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Are Additional Payments for Environmental Services Efficient?*

Anneliese Krautkraemer[†] Sonia Schwartz[‡]

Abstract

The implementation of Payments for Environmental Services (PES) may face a financing constraint, especially when the buyer is a public regulator. An additionality-based PES can address this problem. The objective of this paper is to study the efficiency of PES based on additionality. To do so, we consider a farmer who has to choose to allocate his land between organic production, conventional production causing environmental damage, 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-best PES to limit this behavior is equal to the discounted difference of the marginal environmental benefits obtained in each period. We also establish the second-best 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 market power reduces the distortion due to the additionality-based PES in the initial period but reduces the organic production quantity in the final period. The second-best PES depends on the size of these two effects and environmental taxes under market power have to be amended. Finally, this paper shows that an additionality-based PES never achieves environmental efficiency, even in a competitive market framework. Furthermore, this paper provides new insights into understanding the interactions between different environmental policies in the presence of several types of distortions.

Keywords: Biodiversity; Payment for Environmental Services; Pigouvian Taxes; Additionality

JEL Codes: Q57; Q58

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1 Introduction

The concept of ecosystem services was widely disseminated with the publication of the Millennium Ecosystem Assessment in 2005. Ecosystem services are defined as the many and varied benefits that humans derive from the natural environment and healthy ecosystems. They are categorized into the following four types: provisioning services such as food, water, timber, and fiber; regulating services that affect climate, floods, disease, wastes, and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as soil formation, photosynthesis, and nutrient cycling (Reid et al., 2005).

The notion of ecosystem services and environmental services (ES) are often confused. While ecosystem services refer to the functioning of ecosystems, ES concern to the notion of externalities induced by human activities. The FAO (Food and Agriculture Organization of the United Nations) proposes a definition of ES in terms of ecosystem services. For agriculture, they are defined as the subpart of ecosystem services that can be qualified in terms of externalities, i.e. all ecosystem services except provisioning services. Lugo (2007) draws a distinction between benefits provided by ecosystems and human protection of these ecosystems and use the term ecosystem services to refer to the former exclusively. Thus the term ES can be used to refer to the production of services by farmers in order to protect the environment (FAO, 2007). We can quote several examples. Long crop rotations improve ecosystem services such as support services through improved soil quality. The diversity of productive activities on a farm promotes beneficial interactions between crops and livestock and the management of landscape features such as grass strips, embankments, hedges or watercourses contribute to the ecological functioning of agroecosystems (Duval et al., 2016). All of these definitions make it possible to justify paying farmers for these ES as internalization of externalities. In particular, this leaves room for policy intervention to encourage their optimal provision.

At the European level, the Common Agricultural Policy (CAP) is the main tool for the production objectives of agriculture with those of environmental and human health protection. and human health. One of the major advances of the CAP has been the introduction of agri-environmental measures. They consist of offering financial compensation to farmers for voluntary commitment on their part, over several years, to implement practices or production. Agri-environmental measures can be considered as Payments for Environmental Services (PES).

PES is one policy tool that has been implemented to try to increase the provision of ES. 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 ES 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 ES 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 ES where they would be additional. However, since establishing the baseline level of ES can 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 ES buyer is a public regulator, the issue of additionality is even more important as it prevents wasting public funds.

The economic literature has explored questions associated with additionality (Sills et al., 2008), notably the definition of the baseline ((Kaczan et al., 2017)), and the consequences in terms of new technology development (Pates & Hendricks, 2020). Another branch of the literature looks at agency theory to solve the problem of additionality. Other works have investigated if existing programs, particularly agri-environmental schemes, demonstrate additionality (Mezzatesta et al., 2013; Chabé-Ferret & Subervie, 2013). Nevertheless, the literature has not studied the efficiency of an additionality-based PES to obtain the optimal levels of environmental benefits. That is the main objective of this paper.

To do this study, 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-best PES based on additionality that takes into account the distortion 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.

These results are obtained assuming perfect competition in the good markets. The study of Pigouvian taxes in the presence of market power is well documented in the economic literature. Some of the best known works include Buchanan (1969), Barnett (1980) or Ebert (1991). However, few studies have looked at the definition of PES in this context of market power. Krautkraemer & Schwartz (2022) can be mentioned, but they do not take into account the additionality of the PES. However, the assumption of imperfect competition may be interesting for modelling organic farming markets. 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]

[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).

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 could have market power.

Our analysis is thus extended assuming 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 but also reduces the production quantities in the final period. The second-best level of the additionality-based PES under market power depends on the size of these two effects. The second-best level of environmental taxes are also amended by the market power.

Finally, this paper shows that an additionality-based PES never achieves environmental efficiency, even in a competitive market framework. The PES is set up to correct an environmental distortion but its additional feature is itself the cause of another distortion. Furthermore, this paper provides new insights into understanding the interactions between different environmental policies in the presence of several types of distortions: environmental damages, environmental benefit, additionality and market power.

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.

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.

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 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.

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 implemented in France to estimate their additional and windfall effects. They find different levels of additionality for the different agro-environment schemes, 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 with $p_i^{t\prime}(x_i^t) < 0$, $\forall i, \forall t$.

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., $y^t > 0$.

In order to take into account negative (environmental damage) and positive (biodiversity benefit) externalities, the regulator can use environmental policies, as environmental taxes denoted by t^t and PES denoted by s^t if the PES is implemented in each period and s if the PES is implemented in final period based on additionality.

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:

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

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.

$$W(x_1^0, x_2^0, x_1^1, x_2^1) = \int_0^{x_1^0} p_1^0(u)du + \int_0^{x_2^0} p_2^0(v)dv - c_1(x_1^0) - c_2(x_2^0) + B(T - x_1^0 - x_2^0) - D(x_1^0)$$
$$+ \beta\left\{ \int_0^{x_1^1} p_1^1(w)dw + \int_0^{x_2^1} p_2^1(z)dz - c_1(x_1^1) - c_2(x_2^1) + \psi(y^0)B(T - x_1^1 - x_2^1) - D(x_1^1)\right\}$$

Taking the first order conditions we obtain:

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

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

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

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

In the first-best scenario, the socially optimal levels of conventional and organic agriculture in both time periods occur taking into account social marginal cost of production. The level of conventional agriculture is based on the private marginal cost of production, the marginal biodiversity benefit and marginal damage. Similarly, the level of organic production 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: $t^0 = D'(x_1^{0*}); t^1 = D'(x_1^{1*}); s^0 = B_{y^o} + \beta\psi'(y^{0*})B(y^{1*}); s^1 =$

$\psi(y^{0*})B_{y^{1*}}$ 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 environmental 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 by using a PES in the final period that remunerates the additional environmental benefits generated by the PES between the initial and final periods. The regulator introduces an environmental tax 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. Finally, we get the levels of production and thus of environmental damage and benefits.

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. 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. We can anticipate strategic behaviors.

4.1.1 The second stage: equilibrium quantities in the final 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:

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

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

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: equilibrium quantities in the initial period

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:

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

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

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

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 the 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 PES based on additionality and of the environmental taxes. As the additionality-based PES increases agricultural production levels in the first period, it is expected to have a negative effect on the welfare level. The second-best value of environmental policies has to correct this distortion. In order to design these policies, we replace $x_1^{1c}(t^1, s)$, $x_2^{1c}(s)$, $x_1^{0c}(s, t^0)$, and $x_2^{0c}(s)$ in the welfare function. The regulator maximizes the welfare function with respect to the additionality-based PES and environmental taxes in each period. 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:

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

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

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

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

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

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 condition 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 do not distort the market, unlike the additionality-based 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.

4.3 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:

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

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: the PES which is initially set up to correct an environmental distortion induces another distortion when it is based on additionality. The introduction of the additionality principle implements only one PES in the final period instead of a PES in each period. The second-best level of environmental policies seeks to counteract strategic behavior 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. In the end, PES based on additionality does not achieve environmental efficiency.

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 second-best level of environmental taxes and PES. Finally, we calculate production levels.

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:

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

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

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 and reduce the levels of production. But the organic production level is reduced by the market power and the PES. So there are more grass strips in final period. The environmental benefits are therefore increased.

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:

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

Maximizing the profit function gives the following first order conditions:

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

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

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 the 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 behavior, 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

We will now define the second-best environmental policies. Let's assume $s = -\frac{p_2^{0\prime}(x_2^{0m})x_2^{0m}}{\beta} > 0$. From (19), we see the appropriate incentives would be given by the regulator in the organic market in initial period. However, this PES level would not achieve the optimal market behaviour of conventional agriculture in the same period. There is also no reason why this level of PES should implement the right quantities in final period. It is therefore necessary to maximize the intertemporal welfare function in order to obtain the levels of PES and environmental taxes that result from these different trade-offs. 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^m:

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

The second-best PES is equal to the net present value of the difference in marginal benefits, adjusted for the market power. In each period, the adjusted marginal benefit is lower than the marginal benefit without market power in each period because $p' < 0$. Rearranging s^m, we can identify two terms. The first is similar to PES without market power valued at quantities with market power. The second is the is a market power term. We have:

$$s^m = s^*(y^{0m}, y^{1m}) + \frac{p_2'(x_2^{1m})x_2^{1m} - p_2'(x_2^{0m})x_2^{0m}}{1+\beta}$$

The positivity of the PES now depends on the difference in marginal benefits and also on the market power term:

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

The effects of the market power are different from one period to the next. In the final period, the market power reduces the organic production level, having an effect we can qualify as negative. In the initial period, it limits the strategic behavior on the organic market, which is a positive effect. The additionality-based PES that takes into account the market power, (equation 23), summarizes these effects. If the negative effect in the final period is substantial, the PES with market power will be lower than without market power. Conversely, if the effect in the initial period is high, the PES with market power will be larger. As the PES remunerates the supplementary environmental benefits, one can expect that the organic production quantity will be lower in the final period, i.e. $x_2^{1m} < x_2^{0m}$. In this case, the market power will increase the PES.

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. If the market power increases (decreases) the PES, the tax in the initial period increases (decreases) but the tax in the final period decreases (increases). The environmental taxes are adjusted to take into account the indirect effects of market power on the conventional agriculture market.

5.3 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:

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

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 benefits, additionality and market power.

6 Conclusion

When program budgets are limited, ES buyers want to ensure their payments will lead to an increase in the overall level of ES provision. This is why PES can be based on the principle of additionality. The question is whether these additionality-based PES achieve environmental efficiency. To conduct this study, we used a model with two time periods and we considered the representative farmer's behavior. He allocates his land between organic agricultural production that has a neutral impact on the environment, conventional production that causes environmental damage, and leaving grass strips that generate environmental benefits. The regulator sets a PES as an incentive for the farmer to leave grass strips but only wants to pay for the additional environmental benefits that result from the PES. We show that this PES based on additionality distorts the farmer's behavior in the initial period. The farmer increases his production levels in order to obtain more payment in the final period. The second-best PES has to correct this distortion while taking into account the environmental benefits and damages. In the end, the second-best PES is equal to the discounted difference of the marginal environmental benefit in each period. The second-best environmental taxes in each period are no longer equal to the marginal damage. They are adjusted to correct the distortions induced by the PES.

We then introduced market power in the organic market. If the market power reduces the organic production quantity in the final period, it limits the distortion in the initial period. Depending on the size of these effects, the second-best additionality-based PES either increases or decreases compared to the scenario without market power. The taxes are adjusted to take into account the indirect effects of the market power on the level of conventional production.

Finally, this study has shown that the additionality condition of the PES does not achieve environmental efficiency, even under perfect competition. It also provides a better understanding of the interactions between different types of environmental policies.

It turns out that basing the PES on the additional environmental benefits obtained by the payment is not very easy to characterize in a simple perfect information setting with two time periods. However this study could be extended by considering an infinite time horizon, in order to see how the results hold up. This would mean modeling a strategic behavior in an optimal control model. In the same vein as Barnett (1980), the second-best environmental policies are defined under perfect information, which suggests that the regulator knows the firm's production costs. By mobilizing agency theory, these works could be extended under asymmetric information, which would allow for taking moral hazard into account. Finally, the model could be enriched by introducing the marginal social cost of public funds.

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:

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

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

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

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):

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

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:

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

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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