profits, consumer surplus, and environmental damages and benefits.

$$W(x_1^0, x_2^0, x_1^1, x_2^1) = \int_0^{x_1^0} p_1^0(u)du + \int_0^{x_2^0} p_2^0(v)dv - c_1(x_1^0) - c_2(x_2^0) + B(T - x_1^0 - x_2^0) - D(x_1^0)$$

$$+ \beta\Big\{ \int_0^{x_1^1} p_1^1(w)dw + \int_0^{x_2^1} p_2^1(z)dz - c_1(x_1^1) - c_2(x_2^1) + \psi(y^0)B(T - x_1^1 - x_2^1) - D(x_1^1)\Big\}$$

Taking the first order conditions we obtain:

$$\frac{\partial W}{\partial x_1^0} = p_1^0(x_1^{0*}) - c_1'(x_1^{0*}) - B_{y^{0*}} - \beta\psi'(y^{0*})B(y^{1*}) - D'(x_1^{0*}) = 0 \qquad (2)$$

$$\frac{\partial W}{\partial x_2^0} = p_2^0(x_2^{0*}) - c_2'(x_2^{0*}) - B_{y^{0*}} - \beta\psi'(y^{0*})B(y^{1*}) = 0 \qquad (3)$$

$$\frac{\partial W}{\partial x_1^1} = \beta\big[p_1^1(x_1^{1*}) - c_1'(x_1^{1*}) - \psi(y^{0*})B_{y^{1*}} - D'(x_1^{1*})\big] = 0 \qquad (4)$$

$$\frac{\partial W}{\partial x_2^1} = \beta\big[p_2^1(x_2^{1*}) - c_2'(x_2^{1*}) - \psi(y^{0*})B_{y^{1*}}\big] = 0 \qquad (5)$$

In the first-best scenario, the optimal allocations of conventional agriculture in both time periods occur taking into account marginal cost of production, the marginal biodiversity benefit and marginal damage. Similarly, the optimal organic production quantity in each time period is based on marginal cost and marginal biodiversity benefits. As the level of biodiversity achieved in period 0 positively affects the biodiversity of period 1, it appears that the decision to create grass strips in the initial period generates a marginal biodiversity benefit in both periods, given by $[B_{y^0} + \beta\psi'(y^0)B(y^1)]$.

Comparing the first-best equations and the benchmark, we easily identify first-best environmental policy in each period: $t = D'(x_1^{0*}); t^1 = D'(x_1^{1*}); s = B_{y^o} + \beta\psi'(y^{0*})B(y^{1*}); s^1 = \psi(y^{0*})B_{y^{1*}}$ The first-best allocation must therefore be established by setting environmental taxes and a PES in each period. Each environmental tax should correspond to the environmental damage and each PES to the full marginal benefit. However, the budgetary constraint may lead the regulator to integrate the principle of additionality in the PES, by remunerating only the environmental benefits induced by the PES.

4 Additionality and perfect competition

We assume a regulator wishes to implement the principle of additionality in the remuneration of the PES. We introduce the PES in the final period remunerating the additional environmental benefits generated by the PES between the initial and final period. The regulator introduces an environmental tax t^t on conventional production to correct for the environmental damages in each period. In order to investigate the efficiency of a PES based on additionality, we first analyze the farmer's behavior with environmental policies. Then we identify the second-best level of the environmental tax in each period and of the PES based on additionality.

4.1 Strategic behaviors

In the initial period, the regulator sets an environmental tax in both periods (t^0 and t^1) and announces that a PES will be implemented in the final period (s) on the additional grass strip area compared to the initial period. We can anticipate strategic behaviors. In order to obtain optimal quantities produced in each period, we use backward induction. We first define the subgame-perfect Nash equilibrium obtained in the second stage. Then, we solve quantities produced in the initial period.

4.1.1 The second stage: Profit in final time period

In the final period, the PES is introduced, remunerating only the additional grass strip area compared to the initial period. This quantity is equal to $[y^1 - y^0]$

where $\begin{cases} y^1 - y^0 = T - x_1^1 - x_2^1 - y^0, \\ y^0 = T - x_1^0 - x_2^0 \end{cases}$

We maximize the profit in the final period in order to define the subgame-perfect Nash equilibrium in that period:

$$\pi^1(x_1^1, x_2^1) = p_1^1 x_1^1 + p_2^1 x_2^1 - c_1(x_1^1) - c_2(x_2^1) - t^1 x_1^1 + s(-x_1^1 - x_2^1 + x_1^0 + x_2^0)$$

Calculating the first order conditions, we find:

$$\frac{\partial \pi^1}{\partial x_1^1} = p_1^1 - c_1'(x_1^{1c}) - t^1 - s = 0 \qquad (6)$$

$$\frac{\partial \pi^1}{\partial x_2^1} = p_2^1 - c_2'(x_2^{1c}) - s = 0 \qquad (7)$$

Solving these FOC, we find the equilibrium quantities in the final period: $x_1^{1c}(t^1, s)$; $x_2^{1c}(s)$. Applying the implicit function theorem on (6) and (7) we can investigate how the production levels change in response to the environmental policies. We obtain:

$$\frac{\partial x_1^{1c}}{\partial s} = -\frac{\frac{\partial F}{\partial s}}{\frac{\partial F}{\partial x_1^1}} = -\frac{1}{c_1''(x_1^1)} < 0$$

$$\frac{\partial x_1^{1c}}{\partial t^1} = -\frac{\frac{\partial F}{\partial t^1}}{\frac{\partial F}{\partial x_1^1}} = -\frac{1}{c_1''(x_1^1)} < 0$$

$$\frac{dx_2^{1c}}{ds} = -\frac{\frac{\partial G}{\partial s}}{\frac{\partial G}{\partial x_2^1}} = -\frac{1}{c_2''(x_2^1)} < 0$$

In conformity with intuition, the environmental tax decreases conventional production in the final time period and the PES decreases both agriculture productions in the final time period.

4.1.2 The first–stage

In order to obtain the equilibrium quantities in the initial period, the farmer maximizes his intertemporal profit. We use equilibrium quantities from the final period in the profit function, $x_1^{1c}(t^1, s)$; $x_2^{1c}(s)$. The intertemporal profit is:

$$\begin{aligned}\pi(x_1^0, x_2^0) = {} & p_1^0 x_1^0 + p_2^0 x_2^0 - c_1(x_1^0) - c_2(x_2^0) - t^0 x_1^0 \\ & + \beta\{p_1^1 x_1^{1c}(t^1, s) + p_2^1 x_2^{1c}(s) - c_1(x_1^{1c}(t^1, s)) - c_2(x_2^{1c}(s)) - t^1 x_1^{1c}(t^1, s) + s(y^{1c} - y^0)\}\end{aligned}$$

$$\frac{\partial \pi}{\partial x_1^0} = p_1^0 - c_1'(x_1^{0c}) - t^0 + \beta s = 0 \tag{8}$$

$$\frac{\partial \pi}{\partial x_2^0} = p_2^0 - c_2'(x_2^{0c}) + \beta s = 0 \tag{9}$$

The farmer accounts for the environmental tax in the initial period as well as the PES based on additionality when deciding how to allocate his land in the initial time period. From the first-order conditions we find: $x_1^{0c}(s, t^0); x_2^{0c}(s)$. We can then apply the implicit function theorem on (8) and (9) to see how production levels change in response to the environmental policies. We find:

$$\frac{\partial x_1^{0c}}{\partial s} = -\frac{\frac{\partial J}{\partial s}}{\frac{\partial J}{\partial x_1^0}} = \frac{\beta}{c_1''(x_1^0)} > 0$$

$$\frac{\partial x_1^{0c}}{\partial t^0} = -\frac{\frac{\partial J}{\partial t^0}}{\frac{\partial J}{\partial x_1^0}} = -\frac{1}{c_1''(x_1^0)} < 0$$

$$\frac{dx_2^{0c}}{ds} = -\frac{\frac{\partial K}{\partial s}}{\frac{\partial K}{\partial x_2^0}} = \frac{\beta}{c_2''(x_2^0)} > 0$$

While the environmental tax in the initial period reduces the level of conventional production, the PES based on additionality raises both conventional and organic production levels in initial period. The farmer adopts a strategic behavior in order to capture more payment from the PES in the final period. He distorts the basis for calculating the PES to his advantage.

Proposition 1 *The additional PES creates a strategic behavior in the initial period, leading to less environmental benefit in the initial period.*

The organic production level is still increased in the initial period as a result of the PES policy. The conventional production level is subject to two effects: it increases with the PES but decreases with the tax. To see the net change in conventional production level, we have to see whether the effect of the tax or the PES will be larger:

$$\frac{\beta}{c_1''(x_1^0)} - \frac{1}{c_1''(x_1^0)} = \frac{\beta - 1}{c_1''(x_1^0)} < 0$$

Since $0 < \beta < 1$, the direct effect of the tax will be greater than the indirect effect of the PES, so the net effect will be a decrease in conventional production in the initial period. However, the conventional production level would have decreased more without the additionality requirement of the PES.

4.2 Tax and PES designs

In this section we define the second best level of the environmental taxes and the PES based on additionality. This design has to take into account the strategic behavior coming from the conditionality on additionality for the PES.

4.2.1 Intertemporal welfare function

The regulator maximizes the welfare function with respect to the environmental taxes in each period, and the PES policy based on additionality. Looking at the intertemporal welfare we have:

$$\underset{s,t^0,t^1}{W(x_1^0(s,t^0), x_2^0(s), x_1^1(s,t^1), x_2^1(s))} = \int_0^{x_1^0(s,t^0)} p_1(u)du + \int_0^{x_2^0(s)} p_2(v)dv - c_1(x_1^0(s,t^0)) - c_2(x_2^0(s))$$

$$+ B(T - x_1^0(s,t^0) - x_2^0(s)) - D(x_1^0(s,t^0)) + \beta\Bigg\{ \int_0^{x_1^1(s,t^1)} p_1(w)dw + \int_0^{x_2^1(s)} p_2(z)dz - c_1(x_1^1(s,t^1))$$

$$- c_2(x_2^1(s)) + \psi(T - x_1^0(s,t^0) - x_2^0(s))B(T - x_1^1(s,t^1) - x_2^1(s)) - D(x_1^1(s,t^1))\Bigg\}$$

Taking the first order conditions we obtain:

$$\frac{\partial W}{\partial t^0} = \frac{\partial x_1^0}{\partial t^0}\Big[p_1^0 - c_1'(x_1^0) - B_{y^0} - \beta\psi'(y^0)B(y^1) - D'(x_1^0)\Big] = 0 \tag{10}$$

$$\frac{\partial W}{\partial t^1} = \frac{\partial x_1^1}{\partial t}\beta\Big[p_1^1 - c_1'(x_1^1) - \psi(y^0)B_{y^1} - D'(x_1^1)\Big] = 0 \tag{11}$$

$$\begin{aligned}\frac{\partial W}{\partial s} &= \frac{\partial x_1^1}{\partial s}\beta\left[p_1^1 - c_1'(x_1^1) - \psi(y^0)B_{y^1} - D'(x_1^1)\right] + \frac{dx_2^1}{ds}\beta\left[p_2^1 - c_2'(x_2^1) - \psi(y^0)B_{y^1}\right] \\ &+ \frac{\partial x_1^0}{\partial s}\left[p_1^0 - c_1'(x_1^0) - B_{y^0} - \beta\psi'(y^0)B(y^1) - D'(x_1^0)\right] \\ &+ \frac{dx_2^0}{ds}\left[p_2^0 - c_2'(x_2^0) - B_{y^0} - \beta\psi'(y^0)B(y^1)\right] = 0\end{aligned} \tag{12}$$

Assuming a quadratic form for the cost function (see Appendix A for full calculations), we find the second-best PES level:

$$s^c = \frac{\psi(y^{0c})B_{y^{1c}} - (B_{y^{0c}} + \beta\psi'(y^{0c})B(y^{1c}))}{1+\beta} \tag{13}$$

The second-best PES based on additionality is equal to the discounted difference between the marginal environmental benefit in the final period given by $[\psi(y^0)B_{y^1}]$ and the marginal environmental benefit from the initial period $[B_{y^0} + \beta\psi'(y^0)B(y^1)]$. The latter is composed of the direct effect in the initial period, and the indirect effect of the initial grass strip area on the benefits in the final period. We can obtain conditions on the positivity of the PES:

$$s^c > 0 \Leftrightarrow \psi(y^{0c})B_{y^{1c}} > B_{y^{0c}} + \beta\psi'(y^{0c})B(y^{1c})$$

Proposition 2 *The PES based on additionality is positive if it leads to a greater marginal environmental benefit in the final period compared to the initial period.*

Since the PES reduces agricultural production quantities in the final period, it also generates biodiversity benefits in this period. This is the positive effect of the PES. However, the PES, based on additionality increases the agriculture production quantities in the initial period, leading to a decrease in the biodiversity benefits that could be obtained in both periods. The PES that accounts for these strategic behaviors increases proportionally to an increase in biodiversity benefits obtained in the final period. By setting the value of the PES based on the additional benefits obtained in terms of biodiversity, the regulator partly counteracts the disincentive in the initial period induced by the PES.

There will only be a payment if the PES leads to an additional effect in terms of biodiversity. If the marginal benefits of biodiversity are equal in both periods, there will be no PES. If the marginal benefits are greater in the initial period than in the final period, the PES can be negative: the regulator will seek to tax the grass strips in the final period in order to have more in the initial period, resulting in an additional marginal benefit.

Next, we use the value of the PES to determine the levels of each tax (see Appendix A for full calculations). Starting with the tax in the initial period we obtain:

$$t^{0c} = D'(x_1^{0c}) + \frac{B_{y^{0c}} + \beta[\psi'(y^{0c})B(y^{1c}) + \psi(y^{0c})B_{y^{1c}}]}{1+\beta} \tag{14}$$

Then, for the final period tax we find (see Appendix A for full calculations):

$$t^{1c} = D'(x_1^{1c}) + \frac{B_{y^{0c}} + \beta[\psi'(y^{0c})B(y^{1c}) + \psi(y^{0c})B_{y^{1c}}]}{1+\beta} \tag{15}$$

Both environmental taxes are equal to their respective marginal damages, with an additional term, $\frac{B_{y^0}+\beta[\psi'(y^0)B(y^1)+\psi(y^0)B_{y^1}]}{1+\beta} > 0$, which represents the net present value of biodiversity benefits obtained due to the PES. Both taxes will increase proportional to the net present value of biodiversity benefits. The tax is used to focus behaviors where we obtain the most biodiversity benefits.

Proposition 3 *In the presence of a PES based on additionality, environmental taxes are no longer equal to the marginal damage. They must take into account the distortions due to the additionality of the PES.*

Comparing the levels of environmental policies against their first-best levels, we see that the PES in the initial period is zero, and is therefore too low compared to the first-best. The PES in the second period is also lower than its first-best level. To restore the correct production quantities, the regulator will adjust the amount of environmental taxes, which does not distort the market, unlike the additional PES. Thus, the regulator will use the tax in the initial period to obtain a better level of grass strips. By increasing the tax, he partly bypasses the poor incentive of the PES on the conventional agricultural market. In the final period, since the additional PES is too low compared to its first-best level, the regulator also increases the tax to reduce the level of conventional agriculture and thus obtain more grass strips.

4.2.2 Calculated quantities

We now calculate the levels of conventional and organic agriculture that will result from the policies. We take the equations (13), (14) and (15), and plug these into the profit FOCs (6), (7), (8), and (9). Next, we solve for the quantities of organic and conventional agriculture in both periods and compare these to the quantities from the first best scenario. As with $y^{1c}(x_1^{1c}, x_2^{1c})$ and $y^{0c}(x_1^{0c}, x_2^{0c})$, quantities $(x_1^{1c}, x_2^{1c}, x_1^{0c}, x_2^{0c})$ are obtained solving the following system:

$$\begin{aligned}
p_1 - c_1'(x_1^{0c}) - D'(x_1^{1c}) - B_{y^{0c}} - \beta\psi'(y^{0c})B(y^{1c}) &= 0 \\
p_2 - c_2'(x_2^{1c}) - \frac{\psi(y^{0c})B_{y^{1c}} - (B_{y^{0c}} + \beta\psi'(y^{0c})B(y^{1c}))}{1+\beta} &= 0 \\
p_1 - c_1'(x_1^{1c}) - \psi(y^{0c})B_{y^{1c}} - D'(x_1^{1c}) &= 0 \\
p_2 - c_2'(x_2^{0c}) + \frac{\beta}{1+\beta}\left(\psi(y^{0c})B_{y^{1c}} - B_{y^{0c}} - \beta\psi'(y^{0c})B(y^{1c})\right) &= 0
\end{aligned}$$

In the general case, the quantities chosen are not equal to the first-best quantities. The environmental taxes and the PES set by the regulator do not achieve the first-best. This comes from the following channel: there is a PES in the final period instead of a PES in each period, due to the introduction of the additionality principle. The second-best level of environmental policies seeks to counteract strategic behaviour on the basis of the environmental benefits achieved. Since the taxes cannot indirectly correct for the distorted behavior induced in the initial period by the PES, the production quantities never match the first-best

5 Additionality and imperfect competition

We now add the assumption that the market for the organic agricultural good is imperfectly competitive, while keeping the conventional market perfectly competitive. We seek to determine the implications of the additionality condition of the PES in a context of imperfect competition. After analyzing the behavior of firms in response to the environmental policies, we define the optimal taxes and PES.

5.1 Monopoly: Strategic behaviors

In this subsection, we examine the case where imperfect competition in the organic sector takes the form of a monopoly. We assume environmental taxes in both periods and a PES based on additionality in the final period. We investigate, in this context, the farmer's behavior.

5.1.1 The second stage: equilibrium quantities in the final period

Let us define the subgame-perfect Nash equilibrium in the final period. We use backward induction in order to define production quantities in final period. We maximize the profit function:

$$\pi^1(x_1^1, x_2^1) = p_1^1 x_1^1 + p_2^1(x_2^1)x_2^1 - c_1(x_1^1) - c_2(x_2^1) - t^1 x_1^1 + s(y^1 - y^0)$$

where $\begin{cases} y^1 - y^0 = T - x_1^1 - x_2^1 - y^0, \\ y^0 = T - x_1^0 - x_2^0 \end{cases}$

First order conditions are the following:

$$\frac{\partial \pi^1}{\partial x_1^1} = p_1^1 - c_1'(x_1^{1m}) - t^1 - s = 0 \tag{16}$$

$$\frac{\partial \pi^1}{\partial x_2^1} = p_2^{1'}(x_2^{1m})x_2^{1m} + p_2^1(x_2^{1m}) - c_2'(x_2^{1m}) - s = 0 \tag{17}$$

Solving these FOC, we find the equilibrium quantities in the second time period: $x_1^{1m}(t^1, s)$; $x_2^{1m}(s)$. The market power decreases the organic production level, as the farmer considers the marginal revenue rather than the price when making his land allocation decision. Applying the implicit function theorem on (16) and (17), we can investigate how the environmental policies affects the production quantities. We find:

$$\begin{aligned} \frac{\partial x_1^{1m}}{\partial s} &= -\frac{1}{c_1''(x_1^1)} < 0 \\ \frac{\partial x_1^{1m}}{\partial t^1} &= -\frac{1}{c_1''(x_1^1)} < 0 \\ \frac{dx_2^{1m}}{ds} &= \frac{1}{2p_2'(x_2^1) - c_2''(x_2^1)} < 0 \end{aligned}$$

The environmental policies have the expected effect. In the end, organic production is reduced by the market power and the PES. Environmental policy tools are reducing the level of conventional and organic agricultural production, leading to more grass strips. The environmental benefits are therefore increased in the final period.

5.1.2 The first stage: equilibrium quantities in the initial period

In order to obtain the equilibrium quantities in the initial period, we use equilibrium quantities from the final period, $x_1^{1m}(t^1, s)$; $x_2^{1m}(s)$ in the farmer's intertemporal profit function:

$$\pi(x_1^0, x_2^0) = p_1^0 x_1^0 + p_2^0(x_2^0)x_2^0 - c_1(x_1^0) - c_2(x_2^0) - t^0 x_1^0$$
$$+ \beta\{p_1^1 x_1^{1m} + p_2^1(x_2^{1m})x_2^{1m} - c_1(x_1^{1m}) - c_2(x_2^{1m}) - t^1 x_1^{1m} + s(y^{1m} - y^0)\}$$

Maximizing the profit function gives the following first order conditions:

$$\frac{\partial \pi}{\partial x_1^0} = p_1^0 - c_1'(x_1^{0m}) - t^0 + \beta s = 0 \tag{18}$$

$$\frac{\partial \pi}{\partial x_2^0} = p_2^{0'}(x_2^{0m})x_2^{0m} + p_2^0(x_2^{0m}) - c_2'(x_2^{0m}) + \beta s = 0 \tag{19}$$

The farmer makes his land allocation decision by taking into account the environmental tax in the initial period and the PES. His market power on organic market leads him to consider his marginal revenue when deciding his organic production quantity instead of the price, which results in a lower organic production quantity. From the FOC, we find: $x_1^{0m}(s, t^0); x_2^{0m}(s)$. Applying the implicit function theorem on (18) and (19), we analyze how the environmental policies affect the production quantities:

$$\begin{aligned}
\frac{\partial x_1^{0m}}{\partial s} &= -\frac{\frac{\partial J}{\partial s}}{\frac{\partial J}{\partial x_1^0}} = \frac{\beta}{c_1''(x_1^0)} > 0 \\
\frac{\partial x_1^{0m}}{\partial t^0} &= -\frac{\frac{\partial J}{\partial t^0}}{\frac{\partial J}{\partial x_1^0}} = -\frac{1}{c_1''(x_1^0)} < 0 \\
\frac{dx_2^{0m}}{ds} &= -\frac{\frac{\partial K}{\partial s}}{\frac{\partial K}{\partial x_2^0}} = -\frac{\beta}{2p_2'(x_2^0) - c_2''(x_2^0)} > 0
\end{aligned}$$

The PES implemented in the final period creates a distortion in the initial period. Farmers increase their production levels in the initial period in order to benefit from more PES in the final period. In the initial period, the organic market is subject to two distortions: strategic behavior following the additionality-based PES and market power. Comparing $\frac{dx_2^0}{ds}$ with market power and without market power, we obtain the following proposition:

Proposition 4 *Market power in the organic market reduces the strategic behavior introduced by the additional PES.*

The incentive to change the baseline level of grass strip upon which payment is based by increasing the quantity produced of the organic good is in contrast to price-making behaviour, which leads to a reduction in the quantity produced. Thus, market power reduces strategic behavior in the organic market relative to the competitive situation. In the organic market, the distortion induced by market power partly offsets the distortion induced by the PES.

5.2 Tax and PES designs

Let us now define the second best environmental policies. The regulator has to take into account the environmental externalities, distortions in the farmer's behavior from the PES based on additionality and market power on the organic market.

5.2.1 Intertemporal welfare function

After having substituted in the production quantities $(x_1^{0m}, x_2^{0m}, x_1^{1m}, x_2^{1m})$ that depend on the environmental policies, we obtain the following intertemporal welfare function:

$$\underset{s,t^0,t^1}{W(x_1^0(s,t^0), x_2^0(s), x_1^1(s,t^1), x_2^1(s))} = \int_0^{x_1^0(s,t^0)} p_1(u)du + \int_0^{x_2^0(s)} p_2(v)dv - c_1(x_1^0(s,t^0)) - c_2(x_2^0(s))$$

$$+ B(T - x_1^0(s,t^0) - x_2^0(s)) - D(x_1^0(s,t^0)) + \beta\Bigg\{ \int_0^{x_1^1(s,t^1)} p_1(w)dw + \int_0^{x_2^1(s)} p_2(z)dz - c_1(x_1^1(s,t^1))$$

$$- c_2(x_2^1(s)) + \psi(T - x_1^0(s,t^0) - x_2^0(s))B(T - x_1^1(s,t^1) - x_2^1(s)) - D(x_1^1(s,t^1))\Bigg\}$$

The first order conditions are the following:

$$\frac{\partial W}{\partial t^0} = \frac{\partial x_1^0}{\partial t^0}\Big[p_1 - c_1'(x_1^0) - B_{y^0} - \beta\psi'(y^0)B(y^1) - D'(x_1^0)\Big] = 0 \tag{20}$$

$$\frac{\partial W}{\partial t^1} = \frac{\partial x_1^1}{\partial t}\beta\Big[p_1 - c_1'(x_1^1) - \psi(y^0)B_{y^1} - D'(x_1^1)\Big] = 0 \tag{21}$$

$$\begin{aligned} \frac{\partial W}{\partial s} = {} & \frac{\partial x_1^1}{\partial s}\beta\Big[p_1 - c_1'(x_1^1) - \psi(y^0)B_{y^1} - D'(x_1^1)\Big] + \frac{dx_2^1}{ds}\beta\Big[p_2 - c_2'(x_2^1) - \psi(y^0)B_{y^1}\Big] \\ & + \frac{\partial x_1^0}{\partial s}\Big[p_1 - c_1'(x_1^0) - B_{y^0} - \beta\psi'(y^0)B(y^1) - D'(x_1^0)\Big] \\ & + \frac{dx_2^0}{ds}\Big[p_2 - c_2'(x_2^0) - B_{y^0} - \beta\psi'(y^0)B(y^1)\Big] = 0 \end{aligned} \tag{22}$$

After calculations (see Appendix B), we obtain the PES value, s:

$$s^m = \frac{\psi(y^{0m})B_{y^{1m}} - [B_{y^{0m}} + \beta\psi'(y^{0m})B(y^{1m})]}{1+\beta} + \frac{p_2'(x_2^{1m})x_2^{1m} - p_2'(x_2^{0m})x_2^{0m}}{1+\beta} \tag{23}$$

The second best PES is equal, this time, to the net present value of the difference in marginal benefits, adjusted for the market power. The adjusted marginal benefit is lower than the marginal benefit without market power in each period because $P' < 0$. The PES is positive if the adjusted marginal benefit is higher in the final period than in the initial period.

$$s^m > 0 \Rightarrow \psi(y^{0m})B_{y^{1m}} - [B_{y^{0m}} + \beta\psi'(y^{0m})B(y^{1m}] > [p_2'(x_2^{0m})x_2^{0m} - p_2'(x_2^{1m})x_2^{1m}]$$

The organic production quantity is reduced in the final period due to the PES and increases in the initial period, although this effect is partially compensated by the PES. We can thus expect that $x_2^{0m} > x_2^{1m}$. Consequently, the market power leads to an increase in the PES level.

Next, we use the value of the PES to determine the levels of each tax. We obtain (see Appendix B for calculations):

$$t^{0m} = D'(x_1^{0m}) + \frac{B_{y^{0m}} + \beta[\psi(y^{0m})B_{y^{1m}} + \psi'(y^{0m})B(y^{1m})]}{1+\beta} + \frac{\beta[p_2'(x_2^{1m})x_2^{1m} - p_2'(x_2^{0m})x_2^{0m}]}{1+\beta} \tag{24}$$

$$t^{1m} = D'(x_1^{1m}) + \frac{B_{y^{0m}} + \beta[\psi'(y^{0m})B(y^{1m}) + \psi(y^{0m})B_{y^{1m}}]}{1+\beta} + \frac{-p_2'(x_2^{1m})x_2^{1m} + p_2'(x_2^{0m})x_2^{0m}}{1+\beta} \tag{25}$$

As under perfect competition, taxes depends on the marginal damage and the net present value of biodiversity benefits. This time, they also include a term that takes into account the market power in the organic sector.

5.2.2 Calculated quantities

We now seek to calculate the production levels of conventional and organic agriculture that will result from the policies. We take equations (23), (24), and (25) and plug them into the profit FOCs (16), (17), (18), and (19)

Next, we solve for the quantities of organic and conventional agriculture in both periods and compare these to the quantities from the first best scenario. As with $y^{1m}(x_1^{1m}, x_2^{1m})$ and $y^{0m}(x_2^{0m}, x_2^{0m})$, quantities $(x_1^{1m}, x_2^{1m}, , x_2^{0m}, x_2^{0m})$ are obtained solving the following system:

$$\begin{aligned}
p_1 - c_1'(x_1^1) - D'(x_1^1) + \frac{\beta-1}{1+\beta}\psi(y^0)B_{y^1} &= 0\\
\frac{\beta}{1+\beta}p_2'(x_2^1)x_2^1 + p_2(x_2^1) - c_2'(x_2^1) - \Big(\frac{\psi(y^0)B_{y^1} - p_2'(x_2^0)x_2^0 - B_{y^0} - \beta\psi'(y^0)B(y^1)}{1+\beta}\Big) &= 0\\
p_1 - c_1'(x_1^0) - D'(x_1^0) - B_{y^0} - \beta\psi'(y^0)B(y^1) &= 0\\
\frac{p_2'(x_2^0)x_2^0}{1+\beta} + p_2(x_2^0) - c_2'(x_2^0) + \frac{\beta}{1+\beta}\Big(p_2'(x_2^1)x_2^1 + \psi(y^0)B_{y^1} - B_{y^0} - \beta\psi'(y^0)B(y^1)\Big) &= 0
\end{aligned}$$

The quantities chosen are not equal to the first-best quantities. The second-best environmental taxes and the PES set by the regulator do not achieve the first-best. They fail to take into account several distortions: environmental damages, environmental services related to biodiversity, moral hazard, and market power.

6 Conclusion

The additionality of a PES program is a key factor in evaluating its efficiency or cost-effectiveness. When program budgets are limited, environmental service (ES) buyers want to ensure their payments will lead to an increase in the overall level of ES provision. In a typical PES program there is a problem of asymmetric information, which can lead to adverse selection and moral hazard (Moxey et al., 1999; Laffont & Martimort, 2002; Ferraro, 2008; Pates & Hendricks, 2020). Adverse selection occurs because an ES buyer will not have full information about ES sellers' costs, and the buyer thus risks overpaying sellers or paying for services that would have been provided absent any payment. Common solutions to address adverse selection include the use of a reverse auction to select ES sellers for PES contracts or the use of a menu of contracts to reflect differing costs that ES sellers may face (Ferraro, 2008). Moral hazard arises because the seller may modify their baseline behavior in response to the prospect of a PES policy. For example, an ES seller may delay the adoption of a new technology in order to receive a subsidy even if it would be optimal to adopt the technology without a subsidy (Pates & Hendricks, 2020).

In this paper, we constructed a model with two time periods to evaluate the effects that conditioning PES payments on additionality would have on the representative farmer's behavior and the optimal policy designs in each time period. We included both a biodiversity PES for grass strips and a tax on the environmental damage from pollution linked to conventional agriculture. We also investigated the effect of market power in the organic sector on the policy designs. We find that the PES will be positive if two conditions are met. First, there must be an increase in the marginal benefit of the grass strips, accounting for the market power in the organic sector. Second, the organic production level must be higher in the initial period than in the final period. If the market power reduces the final organic quantity more (less) than the initial organic quantity, then the market power will increase (decrease) the PES. Moreover, if the market power increases the PES, the initial period tax will increase and the final period tax will decrease. The taxes are greater than their respective marginal damages, and will adjust to the difference in market power in each period in order to reduce conventional agriculture more where market power in the organic sector is higher.

We show that in a perfect information scenario the regulator is unable to adjust the levels of the policies to counteract the moral hazard behavior of the farmers, and the quantity of grass strips will be less than optimal. Future research should investigate how to address moral hazard in an asymmetric information setting.

Appendices

A The second-best environmental policies under perfect competition

Determination of s^c

From the profit FOCs given by (6), (7), (8), and (9), we find:

$$\begin{aligned} p_1^1 - c_1'(x_1^{1c}) &= t^1 + s \\ p_2^1 - c_2'(x_2^{1c}) &= s \\ p_1^0 - c_1'(x_1^0) &= t^0 - \beta s \\ p_2^0 - c_2'(x_2^0) &= -\beta s \end{aligned}$$

Plugging these into (10), (11), and (12), we obtain:

$$\frac{\partial x_1^0}{\partial t^0}\Big[t^0 - \beta s - B_{y^0} - \beta\psi'(y^0)B(y^1) - D'(x_1^0)\Big] = 0 \quad (A.1)$$

$$\frac{\partial x_1^1}{\partial t^1}\beta\Big[t^1 + s - \psi(y^0)B_{y^1} - D'(x_1^1)\Big] = 0 \quad (A.2)$$

$$\frac{\partial x_1^1}{\partial s}\beta\Big[t^1 + s - \psi(y^0)B_{y^1} - D'(x_1^1)\Big] + \frac{dx_2^1}{ds}\beta\Big[s - \psi(y^0)B_{y^1}\Big] + \frac{\partial x_1^0}{\partial s}\Big[t^0 - \beta s - B_{y^0} - \beta\psi'(y^0)B(y^1) - D'(x_1^0)\Big] + \frac{dx_2^0}{ds}\Big[-\beta s - B_{y^0} - \beta\psi(y^0)B_{y^1}\Big] = 0 \quad (A.3)$$

We can then solve (A.1) and (A.2) for t^0 and t^1:

$$t^0 = \beta s + B_{y^0} + \beta\psi'(y^0)B(y^1) + D'(x_1^0) \quad (A.4)$$

$$t^1 = -s + \psi(y^0)B_{y^1} + D'(x_1^1) \quad (A.5)$$

We plug these values into (A.3):

$$\begin{aligned} \frac{dx_2^1}{ds}\beta\Big[s - \psi(y^0)B_{y^1}\Big] + \frac{dx_2^0}{ds}\Big[-\beta s - B_{y^0} - \beta\psi'(y^0)B(y^1)\Big] &= 0 \\ s\Big[\frac{dx_2^1}{ds}\beta - \frac{dx_2^0}{ds}\beta\Big] &= \frac{dx_2^1}{ds}\beta\psi(y^0)B_{y^1} + \frac{dx_2^0}{ds}[B_{y^0} + \beta\psi'(y^0)B(y^1)] \\ s &= \frac{\frac{dx_2^1}{ds}\beta\psi(y^0)B_{y^1} + \frac{dx_2^0}{ds}[B_{y^0} + \beta\psi'(y^0)B(y^1)]}{\beta[\frac{dx_2^1}{ds} - \frac{dx_2^0}{ds}]} \end{aligned}$$

We then substitute in $\frac{dx_2^1}{ds} = -\frac{1}{c_2''(x_2^1)}$, and $\frac{dx_2^0}{ds} = \frac{\beta}{c_2''(x_2^0)}$:

$$s = \frac{-\frac{1}{c_2''(x_2^1)}\beta\psi(y^0)B_{y^1} + \frac{\beta}{c_2''(x_2^0)}[B_{y^0} + \beta\psi'(y^0)B(y^1)]}{\beta[-\frac{1}{c_2''(x_2^1)} - \frac{\beta}{c_2''(x_2^0)}]} \quad (A.6)$$

After rearranging, we obtain equation (13).

Determination of t^{0c}
Replacing s in (A.4.4), we have:

$$t^0 = \beta\left[\frac{\psi(y^0)B_{y^1} - (B_{y^0} + \beta\psi'(y^0)B(y^1))}{1+\beta}\right] + B_{y^0} + \beta\psi'(y^0)B(y^1) + D'(x_1^0)$$

Simplifying:

$$t^0 = \frac{\beta\big[\psi(y^0)B_{y^1} - (B_{y^0} + \beta\psi'(y^0)B(y^1))\big] + (1+\beta)\big[B_{y^0} + \beta\psi'(y^0)B(y^1)\big]}{1+\beta} + D'(x_1^0)$$

$$t^0 = \frac{\beta\psi(y^0)B_{y^1} - (\beta B_{y^0} + \beta\beta\psi'(y^0)B(y^1)) + (1+\beta)B_{y^0} + (1+\beta)\beta\psi'(y^0)B(y^1)}{1+\beta} + D'(x_1^0)$$

After rearrangement, we obtain Equation (14).

Determination of t^{1c}
Replacing s in (A.5.5), we have:

$$t^1 = -\left\{\frac{\psi(y^0)B_{y^1} - (B_{y^0} + \beta\psi'(y^0)B(y^1))}{1+\beta}\right\} + \psi(y^0)B_{y^1} + D'(x_1^1)$$

Simplifying:

$$t^1 = D'(x_1^1) - \left\{\frac{\psi(y^0)B_{y^1} - (B_{y^0} + \beta\psi'(y^0)B(y^1))}{1+\beta}\right\} + \frac{(1+\beta)\psi(y^0)B_{y^1}}{1+\beta}$$

After rearrangement, we obtain Equation (15).

B The second-best environmental policies under imperfect competition

Determination of s^m
We rearrange all of the profit FOCs, (16), (17), (18), and (19) and find:

$$\begin{aligned}
p_1 - c_1'(x_1^{1m}) &= t^1 + s \\
p_2(x_2^1) - c_2'(x_2^{1m}) &= s - p_2'(x_2^1)x_2^1 \\
p_1 - c_1'(x_1^0) &= t^0 - \beta s \\
p_2(x_2^0) - c_2'(x_2^0) &= -\beta s - p_2'(x_2^0)x_2^0
\end{aligned}$$

Plugging these into (20), (21), and (22), we obtain:

$$\frac{\partial x_1^0}{\partial t^0}\left[t^0 - \beta s - B_{y^0} - \beta\psi'(y^0)B(y^1) - D'(x_1^0)\right] = 0 \qquad \text{(B.1)}$$

$$\frac{\partial x_1^1}{\partial t^1}\beta\left[t^1 + s - \psi(y^0)B_{y^1} - D'(x_1^1)\right] = 0 \tag{B.2}$$

$$\begin{aligned}
&\frac{\partial x_1^1}{\partial s}\beta\left[t^1 + s - \psi(y^0)B_{y^1} - D'(x_1^1)\right] + \frac{dx_2^1}{ds}\beta\left[s - p_2'(x_2^1)x_2^1 - \psi(y^0)B_{y^1}\right] \\
&+ \frac{\partial x_1^0}{\partial s}\left[t^0 - \beta s - B_{y^0} - \beta\psi'(y^0)B(y^1) - D'(x_1^0)\right] \\
&+ \frac{dx_2^0}{ds}\left[-\beta s - p_2'(x_2^0)x_2^0 - B_{y^0} - \beta\psi(y^0)B_{y^1}\right] = 0
\end{aligned} \tag{B.3}$$

We can then solve (B.1) and (B.2) for t^0 and t^1.

$$t^0 = \beta s + B_{y^0} + \beta\psi'(y^0)B(y^1) + D'(x_1^0) \tag{B.4}$$

$$t^1 = -s + \psi(y^0)B_{y^1} + D'(x_1^1) \tag{B.5}$$

We plug these values into (B.3) in order to obtain the value of s:

$$\frac{dx_2^1}{ds}\beta\left[s - p_2'(x_2^1)x_2^1 - \psi(y^0)B_{y^1}\right] + \frac{dx_2^0}{ds}\left[-\beta s - p_2'(x_2^0)x_2^0 - B_{y^0} - \beta\psi'(y^0)B(y^1)\right] = 0$$

$$s\left[\frac{dx_2^1}{ds}\beta - \frac{dx_2^0}{ds}\beta\right] = \frac{dx_2^1}{ds}\beta[p_2'(x_2^1)x_2^1 + \psi(y^0)B_{y^1}] + \frac{dx_2^0}{ds}[p_2'(x_2^0)x_2^0 + B_{y^0} + \beta\psi'(y^0)B(y^1)]$$

$$s = \frac{\frac{dx_2^1}{ds}\beta[p_2'(x_2^1)x_2^1 + \psi(y^0)B_{y^1}] + \frac{dx_2^0}{ds}[p_2'(x_2^0)x_2^0 + B_{y^0} + \beta\psi'(y^0)B(y^1)]}{\beta[\frac{dx_2^1}{ds} - \frac{dx_2^0}{ds}]}$$

We then substitute in $\frac{dx_2^1}{ds} = \frac{1}{2p_2'(x_2^1) - c_2''(x_2^1)}$, and $\frac{dx_2^0}{ds} = -\frac{\beta}{2p_2'(x_2^0) - c_2''(x_2^0)}$:

$$s = \frac{\frac{1}{2p_2'(x_2^1)-c_2''(x_2^1)}\beta[p_2'(x_2^1)x_2^1 + \psi(y^0)B_{y^1}] - \frac{\beta}{2p_2'(x_2^0)-c_2''(x_2^0)}[p_2'(x_2^0)x_2^0 + B_{y^0} + \beta\psi'(y^0)B(y^1)]}{\beta[\frac{1}{2p_2'(x_2^1)-c_2''(x_2^1)} + \frac{\beta}{2p_2'(x_2^0)-c_2''(x_2^0)}]}$$

Assuming a quadratic form for the cost function, and a linear demand function, we find Equation (23).

The second-best value of t^{0m}

Pluging the value of s into (B.4), we have:

$$t^0 = \beta\left[\frac{p_2'(x_2^1)x_2^1 + \psi(y^0)B_{y^1} - [p_2'(x_2^0)x_2^0 + B_{y^0} + \beta\psi'(y^0)B(y^1)]}{1+\beta}\right] + B_{y^0} + \beta\psi'(y^0)B(y^1) + D'(x_1^0)$$

Simplifying:

$$\begin{aligned}
t^0 =& \frac{\beta\left[p_2'(x_2^1)x_2^1 + \psi(y^0)B_{y^1} - (B_{y^0} + \beta\psi'(y^0)B(y^1)) - p_2'(x_2^0)x_2^0\right] + (1+\beta)\left[B_{y^0} + \beta\psi'(y^0)B(y^1)\right]}{1+\beta} \\
&+ D'(x_1^0)
\end{aligned}$$

After rearrangement, we obtain Equation (24).

Determination of t^{1m}
Plugging s^m into (B.5), we find:

$$t^1 = -\left\{ \frac{p_2'(x_2^1)x_2^1 + \psi(y^0)B_{y^1} - [p_2'(x_2^0)x_2^0 + B_{y^0} + \beta\psi'(y^0)B(y^1)]}{1+\beta} \right\} + \psi(y^0)B_{y^1} + D'(x_1^1)$$

Simplifying:

$$t^1 = D'(x_1^1) - \left\{ \frac{p_2'(x_2^1)x_2^1 + \psi(y^0)B_{y^1} - (p_2'(x_2^0)x_2^0 + B_{y^0} + \beta\psi'(y^0)B(y^1))}{1+\beta} \right\} + \frac{(1+\beta)\psi(y^0)B_{y^1}}{1+\beta}$$

After rearrangement, we obtain Equation (25).

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