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PAYMENTS FOR ENVIRONMENTAL SERVICES UNDER IMPERFECT COMPETITION

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Par

Anneliese KRAUTKRAEMER

sous la direction de:
Pr. Pascale Motel Combes et Pr. Sonia Schwartz

Composition du jury:

Dorothée BRECARD	Professeur, Université de Toulon	Rapporteure
Marie-Hélène HUBERT	Professeur, Université de Rennes 1	Rapporteure, Présidente
Dominique BUREAU	Professeur, Ecole Polytechnique, Président de la Commission de l'Economie du Développement Durable (Ministère de la Transition Ecologique)	Suffragant
Pascale MOTEL-COMBES	Professeur, Université Clermont Auvergne	Directrice
Sonia SCHWARTZ	Professeur, Université Clermont Auvergne	Directrice

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In loving memory of my dad, Jeff Krautkraemer

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Je vous souhaite une très bonne lecture.

Résumé

La thèse étudie la mise en œuvre optimale des paiements pour services environnementaux (PSE) dans un cadre de concurrence imparfaite. Son objectif est de tirer des recommandations en termes d'économie publique pour le régulateur, afin de protéger la biodiversité. Les résultats de la thèse permettent d'identifier des scénarios où les PSE sont inefficaces. La thèse se compose de quatre chapitres. Le chapitre 2 est une revue de la littérature sur les PSE. Les chapitres 3, 4 et 5 examinent chacun un aspect particulier de la concurrence imparfaite.

Le chapitre 3 définit le PSE et la taxe pigouvienne de second rang. Nous supposons un modèle où les agriculteurs répartissent leur terre entre une agriculture conventionnelle, biologique et des bandes enherbées. Le régulateur fixe une taxe environnementale sur l'agriculture conventionnelle, génératrice de dommages environnementaux et un PSE sur les bandes enherbées favorisant la biodiversité. Le secteur conventionnel est concurrentiel et le secteur de l'agriculture biologique oligopolistique. Il s'avère que la taxe environnementale de second rang est supérieure au dommage marginal, tandis que le PSE de second rang est inférieur au bénéfice marginal. Le coût marginal social des fonds publics (MCF) est ensuite introduit. Si la taxe environnementale augmente avec le MCF, le PSE diminue avec le MCF si la demande pour le bien conventionnel est inélastique. Ces résultats mettent en évidence une composante contributive de la taxe incitative. Ce chapitre expose des cas où le PSE est inefficace.

Le chapitre 4 étudie l'efficacité des PSE basés sur l'additionnalité. Ces PSE permettent de prendre en compte des préoccupations d'ordre budgétaire, en ne basant le paiement que sur les services environnementaux supplémentaires obtenus. Nous supposons un modèle à deux périodes où un agriculteur répartit ses terres entre une production biologique, une production conventionnelle causant des dommages à l'environnement et des bandes enherbées génératrices de services environnementaux. Le PSE est introduit dans la dernière période. Ce PSE additionnel génère des distorsions dans le comportement de l'agriculteur en première période afin d'obtenir un paiement plus important en période finale. Le PSE de second rang prenant en compte cette distorsion est égal à la différence actualisée des bénéfices environnementaux marginaux obtenus à chaque période. En présence de PSE additionnels, les taxes environnementales de second rang ne sont plus égales au dommage marginal et s'ajustent pour tenir compte des distorsions causées par le PSE. Un pouvoir de marché sur le marché biologique est ensuite introduit. Il réduit la distorsion due à l'additionnalité dans la période initiale mais aussi la quantité de production biologique dans la période finale. Le PSE additionnel de second rang dépend de l'ampleur de ces deux effets, ce qui modifie également la valeur des taxes environnementales. Le chapitre 4 montre qu'un PSE additionnel ne permet jamais d'atteindre l'efficacité environnementale, même lorsque les marchés fonctionnent de façon concurrentielle.

Le chapitre 5 analyse le principe de « pas de perte nette » d'une politique de protection de la biodiversité, couplé à la séquence Eviter Réduire Compenser (ERC). Il étudie le comportement d'un aménageur confronté à cette politique. L'analyse souligne la difficulté à transposer dans l'analyse économique les concepts de la séquence ERC. Supposant un cadre d'information parfaite, il est montré que la demande de compensation ne dépend pas de son prix, contrairement à l'offre de compensation. En information asymétrique, le développeur utilise son information de façon stratégique. Il définit simultanément sa demande de compensation et le niveau de réduction des dommages en fonction du prix de la compensation. Au final, le choix du projet se base aussi sur ce prix. Le chapitre 5 montre que la séquence ERC est inefficace à protéger la biodiversité lorsque l'information est asymétrique.

Mots-clés : Protection de la biodiversité · Paiements pour services environnementaux · Coût social des fonds publiques · Pouvoir de marché · Additionnalité · Hiérarchie de compensation

Codes JEL : Q57 · Q58

Abstract

The thesis studies the optimal implementation of payments for environmental services (PES) under imperfect competition. It draws lessons from public economics for regulators on how to implement PES to protect biodiversity. The results show cases where PES is ineffective at promoting biodiversity. The thesis consists of four chapters. Chapter 2 reviews the literature on PES, while Chapters 3, 4 and 5 each examine an aspect of imperfect competition.

Chapter 3 designs the second-best PES and environmental tax under imperfect competition. Farmers allocate their land between conventional agriculture, organic agriculture, and buffer strips. The regulator sets an environmental tax on conventional agriculture as it causes environmental damages, and a PES on buffer strips as they favor biodiversity. The conventional sector is perfectly competitive, while the organic sector is organized under an oligopoly. We show that the second-best environmental tax is higher than the marginal damage while the PES is lower than the marginal benefit. We then include the social cost of public funds (MCF). The environmental tax increases and the PES decreases with the MCF as long as demand for the conventional good is inelastic. We thus highlight a contributory component of the incentive tax. Chapter 3 also identifies specific scenario where the PES is ineffective.

Chapter 4 studies the efficiency of additionality-based PES. They can address budget constraint concerns by only paying for additional environmental services. We look at a farmer who allocates his land between organic production, conventional production causing environmental damage, or grass strips generating biodiversity. Using a two-period model, we introduce a PES in the final period, rewarding the additional grass strips provided by the farmer. We show that the additionality-based PES distorts the behavior in the initial period in order to get more payment in the final period. The second-best PES to limit this behavior equals the discounted difference of the marginal environmental benefits obtained in each period. We define the second-best value of environmental taxes in the presence of the additionality-based PES. They no longer equal the marginal damage and adjust to account for the distortions caused by PES. We then introduce market power in the organic market. Market power reduces the distortion due to the PES in the initial period but reduces the organic production quantity in the final period. The second-best PES depends on the size of both effects and environmental taxes under market power have to be amended. In any case, Chapter 4 shows that an additionality-based PES never achieves environmental efficiency, even in a competitive market framework.

Chapter 5 focuses on the “no net loss principle” of a biodiversity protection policy, accompanied by the Avoid Reduce Compensate (ARC) sequence and studies the behavior of a developer facing this policy. The analysis highlights the difficulty of transposing the concepts of the ARC sequence into economic analysis. Assuming perfect information, we show that the demand for compensation does not depend on its price, unlike the supply of compensation. Under asymmetric information, the developer behaves strategically. He simultaneously defines his demand for offsets and the level of damage reduction based on the offset price. In the end, the project choice is made based on the price of the offset. Chapter 5 shows that the mitigation hierarchy is ineffective under asymmetric information.

Keywords : Biodiversity Conservation · Payments for Environmental Services · Marginal Social Cost of Public Funds · Market Power · Additionality · Mitigation Hierarchy

JEL Codes : Q57 · Q58

Contents

CHAPTER 1

Introduction

1.1 From biodiversity to environmental services

The Convention on Biological Diversity (CBD) defines biodiversity as “the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems” (Convention on Biological Diversity, 2010). A diversity of life and ecosystems also allows for a diversity of environmental services. Dasgupta (2021) has made the comparison to financial portfolios, where a diversity of investments helps mitigate risks; biodiversity can similarly help to mitigate risks to help nature be more productive, resilient, and adaptable.

The decline in biodiversity is a well-documented phenomenon, which is likely to worsen with climate change (Díaz et al., 2019; Ruckelshaus et al., 2020; Dasgupta, 2021). One of the main causes of biodiversity decline is the loss of various habitats due to land use change (Lewis et al., 2011; Bamière et al., 2013). A large part of the terrestrial biodiversity loss has occurred on agricultural lands, which were once home to an abundance and variety of species, but land intensification and increasing farm size has transformed and fragmented natural habitats, leading to a decline in many species. According to Dasgupta (2021), an estimated 20 percent of species may become extinct in the next few decades, and perhaps double that by the end of the century.

In 1977 the term ‘nature’s services’ first appeared in the academic literature in a paper by Walter Westman (Westman, 1977). This was followed by the term “ecosystem services”, which first appeared in the literature in 1981 (Costanza et al., 2017). However, it was not until the late 1990s, when an article in Nature estimated that the total value of all ecosystem services in the biosphere was between 16-54 trillion USD, that ecosystem services gained substantial popularity as a topic in academic literature (Costanza et al., 1997).

The Millennium Ecosystem Assessment explains that "Ecosystem services are the benefits people obtain from ecosystems. These include *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 economic literature distinguishes between ecosystem services and environmental services (ES). The term "ecosystem services" refers to the benefits provided by ecosystems while "environmental services" refers to the protection of these ecosystems by humans and to the notion of externalities induced by human activities. For example, the Food and Agriculture Organization of the United Nations (FAO) proposes a definition of ES in terms of ecosystem services. For agriculture, ES are defined as the subpart of ecosystem services that can be qualified in terms of externalities, that is, all ecosystem services except provisioning services (Lugo, 2007). ES can be used to refer to the production of services by farmers to protect the environment. We can cite several examples. Long crop rotations improve ecosystem services such as supporting 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 buffer strips, slopes, hedgerows, or watercourses contribute to the ecological functioning of agroecosystems. All of these definitions make it possible to justify the remuneration for these ES as an internalization of externalities. This leaves room for policy intervention to encourage their optimal provision, such as payments for environmental services (PES), which have become a familiar tool for conserving and restoring ecosystems and the services they provide (Dasgupta, 2021).

1.2 Payments for environmental services

One of the most widely cited definitions of PES comes from Wunder (2005), which defines PES as a voluntary transaction in which a well-defined ES or land use that can produce that service is purchased by (at least) one ES buyer from (at least) one ES provider if and only if the ES provider guarantees the provision of ES (conditionality). Conditionality can be difficult to assess in outcome-based PES schemes, as some ES are difficult to measure. In practice, it is much more common to see action-based PES schemes that are conditional on specific land use or management practices.

The above definition illustrates the Coase theorem, whereby an externality can be resolved by private negotiation and the optimal allocation of ES can be achieved, regardless of the initial property allocation and assuming sufficiently low transaction costs and well-defined property rights (Coase, 1960). An example of a Coasean PES is the Vittel PES in northeastern France, where Nestlé made an agreement with local farmers to compensate them for reducing their use of fertilizers in order to prevent nitrate pollution in the aquifers (Bingham, 2021).

The definition of PES can be expanded to include certain types of government interventions that reflect a Pigouvian subsidy (Pigou, 1920; Sattler and Matzdorf, 2013). This type of PES is much more common in practice than a Coasean PES. For example, European agri-environmental schemes (AES) are publicly funded, and the government acts as an intermediary between the buyers of ES (the public) and the sellers of ES (the farmers who receive PES grants). Both Coasean and Pigouvian PES schemes follow the beneficiary-pays principle.

Yet another alternative definition is provided by Muradian et al. (2010), describing PES as a transfer of resources between social actors, which aims to create incentives to align individual and/or collective land use decisions with social interest in natural resource management. This definition is more flexible than that of Wunder (2005), and better reflects what happens in actual PES schemes than what should happen in theory. This definition also reflects the fact that payments are not necessarily monetary, but can also be in-kind transfers.

Various forms of PES programs have been implemented in both developing and developed countries. In the United States, the Conservation Reserve Program has been in place since 1985 (Hellerstein, 2017). Costa Rica is one of the first countries to adopt a national PES program, establishing theirs in 1997 (Pagiola, 2008). In China, the Sloping Land Conversion Program and Natural Forest Conservation Program invested over 50 billion USD from 2000-2009 (Salzman et al., 2018). One program that links developed and developing countries is REDD+, conceptualized in 2007 which is aimed at reducing carbon emissions from deforestation and forest degradation by incentivizing developing countries to keep their forests in tact by offering payments financed by developed countries for actions taken to reduce or stop deforestation (Chiroleu-Assouline et al., 2018). Biodiversity protection policies often focus on agricultural lands, such as the AES in Europe, which member states have been required to apply since 1992. AES are a type of PES that remunerate farmers for voluntary actions taken to preserve and improve the environment. In fact, in the European Union, the largest source for practical nature conservation comes from the AES applied under the Common Agricultural Policy (CAP) (Herzon et al., 2018). Practices adopted under the AES include the reduction of fertilizers and/or pesticides, the establishment of grass buffer strips near rivers, and adaptations to crop rotations. More recently, according to the 2018 National Biodiversity Plan in France, water agencies are testing their own PES programs. They have been allocated 150 million euros from France's national budget, with the objective of maintaining or creating good ecological practices, such as reducing pesticides, planting cover crops, etc. This new program also aims at results-based instead of action-based payments, with annual monitoring to determine the results. Either maintaining or creating good practices will be rewarded, but creating good practices will receive higher payments (up to 676 euros/ha/year, compared to up to 66 euros/ha/year for the maintenance of good practices).

Classifying the wide variety of PES schemes is not an easy task. As Sattler et al. (2013) point out, PES schemes rely on a multitude of approaches that differ greatly in terms of the ES addressed, price formation mechanisms, origins and levels of payment, characteristics of buyers and sellers, rules governing the contract between the parties involved, level of complexity, etc. According to Wunder (2005), the main ES addressed by PES are carbon sequestration and storage, biodiversity protection, watershed protection and landscape beauty.

1.3 Motivation

Despite the vast literature on PES, there are still research questions to explore. First, there is a need to analyze how PES interact with other public policies, such as Pigouvian taxes, and to define their level in multi-policy contexts. There are already a few studies that look at the interactions between public policies. According to Bryan and Crossman (2013), the interaction effects of multiple financial incentives can reduce the effectiveness of policies when multiple incentives encourage the provision of services from agro-ecosystems. Agri-environmental measures need to take into account that policies are typically packages of different policy tools arranged in policy mixes and that financial incentives for different ecosystem services interact (Huber et al., 2017). Finally, Lankoski and Ollikainen (2003) provide an interesting framework for a theoretical analysis to find the optimal level of a PES and Pigouvian tax in the agricultural sector.

Another question not well developed in the PES literature is how market power can change the optimal level of PES. This question has already been addressed in the literature on Pigouvian taxes, which has found that under market power, the optimal second-best tax should be less than the marginal damage (Barnett, 1980; Ebert, 1991). However, no papers on the level of PES under imperfect competition have been found. Market power leads to a suboptimal production level, as firms restrict production to increase their profits. Since both taxes and PES influence production levels, they must take into account any market power in order to not further distort production away from the socially optimal level.

Moreover, when PES are publicly funded, it is necessary to raise funds through taxes, which can then distort markets. Increasing contributory taxes can alter the allocation of resources in an economy by influencing consumption, labor and investment decisions. Therefore, it seems important to take into account the social cost of public funds in our analysis. This is a measure of the welfare loss suffered by society as a result of mobilizing additional revenues to finance public expenditures (Browning, 1976; Dahlby, 2008). For example, Browning (1976) estimates the MCF of the U.S. labor income tax, and finds an MCF of 1.09−1.16 per dollar of tax revenue collected. According to Beaud (2008), this cost is equal to 1.2 for France. Thus, when the regulator collects one euro of tax, it costs society 1.2 euros. This aspect should therefore not be neglected in the decision to set up a PES.

Next, an important factor in the economic efficiency of PES programs is whether or not they are additional, that is, whether they entail the provision of an ES that would not have occurred in the absence of any payment. Early in the development of PES, the majority of programs had no additionality requirement, perhaps due to the idea that monitoring additionality would prove too costly. Or, as in the case of Costa Rica's national program, the goal may be to recognize and pay for any provision of ES regardless of its additionality. It is only more recently that the assessment of additionality of PES programs has become a concern, even though it is essential for a PES scheme to achieve its environmental objective with economic efficiency while maintaining investor confidence (Bennett, 2010).

Finally, mitigation banks are a type of PES, as both instruments involve paying for actions to restore, preserve, and/or manage biodiversity and ecosystems. Indeed, Salzman et al. (2018) refer to mitigation banks as a type of compliance PES. Rather than using a Pigouvian subsidy, the mitigation bank involves tradable permits, and is therefore a quantity rather than a price mechanism. Before credits can be purchased from a mitigation bank, one must, in theory, follow what is called a mitigation hierarchy with the goal of no net loss (of biodiversity or environmental services). When designing a project that will have negative impacts on the surrounding environment, a developer must first avoid any possible damage by modifying the project. Next, any damage that cannot be avoided must be reduced. Finally, any residual damage after avoiding and reducing must be compensated, either by restoring another equivalent area of land or by purchasing credits from a mitigation bank. However, in reality, the mitigation hierarchy is not properly followed, as it is not rational to do so.

1.4 Contributions

The objective of this thesis is to analyze these questions, in order to deepen the knowledge of PES. This thesis consists of a review of the literature on PES and then three papers in which we address some of the remaining gaps in the literature on PES.

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

The implementation of PES may face a financing constraint, especially when the buyer is a public regulator. An additionality-based PES can address this problem by only paying for additional ES. The objective of the second paper is to study the efficiency of an additionality-based PES. 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 adjusted 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. In any case, the second paper shows that an additionality-based PES never achieves environmental efficiency, even in a competitive market framework. Furthermore, it provides new insights into understanding the interactions between different environmental policies in the presence of several types of distortions.

Finally, the third paper focuses on the no net loss principle of a biodiversity protection policy, accompanied by the “avoid, reduce, compensate” (ARC) sequence and studies the behavior of a developer facing this policy. The definition of each step in the sequence is highly conceptual. First, we show that it is difficult to transpose into a microeconomic decision model. Starting with a perfect information scenario, we show that the demand for compensation does not depend on its price, unlike the supply of compensation. We then assume that the regulator does not have the same information as the developer about the environmental damage of the project or the marginal costs of reducing the damage. In this case, the developer strategically uses this asymmetric information. Using backward induction reasoning, he simultaneously defines his demand for offsets and the level of environmental damage reduction based on the offset price. In the end, the project choice is made by also taking into account the price of the offset. The third paper shows that the mitigation hierarchy is ineffective under asymmetric information, making the safeguarding of biodiversity inefficient.

Chapter 2

Payments for Environmental Services: A literature review

This literature review begins by defining payments for environmental services in Section 2.1 followed by a discussion of the literature regarding the efficiency of PES programs in Section 2.2. Next, Section 2.3 reviews the literature on the agglomeration bonus, which aims to improve the environmental outcomes of PES schemes. Then, Section 2.4 reviews the literature on mitigation banking, which can be thought of as a PES program that is quantity-based instead of price-based. Finally, Section 2.5 concludes.

2.1 Defining payments for environmental services

We begin by defining biodiversity and discussing its importance to human well-being. Then, we discuss the definition of payments for environmental services, a policy that aims to conserve biodiversity.

2.1.1 From biodiversity to environmental services

The Convention on Biological Diversity (CBD) defines biodiversity as "the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (Convention on Biological Diversity, 2010). A diversity of life and ecosystems also allows for a diversity of environmental services. Dasgupta (2021) made the comparison to financial portfolios, where a diversity of investments helps mitigate risks; biodiversity can likewise help to mitigate risks to help nature be more productive, resilient, and adaptable.

The decline in biodiversity is a well-documented phenomenon, which is likely to worsen with climate change (Díaz et al., 2019; Ruckelshaus et al., 2020; Dasgupta, 2021). One of the main causes of biodiversity decline is the loss of various habitats due to land use change (Lewis et al., 2011; Bamière et al., 2013). A large part of the terrestrial biodiversity loss has occurred on agricultural lands, which were once home to an abundance and variety of species, but land intensification and increasing farm size has transformed and fragmented natural habitats, leading to a decline in many species. According to Dasgupta (2021), an estimated 20% of species may become extinct in the next few decades, and perhaps double that by the end of the century.

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2.1.2 Payments for environmental services

One of the most widely cited definitions of PES comes from Wunder (2005), which defines PES as a voluntary transaction in which a well-defined ES or land use that can produce that service is purchased by (at least) one ES buyer from (at least) one ES provider if and only if the ES provider guarantees the provision of ES (conditionality). Conditionality can be difficult to assess in outcome-based PES schemes, as some ES are difficult to measure. In practice, it is much more common to see action-based PES schemes that are conditional on specific land use or management practices.

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Yet another alternative definition is provided by Muradian et al. (2010), describing PES as a transfer of resources between social actors, which aims to create incentives to align individual and/or collective land use decisions with social interest in natural resource management. This definition is more flexible than that of Wunder (2005), and better reflects what happens in actual PES schemes than what should happen in theory. This definition also reflects the fact that payments are not necessarily monetary, but can also be in-kind transfers.

Over 550 active PES programs exist globally, with an estimated 36-42 billion USD in annual transactions (Salzman et al., 2018). In the United States, the Conservation Reserve Program has been in place since 1985 (Hellerstein, 2017). Costa Rica is one of the first countries to adopt a national PES program, establishing theirs in 1997 (Pagiola, 2008). In China, the Sloping Land Conversion Program and Natural Forest Conservation Program invested over 50 billion USD from 2000-2009 (Salzman et al., 2018). One program, conceptualized in 2007, that links developed and developing countries is REDD+, which aims to reduce carbon emissions from deforestation and forest degradation by incentivizing developing countries to keep their forests in tact by offering payments financed by developed countries for actions taken to reduce or stop deforestation (Chiroleu-Assouline et al., 2018). Biodiversity protection policies often focus on agricultural lands, such as the AES in Europe, which member states have been required to adopt since 1992. AES are a type of PES that remunerate farmers for voluntary actions taken to preserve and improve the environment. In fact, in the European Union, the largest source for practical nature conservation comes from the AES applied under the Common Agricultural Policy (CAP) (Herzon et al., 2018). Practices adopted under the AES include the reduction of fertilizers and/or pesticides, the establishment of grass buffer strips near rivers, and adaptations to crop rotations. More recently, according to the 2018 National Biodiversity Plan in France, water agencies are testing their own PES programs. They have been allocated 150 million euros from France's national budget, with the objective of maintaining or creating good ecological practices, such as reducing pesticides, planting cover crops, etc. This new program also aims at results-based instead of action-based payments, with annual monitoring to determine the results. Either maintaining or creating good practices will be rewarded, but creating good practices will receive higher payments (up to 676 euros/ha/year, compared to up to 66 euros/ha/year for the maintenance of good practices).

Classifying the wide variety of PES schemes is not an easy task. As Sattler et al. (2013) point out, PES schemes rely on a multitude of approaches that differ greatly in terms of the ES addressed, price formation mechanisms, origins and levels of payment, characteristics of buyers and sellers, rules governing the contract between the parties involved, level of complexity, among others. According to Wunder (2005), the main ES addressed by PES are carbon sequestration and storage, biodiversity protection, watershed protection and landscape beauty.

2.2 Are PES programs efficient?

The literature regarding the efficiency of PES programs includes theoretical models, lab experiments, and empirical analyses of real world programs. Most studies evaluate the cost-effectiveness of PES programs, which entails either maximizing ES provision for a given budget, or minimizing the budget to provide a given level of ES.

Many of the obstacles to PES program efficiency originate from the asymmetric information between ES buyers and sellers regarding the costs that ES sellers incur when participating in a PES scheme. The PES literature investigates how asymmetric information impacts the additionality of PES programs and proposes solutions to reduce information asymmetries, such as reverse auctions. Other topics to consider when analyzing PES policy efficiency include transaction costs, the social cost of the public funds raised to finance PES programs, and their long-term impacts.

When designing efficient PES contracts, one must consider the asymmetric information about conservation between the ES seller(s) and the ES buyer(s), whether the buyer is a private individual or a public regulator. Asymmetric information gives rise to two incentive problems: moral hazard (hidden action) and adverse selection (hidden information) (Latacz-Lohmann and Van der Hamsvoort, 1998; Ferraro, 2008). Moral hazard arises from the buyer's imperfect information about contract compliance. Empirically, monitoring studies in England, Germany, and the US have found that as few as 4% or as many as one-third of participants did not fully comply with their contractual obligations (Hart and Latacz-Lohmann, 2005). Adverse selection arises because of asymmetric information about conservation costs, which can lead to informational rents for landowners, as they have incentive to inflate their costs in order to receive higher payments. According to Börner et al. (2017), adverse selection is likely to be more severe where baseline compliance levels are high, payments are too low to cover compliance costs, and program take up rates are low. ES buyers need to reduce informational rents if they want to maximize the environmental services obtained within their budget constraint (Ferraro, 2008). Moreover, selecting the lowest-cost ES sellers can also imply lower ES gains than selecting high-cost sellers.

The rest of this section analyzes factors that influence the efficiency of PES. First, the literature on the additionality of PES programs is explored. Next, we look at whether conservation auctions can improve efficiency compared to fixed payments. Finally, this section concludes with a discussion of other points analyzed in the literature on PES efficiency.

2.2.1 Additionality

One of the main concerns when evaluating PES programs is whether or not they are *additional*; that is whether they lead to the provision of environmental services that would not have been provided otherwise. If a program pays for ES that would have been provided absent any payment, this means they are paying windfall gains to the ES seller. 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). Adverse selection and moral hazard as described above both offer challenges to achieving additionality, and Sills et al. (2008) describe two other challenges, namely spillovers or leakage, 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 (Pattanayak et al., 2010). 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.

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 prohibitively costly, a regulator or other ES buyer may rely on the ES seller to report this information. 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. When the ES buyer is a public regulator, the issue of additionality is even more important as it prevents wasting public funds. Determining the baseline ES provision for many individual sellers can be quite costly, so 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. When the PES payments are conditioned on a group's additionality they find that lower contributors raised their contributions and overall additionality increased.

Additionality concerns are particularly important for carbon markets (Bennett, 2010). Those paying for carbon offset credits risk paying forest managers to protect forest area that would have remained in tact in the absence of any payments. Moreover, leakage of the deforestation activities may occur if a forest PES leads to market conditions that make it more profitable for forest managers in other regions to increase their deforestation rates, thus leading to a displacement of carbon emissions from deforestation rather than a net increase in carbon sequestration. Since the objective behind carbon offsets is to achieve net zero carbon emissions in order to limit global climate change, the additionality of such a program is crucial.

The additionality literature includes theoretical models of conservation contracts. For example, Mason and Plantinga (2013) look at contracts for carbon sequestration from land placed in forest use serving as offsets to meet emissions reduction goals. A government or business seeking to purchase offsets to reduce their emissions will want to minimize expenditures while maximizing additionality, 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 in the absence of any payment. The authors 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 it does not achieve the first best 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 and Hendricks (2020) take another approach to additionality, framing 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 get a subsidy 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. 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.

Other papers have investigated the empirical evidence of additionality in PES schemes. For example, Chabé-Ferret and 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 treated effect on the treated (ATT), defined 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 when there is no additionality in forest cover due to the PES the result is economic loss. Next, Mohebalian and 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. Finally, Ezzine-de Blas et al. (2016) perform a meta-analysis on 55 PES programs around the world and find that additionality is positively influenced by spatial targeting, payment differentiation, and strong conditionality.

2.2.2 Using auctions to reveal conservation cost information

One well-studied policy instrument that could be used to alleviate the problems arising from asymmetric information and to improve the economic efficiency of PES schemes is the reverse auction, where ES sellers submit bids (based on their conservation costs) to the ES buyer, who selects the lowest bidder(s). Latacz-Lohmann and Van der Hamsvoort (1997) is the first paper to look at using reverse auctions for conservation contracts. Using simulations of a theoretical model they demonstrate that, compared to fixed rate PES payments, competitive bidding can significantly increase the cost-effectiveness of an agricultural PES program by reducing the information rents for the bidders and by encouraging higher opportunity cost farmers to participate, which can increase environmental effectiveness. Furthermore, these advantages of auctions compared to fixed payments increase when the initial information asymmetry is more severe. The authors analyze the farmer's optimal bidding strategy, which is to maximize net profit while maintaining a high enough probability of bid acceptance, given his expectations of the maximum acceptable bid. Furthermore, bidding strategy will depend on the risk attitude of the farmer. If the farmer is risk-neutral, his optimal bidding strategy will be a linearly increasing function of opportunity costs and the expected bid cap. For a risk averse farmer, the conservation payment can be considered as a non-stochastic income component, and the optimal bid will depend on foregone profits and the difference in risk premiums.

Another theoretical model by Lewis and Polasky (2018) builds on previous works from

Vickrey (1961) Clarke (1971), Groves (1973), and Polasky et al. (2014) and defines an auction mechanism that implements optimal environmental service provision over time. They allow for the benefits from the environmental services to change over time, depending on the landscape pattern and climate change. Their auction design leads to landowners truthfully revealing their private information about the returns they would receive in an alternate use that does not provide environmental services while bidding on current and future development values of their land. Additionally, their auction mechanism can either be used in a procurement auction where bidders compete for a subsidy, or it can be used in a normal auction where bidders compete for development rights on the land, which is useful when environmentally important areas are owned by the government.

Auctions are used to allocate PES contracts in different programs around the world. The United States Department of Agriculture (USDA) has been using an auction mechanism to allocate land retirement contracts through the Conservation Reserve Program (CRP) since 1986 (Latacz-Lohmann and Van der Hamsvoort, 1997). Latacz-Lohmann and Van der Hamsvoort (1998) describe two types of auctions that can be used for countryside public goods provision. The first type, which the US CRP exemplifies, is a government procurement auction, where a government agency acts as the buyer and the farmers act as sellers, and the commodity being traded is a public good. The second type is an auction of certificates, where the traded commodity is property rights to receive pre-determined financial rewards for the provision of countryside benefits, with the government agency acting as the seller and farmers as the buyers, paying in terms of environmental commitments.

2.2.2.1 Factors affecting auction efficiency

Different design features and rules can impact auction efficiency in different contexts. Uniform price auctions pay all winning bidders the same level, often the highest accepted bid, while discriminatory price auctions pay each winning bidder their bid level. Uniform price offers more incentive for bidders to reveal their true costs since the payment level is not necessarily the same as their bid. Sealed bidding keep bids private while open bidding allows bidders to know each other's bids. Auctions may be budget constrained, where they accept the lowest bids up until a budget level is reached. Alternatively, they could be target constrained, i.e., the lowest bids are accepted until a certain area of land is enrolled. The criteria used to accept or reject bids may also combine the price with an estimated value of the environmental benefits that would be provided. For example, the US CRP procurement auction uses an environmental benefits index (EBI) to select land for enrollment (Claassen et al., 2008). Finally, whether or not auctions are repeated will impact their efficiency as bidders have the opportunity to adjust their expectations about the maximum acceptable bid when auctions are repeated.

Much of the work on conservation auctions has involved lab experiments and Schilizzi (2017) provides an overview of results from these studies that analyze different causal and outcome factors of auction features. In regard to the format of the auction, the author's key findings include that discriminatory price auctions perform better than uniform price auctions in terms of cost-effectiveness, despite bid shading, although uniform pricing is better for learning about unknown conservation costs. Kawasaki et al. (2012) looks at compliance in conservation auctions both theoretically and using a lab experiment. While the theoretical analysis predicts that budgetary cost-effectiveness, allocative efficiency, total payment, and number of compliant winners will be equal between the two payment types, the lab experiment resulted in higher budgetary cost-effectiveness and allocative efficiency when payments were uniform than when they were discriminatory. Furthermore, they found that in a repeated auction setting budget-constrained auctions are more robust than target-constrained auctions. When communication is allowed among bidders, uniform pricing mitigates collusion rents relative to discriminatory pricing. Similarly, when cost curves are more heterogeneous, uniform pricing should also perform better than discriminatory pricing. Arnold et al. (2013) found that a budget-constrained discriminatory auction may decrease the pool of potential bidders, inducing adverse selection. Another interesting result comes from Cason and Gangadharan (2004) who summarize a lab experiment that showed that landowners increased their bids when they were given information before bidding about the environmental benefits of the actions they planned to take if they won the contract. Glebe (2013) later confirmed this finding theoretically, but also found that revealing environmental benefit information could induce higher participation rates for the auction and a thicker market.

A more recent paper by Santos et al. (2021) incorporates the idea of asset specificity to conservation auctions to see how cost-effectiveness is impacted. They argue that participating in a PES scheme can require making investments that are specific to ES provision and these investments yield lower returns in any alternative use. Consequently, this can lead to potential PES participants requiring higher payments to compensate for risk, or asking for ex-ante rather than ex-post payments, which can lower the incentive to comply with program requirements. The authors use an agent-based model to simulate a PES scheme that aims to increase carbon capture by paying for the retirement of land from agricultural production, the investment in reforestation, and the conservation of these trees. They evaluate the cost-effectiveness of uniform and discriminatory auctions to allocate the PES contracts to liquidity constrained land users who require ex-ante payments in order to finance their initial investment. Their results imply that a higher number of long-term contracts can be allocated by auctions as compared to fixed payments. Moreover, they find that discriminatory auctions are more additional and cost-effective than uniform price auctions. When land users have high time preferences (and thus high discount rates), short-term contracts are more cost-effective than long-term contracts. Finally, they find that asset specificity, liquidity constraints, high time preferences, and absence of trust in the agency can all exacerbate the challenge of asymmetric information.

2.2.2.2 Potential drawbacks of auctions

Auctions for public goods such as environmental services diverge from the standard auction model in several ways, which can make them more vulnerable to failure. Compared to fixed payments, auctions provide the most benefits when the informational asymmetry and number of potential participants are high, contracts are homogeneous, farms are heterogeneous, and when the environmental service production is separable between farms (Latacz-Lohmann and Van der Hamsvoort, 1998). The two main drawbacks of using auctions in the provision of public goods are higher transaction costs than fixed payments and the potential for strategic bidding due to the common-value characteristic of public goods (Latacz-Lohmann and Van der Hamsvoort, 1998).

Additionally, conservation contract auctions also generally involve multiple sign up periods (sequential auctions), which can be affected by Bayesian learning, leading to higher average bids and a smaller distribution of bids as bidders learn what the highest accepted bid is (Latacz-Lohmann and Van der Hamsvoort, 1997). In fact, Schilizzi and Latacz-Lohmann (2007) found that while both budget-constrained and target-constrained discriminatory price auctions had higher cost-effectiveness than fixed payments in a single time period, the gain from using an auction diminished when considering multiple time periods.

Indeed, while much of the literature on conservation auctions suggests they are likely more efficient than fixed payments, other studies investigate scenarios where auctions do not improve the cost-effectiveness of PES programs. Lundberg et al. (2018) use a conceptual agent based simulation model to assess the cost-effectiveness of fixed payments and procurement auctions in different contexts. They find that contextual factors such as baseline compliance rates, the distribution of provision costs across the landscape, and the correlation of provision costs and ES provision affect whether fixed payments or procurement auctions are more cost-effective. Their results show that discriminatory auctions are likely to be the most effective design when baseline compliance is low and/or when differentiated payments are politically feasible, i.e. perceived to be fair. A fixed payment scheme that offers high payments and uses targeting is more likely to be additional in contexts where baseline compliance is high, the correlation between ES provision and costs is positive, and/or the budget for the program is small. In this context, auctions could exacerbate the adverse selection problem, leading to lower additionality and thus lower cost-effectiveness. However, even when fixed payments are preferred, an initial one-shot auction may be useful to gather information about provision costs in order to set an appropriate price for the fixed price scheme.

Arguedas and van Soest (2011) evaluate the cost-effectiveness of using a menu of contracts, as suggested by previous literature (Smith, 1995; Smith and Tomasi, 1995; Wu and Babcock, 1995, 1996; Moxey et al., 1999) compared to procurement auctions. While offering a menu of contracts can improve efficiency compared to uniform fixed payments, contract menus are rarely used in practice (Ferraro, 2008). Designing a menu of contracts requires more information, which can be costly to acquire, and the menu of contracts that would be offered under perfect information is typically not incentive-compatible where there is asymmetric information, meaning the net benefits of offering a menu of contracts may be too low to justify the costs of acquiring the necessary information. However, Arguedas and van Soest (2011) show that if conservation costs include fixed costs as well as variable costs the complete information solution can be incentive compatible in the presence of asymmetric information, as long as ES providers with lower variable costs face higher fixed costs (and vice versa). This is likely to occur if the same circumstances are conducive to both conservation and production. For example, hydrological circumstances in arid regions can lead to negatively correlated fixed and variable costs of conservation as less access to water can make the fixed costs of restoring habitat higher, but variable opportunity costs lower as the land would be less productive for agriculture.

2.2.3 Other considerations

Here, we look at transaction costs, other benefits of PES, the duration of contracts, motivational crowding, and the marginal social cost of public funds.

2.2.3.1 Transaction costs

The transaction costs involved in implementing PES policies are another main obstacle to achieving efficiency (Börner et al., 2017). Indeed, Salzman et al. (2018) cite low-transaction-cost institutions as one of four key features needed to scale up PES. Williamson (1975) distinguishes between ex-ante and ex-post transaction costs, with the former including the costs of information gathering, preparing, and negotiating a conservation agreement, while the latter includes the costs of monitoring compliance and any conflict resolution costs. There is often a tradeoff between improving the effectiveness of a policy and increasing transaction costs. For example, the ex-ante transaction costs for an auction are likely to be higher than for a fixed payment scheme (Latacz-Lohmann and Van der Hamsvoort, 1998). Similarly, a PES that includes spatial targeting to improve cost-effectiveness implies higher transaction costs (Uthes et al., 2010).

Armsworth et al. (2012) uses an ecological-economic model to assess the effectiveness of different payment schemes that vary in complexity, and thus transaction costs. They define an optimal policy design that maximizes biodiversity improvement for a given budget while leaving each farmer indifferent between participating or not in the PES, i.e. the payments only cover the participation costs and offer no windfall gains. Next, they evaluate policies that add simplifications, namely using a uniform fixed payment and no spatial targeting, both of which are commonly used to simplify existing agri-environmental schemes. Compared to the optimal policy, they find that the policy simplifications lead to a 49-100% reduction in biodiversity provision for a given budget level. Moreover, they find that the added implementation costs of the more complex optimal policy are worth incurring, even if they amount to over 70% of the payments that would have otherwise gone to the participating farmers.

2.2.3.2 Other benefits to consider

Although levying taxes to finance PES programs can lead to social costs, PES programs can sometimes offer benefits other than environmental services. A strand of the literature on PES in developing countries looks at poverty alleviation as a possible secondary objective of PES programs (e.g., Suich et al. (2015); Wünscher and Wunder (2017); Ola et al. (2019) among others). PES programs may also have other positive impacts in developed countries as well. Schirpke et al. (2018) evaluated the socio-economic benefits of 50 cases in 21 Natura 2000 sites in Italy and found that, in addition to improvements in defined conservation objectives, there were positive effects on socio-economic development of the local communities.

2.2.3.3 Contract duration

Most existing PES programs involve contracts for relatively short periods of time, often five or ten years, raising the question of whether ES provision will continue or be reversed once payments end. This is commonly referred to in the literature as permanence, and sometimes also referred to as persistence, continuance, maintenance, or confirmation (Dayer et al., 2018). Empirically, a recent study by Kemigisha et al. (2023) found weak permanence in a PES program in Uganda where it was clear that forest owners had abandoned the PES-induced practices four years after payments ended.

2.2.3.4 Motivation crowding: what happens after PES?

Related to the permanence concern is the idea of motivational crowding, the idea that extrinsic motivations, such as financial payments like PES, can "crowd out" the intrinsic motivations in individuals that may arise from altruism or pro-social attitudes and undermine long-term conservation efforts (Kosoy and Corbera, 2010; Vatn, 2010; Gómez-Baggethun and Ruiz-Pérez, 2011; Luck et al., 2012; De Snoo et al., 2013; Muradian et al., 2013). Alternatively, participation in a PES scheme could potentially "crowd in" intrinsic motivation for conservation. Whether a PES scheme crowds in or crowds out intrinsic motivations will impact the likelihood of the scheme persisting after payments end. This is important, as some PES programs state permanence of the land uses or management techniques being incentivized as an objective of the program. For example, the National Landcare Program in Australia is based on the idea that investments will lead to long-term changes in management practices (Dayer et al., 2018). Pro-environmental attitude shifts are also an implicit goal of voluntary agri-environmental schemes in the EU (Burton et al., 2008).

Albers et al. (2008) investigate whether motivation crowding occurs when a public and a private entity interact in conservation. They look at how properties of the conservation benefit function can impact the interaction between the private and public entities. Specifically, they look at how results change when the private entity's benefit function displays diminishing marginal benefits versus increasing marginal benefits. They find that whether increased public conservation crowds out private conservation will depend on the trust's benefit function. If it displays diminishing marginal benefits private conservation will be crowded out, whereas if it displays increasing marginal benefits, private conservation will be crowded in.

Dayer et al. (2018) suggest five theory-based explanations, which likely covary and interact with one another, for whether conservation behaviors can be expected to persist or revert when payments stop. First, they address landowner cognitions, i.e. attitudes toward the environment and certain management practices, and posit that if a conservation program can positively change landowner cognitions, permanence is more likely to occur. Empirically, Kuhfuss et al. (016a) find that French farmers who perceived a higher quality of life while participating in an agri-environmental scheme were more likely to state an intention to continue the conservation behaviors after payments ended whereas those who experienced technical difficulties had 50% lower intentions to persist. A second explanation is motivation crowding. Indeed, Deci et al. (1999) performed a meta-analysis of social psychology experiments and found evidence of the crowding out effect. Regarding PES programs, several papers have found evidence of crowding out effects (De Snoo et al., 2013; Rode et al., 2015). For example, Kits et al. (2014) uses a lab experiment to evaluate motivation crowding in conservation auctions and found an 18% reduction in beneficial management practices due to motivational crowding. However, Rode et al. (2015) also found four studies that indicated crowding in effects, though out of these four only Rodriguez-Sickert et al. (2008) presented a statistically significant result. Third, if the conservation behavior is habit forming (i.e. simple and frequently repeated actions) it will be more likely to persist after payments. Fourth, they discuss the importance of financial resources, and, of course, having sufficient resources absent any payment to continue the behavior makes persistence more likely. If incentivized practices generate a better sale value for farm products (e.g. a price premium for an eco-labeled product), a farmer will be more likely to continue the practices once the program ends (Kuhfuss et al., 016b; Dayer et al., 2018).

2.2.3.5 Social cost of public funds

Implementing a publicly funded PES program requires raising public funds, which can change the allocation of resources in an economy through impacts on consumption, labor, and investment decisions (Dahlby, 2008). The marginal social cost of public funds (MCF) is a measure of the welfare loss to society as a result of raising additional revenues to finance government spending (Browning, 1976; Dahlby, 2008). Empirically, Browning (1976) estimates the MCF of labor income taxes in the United States, finding a MCF of \$1.09-\$1.16 per dollar tax revenue raised. According to Beaud (2008), this cost is equal to 1.2 for France. Most of the PES literature does not explicitly take the MCF into account when evaluating efficiency, though some papers do acknowledge its impact, e.g. Ferraro (2008). The general lack of consideration of the MCF when evaluating PES efficiency is a clear gap in the literature.

2.3 Agglomeration Bonus

Habitat fragmentation, the process of dividing a contiguous area of natural habitat into smaller, more isolated patches is deemed as a key pressure contributing to biodiversity loss (Wilcove et al., 1986; Fooks et al., 2016). So, the spatial configuration of areas used for biodiversity conservation matters as it impacts the chance a species has to survive. Most commonly, connected land is thought to be better for preserving species (Albers et al., 2018). There are species, however, that prefer other spatial configurations, and this will be briefly discussed later in the literature review. The importance of the spatial connection of habitats has led to the idea of an Agglomeration Bonus (AB), an extension of PES schemes that aims to incentivize neighboring landowners to coordinate their land management decisions to connect habitat conservation areas (Banerjee et al., 2011). This mechanism was first proposed by Parkhurst et al. (2002) and has since been explored by numerous other authors. The agglomeration bonus is a bonus payment on top of a flat participation payment that is awarded to landowners when they conserve contiguous parcels of land. Another possibility is an agglomeration payment, where instead of offering a bonus, the participation payment is also contingent upon achieving contiguous conserved land.

The main drawback of an agglomeration bonus mechanism is the potential for multiple Nash equilibria which entails the classic coordination problem (Parkhurst et al., 2002). Amongst all possible Nash equilibria, there is only one first best equilibrium for society, called the Pareto dominant Nash equilibrium (Parkhurst and Shogren, 2007). The challenge is then getting landowners to coordinate in a way to conserve land that results in the Pareto dominant Nash equilibrium rather than any other equilibrium. Several papers indeed find the existence of multiple Nash equilibria in different scenarios in their models, and coordination failure is documented in some experimental papers (Albers et al., 2008).

Following the suggestion in Parkhurst et al. (2002) to use an agglomeration bonus, other authors have used simulations and experiments to study different properties of agglomeration bonuses. The first subsection will address how the literature evaluates the success of the agglomeration bonus mechanism in regard to conservation goals, compared to other mechanisms. Next, some authors look at how changing the design or accounting for transaction costs impacts the efficiency of the agglomeration bonus. Finally, this section concludes with a discussion of existing agglomeration bonus schemes in the US and Switzerland.

2.3.1 Evaluating the Agglomeration Bonus

The literature addressed in this review mostly evaluates agglomeration bonuses based on cost-effectiveness (Wätzold and Drechsler, 2014; Bell et al., 2016; Bamière et al., 2013; Liu et al., 2019; Kuhfuss et al., 016a; Delacote et al., 2016) and environmental effectiveness, (Krämer and Wätzold, 2018; Bell et al., 2016; Parkhurst and Shogren, 2007, 2008; Liu et al., 2019). The latter is usually measured through proxies such as amount of land enrolled in a program or to what extent the desired configuration of land is achieved rather than through environmental indicators, which can be costly to measure. Other criteria used to analyze the efficiency of the agglomeration bonus mechanism include economic efficiency (Parkhurst and Shogren, 2007; Fooks et al., 2016; Albers et al., 2008; Grout, 2009), and fairness (Ferré et al., 2018; Drechsler, 2017).

2.3.1.1 Cost-effectiveness

Cost-effectiveness is a measure to compare different policy tools to see which tool either minimizes the cost of achieving a certain objective or maximizes outcomes given a certain budget constraint. Accordingly, there are several papers that compare agglomeration bonuses to standard PES programs or other policies to see if they can improve the cost-effectiveness. A couple papers find that including an agglomeration bonus improves cost-effectiveness. First, Bell et al. (2016) develops an agent-based model and finds that including an agglomeration bonus can improve cost-effectiveness, so long as some monitoring effort is present. Next, Kuhfuss et al. (016a) examines both the decision to enroll in a program and the decision of how many hectares to enroll. They find that once a bonus is introduced the minimum willingness to accept for participants is lowered by an amount that is even greater than the value of the bonus. They likewise find that including the bonus also encourages enrolling a larger share of land in the contract, given the decision to enroll.

Conversely, some papers find less clear results about how agglomeration bonuses affect cost-effectiveness. For example, Delacote et al. (2016) develop a spatial model and run simulations to measure leakage resulting from different avoided deforestation policies. They compare two different PES policies with an agglomeration bonus and a conservation area policy, while looking at four cases where similar patches are either clustered or dispersed and there is either high or low interaction between landowners. They find that the spatial distribution affects which policy is most cost-effective. For example, the agglomeration bonus results in the least leakage per unit cost in the case where similar patches are clustered and there is low interaction between landowners, but it has intermediate cost-effectiveness for leakage in the three other cases. Furthermore, the agglomeration bonus results in the lowest avoided deforestation per unit cost in both dispersed cases, making it the least cost-effective for this measure. Next, Wätzold and Drechsler (2014) compare an agglomeration payment where the base payment and bonus are both contingent on the spatial connectivity, an agglomeration bonus where only the bonus is contingent on the spatial connectivity, and a homogeneous payment where landowners receive a base payment for conserved land parcels. Their results show that an agglomeration bonus never substantially dominates the two alternatives. However, they find that the agglomeration payment performs better than the homogeneous payment in most scenarios in terms of cost-effectiveness.

Another part of the literature looks at using agglomeration bonuses with procurement auctions. For example, Liu et al. (2019) conducts a framed field experiment, using forest owners in rural China as subjects, and investigates the use of an agglomeration bonus in conjunction with a PES auction for conservation contracts. While they find that overall bidders in the agglomeration bonus treatment group bid less than their counterparts in the control group in anticipation of receiving a bonus, they caution that this result is only statistically significant for a subsample that excludes players who clearly misunderstood the experiment or who exhibited protest attitudes. Furthermore, they suggest that while bids may decrease, the agglomeration bonus may include 'nontrivial additional costs' compared to the control group, as total costs become similar between the two groups once the bonus payments are taken into account. Next, Schilizzi (2017) found that using an agglomeration bonus in an auction setting increases the size and quality of the pool of submitted offers.

Bamière et al. (2013) study a unique case where the ideal spatial pattern of conserved land is a random mosaic rather than contiguous habitat. They compare a per-hectare subsidy, an auction, and an agglomeration malus (a penalty for conserving a parcel adjacent to an existing reserve since contiguity is not desired here) when the objective is reaching 15% reserved land. They argue that there is a trade-off between minimizing public costs and reaching the desired spatial pattern, since their results show that the auction is the most cost-efficient tool, but the agglomeration malus achieves a more desirable spatial pattern.

2.3.1.2 Environmental effectiveness

Environmental effectiveness can be prohibitively costly to measure, which is why most studies rely on proxy measures, such as the total area of land enrolled in a PES program and the degree of connectivity. Some studies find that using an agglomeration bonus has a positive impact on environmental effectiveness, though others find mixed results.

Starting with papers that find positive impacts on environmental effectiveness, Parkhurst and Shogren (2007, 2008) conduct lab experiments using a spatial coordination game to test the robustness of an agglomeration bonus. They consider four different conservation targets that consist of different configurations of connected habitats. They measure the percentage of the desired conservation objective that is achieved, denoting this measure biological efficiency. These papers find that an agglomeration bonus leads to higher biological efficiency, and that this efficiency increases with experience as players play more rounds, but decreases with increased complexity of the coordination problem. Parkhurst and Shogren (2008) find that including an agglomeration bonus led to higher biological efficiency than current policies such as fixed payments or compulsion. Next, Bell et al. (2016) use an agent based model and find that agglomeration payments have the potential to increase the adoption of pro-environmental practices as well as improve the contiguity of these practices.

Other studies find caveats to the positive impacts on environmental effectiveness. Fooks et al. (2016) run an experiment using both landowners and students as participants. They look at both spatial targeting and network bonuses in the context of a reverse auction, evaluating four different scenarios: one where only spatial targeting is used, one where only a network bonus is used, one where both are used, and finally a scenario where neither is used. They model a function of the value the buyer places on specific configurations of enrolled parcels in order to measure environmental effectiveness. Their results show that the bonus was able to induce more parcels to enter the auction, especially those that are higher value in terms of the conservation objective. However, they find that network bonuses on their own result in worse outcomes than the baseline reverse auction. When network bonuses are combined with spatial targeting, welfare outcomes are positively affected, suggesting that spatial targeting can mitigate the welfare loss from an auction with a network bonus. Next, using avoided deforestation and leakage as measures of environmental effectiveness, Delacote et al. (2016) find that an agglomeration policy reduces the amount of leakage in an avoided deforestation scheme, but also reduces avoided deforestation within the intervention area. They point out that increasing the direct payment component can help counter the reduction in avoided deforestation, but this of course leads to higher program costs. Additionally, they caution that they only look at the service of carbon sequestration, and avoided deforestation can impact other ecosystem services, such as flood control. Finally, Liu et al. (2019) hypothesize that using an agglomeration bonus in an auction will lead bidders with more neighbors to lower their bids in order to increase their probability of getting selected into the program, and that this would promote more contiguous conservation, However, their experimental data does not show a statistically significant difference between contiguity and connectivity indicators in the treated and control groups.

2.3.1.3 Economic efficiency

Very few papers evaluate the success of the agglomeration bonus based on economic efficiency. This measure can be difficult to estimate as there is a lot of uncertainty around the monetary value of the environmental benefits and what the optimal allocation of ecosystem services should be. Furthermore, increased provision of one ecosystem service can impact the provision of other ecosystem services, either in a positive or negative way, which can complicate the calculation of the optimal allocation. Nevertheless, the following papers seek to evaluate the economic efficiency of agglomeration bonuses.

Albers et al. (2008) examines the impact of public policy on the amount and configuration of privately conserved land and the extent to which the social optimum is achieved in different scenarios. In their model, agents face the same cost function, but can vary in regard to benefit functions and budget constraints. When analysing the impact of an agglomeration bonus, the authors look at two land trusts who each have preferences about agglomeration. When one trust has a preference for agglomeration while the other is indifferent, an agglomeration bonus, even if it is very small, will induce the socially optimal conservation pattern with certainty in a sequential move game, though it will have less success in a simultaneous move game due to coordination failure. If at least one of the trusts has preferences against adjacent conservation patterns, the agglomeration bonus should compensate the trust for any disamenity it experiences from conserving agglomerated land. A final caveat for this study is that it assumes perfect information about agents' preferences, whereas in reality one agent is not likely to fully know another agent's preferences.

2.3.2 Agglomeration bonus design

Since the inception of the idea of an agglomeration bonus by Parkhurst et al. (2002), the literature has expanded to include analyses on different ways to design an agglomeration bonus and the impacts of design choices on its performance. The papers below look at such factors as side payments and communication between landowners, the role of transaction costs, and how payments should be structured.

Several papers allow for side payments between landowners as a way for one landowner to incentivize his neighbor to participate when the neighbor has opportunity costs that otherwise outweigh their private benefits from enrolling in a conservation program. For this to occur, the agglomeration bonus must be large enough such that the landowner can cover the difference between his neighbor's opportunity costs and the conservation payment. The literature finds that side payments can improve the performance of agglomeration bonuses (Albers et al., 2008; Bell et al., 2016). Interestingly, other motives can lead to side payments between landowners, for example, Ferré et al. (2018) find that players in their experiment who have no economic incentive to offer a side payment sometimes do so in the interest of diminishing payoff inequality.

Related to side payments, is whether or not experiments allow for communication between subjects as they decide whether or not to enroll in the incentive program. A handful of studies look at the impact of communication on the performance of the agglomeration bonus. Banerjee et al. (2017) allow communication in some groups but not others, and they impose a small messaging fee to communicate with a neighbor. They find that participation rate in the agglomeration bonus scheme is on average higher in groups with communication than those without communication, for both high and low transaction cost settings. Moreover, they find that allowing communication increases performance of the agglomeration bonus when transaction costs are high, though the impact of communication when transaction costs are low depends on whether participants previously experienced the high transaction cost setting. Parkhurst et al. (2002) find that allowing communication before longer-term contracts could be a key to contiguous habitat creation with the agglomeration bonus mechanism.

Bell et al. (2016) include communication, side payments, and monitoring in their agent based model. Communication occurs during an interaction step in which farmers choose to participate with a given probability. If they choose to participate in the interaction step, they exchange information on past yields and fines for cheating (when cheating and monitoring has occurred). They find that side payments only account for at most 4% of adoption in cases with low overall program spending. Monitoring is represented by a probability of getting caught cheating, and a higher probability means higher monitoring costs. They find three main consequences of including an agglomeration bonus in a PES program. First, absolute uptake is increased. Second, overall payment costs may decrease. And third, program monitoring demands may be reduced. Another finding they discuss is that when there is some monitoring effort, the agglomeration bonus can improve the cost-effectiveness of the program, which can be partly attributed to a peer effect related to side payments, since a farmer is unlikely to honor a side payment offer if their neighbor cheats, so if the neighbor wants to guarantee that they receive the side payment, they need to adopt the conservation practice.

Some papers try to incorporate transaction costs into their analyses. For example, Banerjee et al. (2017) use a lab experiment to find the effect of varying transaction costs on participation rates and spatial coordination in an agglomeration bonus scheme. They look at two levels of transaction costs, high and low, and find that when transaction costs are high, there are significantly lower participation rates in the bonus scheme, though communication somewhat mitigates this effect. Next, they look at the impact on spatial coordination on a circular network, both locally (coordinating with your two direct neighbors) and globally (all eight group members choose the same land use). Without communication, global coordination is not impacted by different transaction costs, while allowing communication improves global coordination.

In regard to the magnitude of agglomeration payments over time, Ferré et al. (2018) look at whether agglomeration payments should remain constant over time, or change with changing opportunity costs. They analyze this question in the context of rewetting organic soils in Switzerland and find that, in terms of funds spent per unit of preserved peat soil, the constant payment has the highest cost-effectiveness compared to the variable payment and the baseline scenarios. Their experiment shows that the constant agglomeration bonus outperforms both the variable agglomeration payment and the baseline scenario in terms of participation. Additionally, unlike with the variable agglomeration payment, a majority of players are able to coordinate over all ten time periods with the constant agglomeration payment.

Finally, Grout (2009) proposes a conditional agglomeration bonus to mitigate the complexity of the coordination problem. Essentially, he proposes that a landowner's agreement to enroll his or her land is only binding if the desired spatial configuration is met. The paper argues that this modification improves the applicability of the agglomeration bonus by limiting the information burden for landowners to their own opportunity costs and eliminating the need to coordinate enrollment decisions with the other landowners. Making enrollment and payments conditional on achieving a certain spatial configuration results in an expected payoff of zero if coordination fails to achieve the spatial configuration. So, each landowner then only has to evaluate if their expected payoff is greater than zero if the spatial configuration is achieved, and they no longer have to consider the decisions of the other landowners.

2.3.3 Existing programs with agglomeration bonuses

While the theoretical and experimental literature on agglomeration bonuses is growing, there are very few real world examples of PES programs that include an agglomeration bonus or agglomeration payment. In fact, only two such programs are cited in the literature: the Conservation Reserve Enhancement Program in Oregon, in the United States, which expands on the national Conservation Reserve Program in the US, and the Swiss network bonus for connected ecological compensation areas. These programs are briefly explained in the following subsections.

2.3.3.1 Conservation Reserve Enhancement Program

The United States has a national program for land conservation called the Conservation Reserve Program, which allocates contracts via auction to farmers who then receive payments to take land out of crop production in order to favor conservation measures aimed at environmental objectives such as reducing soil erosion, improving air and water quality, and providing wildlife habitat (Grout, 2009). On a state level, Oregon state signed an agreement with the US Department of Agriculture (USDA) in 1998 to create the Conservation Reserve Enhancement Program (CREP), which pays a one-time bonus to participants along a stream if at least 50% of the stream bank within a 5-mile stream segment is enrolled in the CRP, though the retired acres are not required to be contiguous (Parkhurst et al., 2002).

The CREP aims to restore, maintain, and enhance riparian areas along agricultural lands to benefit fish, wildlife, and water quality. The program includes annual rental payments and a one-time bonus equal to four times the annual rental rate for each acre enrolled (Parkhurst et al., 2002). This ‘cumulative impact incentive payment’ rewards landowners (or a group of landowners) if their riparian establishment is more than 2.5 miles of a 5-mile stream segment. Contracts last for 10-15 years. Since the start of the program, roughly 38,500 acres have been enrolled, and the State of Oregon has invested around $25.4 million since 1999 (Oregon Watershed Enhancement Board, 2018). The 2018 CREP Annual Report does not present the monitoring results, but states that approximately 300 site visits and inspections took place in the fiscal year of 2018.

2.3.3.2 Swiss network bonus

Switzerland implemented their Agricultural Act in 1993, which included financial support for 'ecological compensation areas' (Krämer and Wätzold, 2018). While the share of ecological compensation areas increased over time, there was criticism that they were not effective in conserving biodiversity. As a result, two types of payments on top of the standard payment were introduced: a 'quality bonus' for meeting exceptional biological quality, and a 'network bonus' for creating connected ecological compensation areas (Krämer and Wätzold, 2018). Requirements for the network bonus are decided at the canton level, but have to fulfill minimum standards that are set at the national level. To facilitate the monitoring process, the initial situation of a project area is documented on a map.

Krämer and Wätzold (2018) investigate three case studies of projects in the Swiss network bonus program. While they caution that the results are not necessarily representative for Switzerland as a whole, they provide some conclusions. First, they find that overall, the introduction of the network and quality bonuses led to an increase in the size of contracted ecological compensation areas, with an increase in participation and/or an increase in the size of conservation areas. They also find that the overall quality of areas that were contracted before the introduction of the network bonus has improved. Despite evidence of some improvements, it is still somewhat unclear to what extent the improved quality and increased emphasis on spatial coordination has had a positive impact on biodiversity in general and the target species in particular, so the authors call for better monitoring data in order to more clearly assess these outcomes.

2.4 Mitigation banking: PES using tradable permits

The United States Clean Water Act of 1972 laid the groundwork for mitigation banking by requiring permits for projects that would negatively impact wetland area. In order to obtain said permit, one must follow what is called the mitigation hierarchy. The policy objective of the mitigation hierarchy is often ‘no net loss’ (NNL) of biodiversity, though sometimes it is more ambitious and aims for a net gain of biodiversity. When designing a project that will have negative impacts on the surrounding environment, a developer must first avoid any possible damages by altering the project; then, damages that cannot be avoided must be reduced; and finally, any residual damage after following the first two steps must be compensated, either by restoring another equivalent area of land or by purchasing offset credits from a mitigation bank. This is also referred to as the ‘avoid, reduce, compensate’ (ARC) sequence. Using a mitigation bank allows for the compensation activities to be carried out by another agent, who can then sell credits to the mitigation bank that developers can then purchase. The US wetland mitigation banking program was the first market of tradable permits to protect biodiversity (de Muelenaere, 2011) and the idea of habitat banking and biodiversity offsets has since spread around the world, with at least 3,000 offset projects recorded worldwide covering at least 153,670 sq km (Bull and Strange, 2018).

Mitigation banks can be considered a type of PES, as both instruments involve providing payment for the restoration, preservation and/or management of biodiversity and ecosystems (Bureau, 2010; Salzman et al., 2018; Combe, 2020). Rather than using a Pigouvian subsidy, mitigation banking involves tradable permits, usually in the form of biodiversity offsets, and thus is a quantity-based rather than a price-based instrument. In contrast to tradable pollution permits, where a regulator determines the supply of permits by setting a cap on the amount of pollution allowed, offset market supply is endogenous, since the supply of permits depends on the number, size, and quality of compensation areas being created, which is in turn influenced by the price of an offset credit (Simpson et al., 2021).

In France, the mitigation hierarchy was introduced by the founding law for the Protection of Nature of 1976. The effectiveness of the mitigation hierarchy is measured via impact studies, which are required when obtaining a permit for development projects of a certain nature or size that are likely to affect protected species or habitats (Bigard et al., 2018; Levrel et al., 2018). It applies to projects, plans and programs subject to environmental assessment as well as to projects subject to various administrative authorization procedures under the Environmental Code, such as environmental authorization, derogations for species protection or Natura 2000 impact assessment. The ARC sequence is widely practiced in European environmental policy, and EU Directives, such as the Habitats Directive, have been a major driver in the reinforcement of the ARC sequence in France (Quétier et al., 2014). France's Law 2010-788 of July 12, 2010 led to important reforms concerning the mitigation of development impacts on biodiversity, including reforms on the requirements for impact assessments and enforcement capabilities (Quétier et al., 2014). Governmental guidance from 2012 states that compensatory actions should last as long as impacts, but there is little guidance about design, duration, or frequency of monitoring efforts (Quétier et al., 2014). The 2016 Biodiversity Law resulted in compensation becoming mandatory for residual impacts (Levrel et al., 2018) and introduced the use of mitigation banks in the form of natural compensation sites to anticipate future compensation demands (Aubry et al., 2021). The idea behind natural compensation sites is to create a supply of compensation credits by restoring larger connected areas, in order to avoid the time lag between damaging habitats and restoring compensation areas. The first French natural compensation site materialized with the pilot project on the Cossure site in the Bouches-du-Rhône department. This site was created in 2009 by the organization CDC Biodiversité, with the support of the Ministry of Ecology and Sustainable Development (MEDD) (Dutoit et al., 2018).

An example of another mitigation bank policy in France that is essentially a privately funded PES is the agri-environmental biodiversity offset schemes (ABOS), where developers can obtain biodiversity offset credits by financing agri-environmental schemes (AES) contracts with farmers (Le Coent et al., 2017; Calvet et al., 2019). Since the developer is the one paying for the contract, an ABOS has an advantage compared to the publicly funded AES in that it does not incur the social cost of public funds. Indeed, ABOS have the same framework as AES, and technical practices are often identical for the same areas (Le Coent et al., 2017). Simpson et al. (2021) build an ecological-economic model of an ABOS where farmers create biodiversity offset credits that they sell to housing developers in order to see what effect of different biodiversity conservation targets will have on the price and quantity of offsets in the market. They look at eight policy scenarios, including one laissez-faire scenario, a no net loss target, and then six different net gain targets, ranging from a 5% to a 50% increase in the target biodiversity indicator. Applying their model to a case study in Scotland, they find that increasing the net gain target had ambiguous results and depended on the context. If offset demand is inelastic (elastic) at the no net loss equilibrium, then a net gain policy initially increases (decreases) the equilibrium offset quantity and price.

While the mitigation hierarchy and mitigation banking are widely used, there remains a lack of evidence of their efficacy (Brown and Land, 1999; Turner et al., 2001; Burgin, 2010; Needham et al., 2019; Damiens et al., 2021). As the oldest mitigation banking program, the US wetland mitigation bank is perhaps the most widely studied program and many argue that the US wetland mitigation banks have fallen short of their NNL objective, though the Army Corp of Engineers has failed to keep sufficient records to properly assess the objective (Burgin, 2010). Brown and Land (1999) found that only 74% of the individual banks met the NNL requirement by acreage, which does not even take into account the functional aspect of the compensation area. As with price-based PES, additionality is also an issue in mitigation banking. Burgin (2010) found that 75% of the wetland conservation banks likely would have been developed even without the legal requirement to mitigate lost wetland area. The literature generally focuses on either the feasibility of the compensation step or the lack of application of the avoidance step.

2.4.1 Compensation feasibility

The final step in the mitigation hierarchy, compensation, requires restoring or creating new habitat areas to offset those lost due to a project. It is considered to be the most controversial step of the mitigation hierarchy (Arlidge et al., 2018). However, while the loss is certain, the gains from the compensation areas is uncertain (Weissgerber et al., 2019). Even when focusing on a particular ecosystem category, such as wetlands, there can be a wide variety of species and ecosystem functions such that it is difficult to find an identical or even comparable area for compensation actions. Moreover, criteria for finding an equivalent compensation area may be simplified in order to allow for more participation in compensation markets (de Muelenaere, 2011). It is challenging and costly to calculate all the dimensions of biodiversity loss, and as such the areas traded via compensation banks tend to be measured based on simplistic measurements such as land area. For the most part, it seems that compensation areas used to generate offset credits do not measure up to the damaged and lost areas, resulting in a net loss when the size of the two areas is equal.

From an ecological point of view, the results of various monitoring studies of the Cossure pilot project in France show that the goal of restoring herbaceous vegetation has been successful so far, and that its maintenance should be upheld thanks to the re-establishment of pastoral practices in the area (Dutoit et al., 2018). However, the final ecological assessment of the restoration actions in the Cossure project can only be carried out with a longer time span, as varying weather conditions can lead to different invasive species thriving, as happened in 2014 when a particularly rainy summer allowed an invasive species to proliferate (Dutoit et al., 2018). While the natural compensation site has demonstrated the possibility to restore some parts of a natural habitat, it has also demonstrated the limitations of compensation actions to fully restore lost ecosystems (Dutoit et al., 2018).

A study by Turner et al. (2001) found that roughly 80% of the wetlands built for mitigation purposes did not become fully functional. Similarly, Campbell et al. (2002) compare natural and created wetlands in the state of Pennsylvania, looking at variables related to soil and plant quality and found that even the oldest created wetlands had few similarities with their natural counterparts. Tillman et al. (2022) looked at wetland mitigation banks that have aged past the required 5-year management and monitoring periods and found that plant communities in wetland banks have greater conservation value than the lowest quality, degraded natural wetlands, but were not close to the same value as high-quality, reference natural wetlands. Reiss et al. (2009) studied wetland mitigation banks in Florida and found that while most banks were deemed successful in terms of permit criteria, the permit criteria were not explicitly tied to ecological criteria, and so the functional performance provided by the wetland banks remains unclear. While the scientific knowledge base on ecological restoration is still relatively young (Pullin and Knight, 2009; Suding, 2011), there is evidence that restoring degraded habitats is more likely to be effective than creating new habitat because it is more likely to re-establish the necessary ecosystem functions (Mitsch and Wilson, 1996; Kozich and Halvorsen, 2012; Moreno-Mateos et al., 2012).

Location is crucial when discussing the compensation site. A main drawback of the compensation step is the inevitable geographic relocation of habitat area (Brown and Land, 1999). In particular, lower land prices in rural areas can lead to a displacement of wetlands or other natural areas from more urban to more rural areas. Quétier et al. (2014) argue that guidance on offset location is essential to avoid targeting the least expensive land without considering the potential effectiveness of an offset site. Grouping offsets for multiple projects into one compensation site is more likely to achieve the NNL objective, but also comes with risks. For example, if the same restoration action is used across the entire site and fails in one part of the site it is more likely to fail in the other parts as well (Moilanen et al., 2009). In the US, the 2008 Mitigation Rule codified the idea of service areas—that is, the geographic areas for which a mitigation bank can provide compensation (Martin and Brumbaugh, 2013). This, of course, then affects the decision of which sites to restore as some may have a more limited service area. Finally, the location of the impacted site also has consequences, as there can be cumulative impacts from multiple projects impacting the same site (Kiesecker et al., 2010).

The timing of compensation is another factor to consider, especially since restoring areas to a desired quality can take time, leading to a lag between damages and offsets (Burgin, 2010; de Muelenaere, 2011; Damiens et al., 2021). Additionally, long-term retention of biodiversity on compensation sites is crucial to reaching the NNL objective (Damiens et al., 2021). This can be complicated by institutions that are subject to shorter-term policy and election cycles, though some legal instruments, such as the use of conservation easements, have been proposed as a way to protect biodiversity gains on compensation sites from incompatible land uses over time (Damiens et al., 2021). Another way to account for losses during time lags is to use trading ratios when calculating the number of offsets required to compensate an impacted area (Needham et al., 2019; Damiens et al., 2021). For example, when there is a long time lag between the negative impact and the compensation, a developer may be required to purchase more offsets than if there were no time lag.

2.4.2 A lack of avoidance

While the compensation step of the sequence has arguably received the most attention in the literature, other studies regarding the mitigation hierarchy also highlight that the first step, avoidance, is the most important but is "more often ignored than implemented" (Clare et al., 2011). Indeed, avoidance is the most certain and effective way to limit impacts on biodiversity, as it does not engender the same problems as compensation, such as restoration time lags, limitations to what can be offset, and negative social implications from taking away biodiversity in one area and improving it in another (Phalan et al., 2018). A few papers describe different reasons for which the avoidance step is not properly implemented. Clare et al. (2011) identify five key factors that lead decision-makers to fail to prioritize wetland impact avoidance and reduction above compensation in the US and Canada, namely a lack of consensus on what constitutes avoidance, a failure of land-use planning approaches to identify high-priority wetlands in advance of development, an economic undervaluation of wetlands, a ‘techno-arrogance’ associated with wetland creation and restoration that results in wetland loss, and finally inadequate enforcement of compensation requirements. Similarly, Phalan et al. (2018) identify five challenges for effective impact avoidance: political will, legislation quality and its implementation in practice, process, capacity (informational and transaction costs), and technical knowledge. Finally, Levrel et al. (2018) identify some obstacles that undermine the additionality of the ARC sequence in France, which relate to a diversion of resources from existing conservation actions toward compensation measures and the pursuit of rents and cost minimization by different stakeholders.

Bigard et al. (2018) sought to evaluate how the execution of the ARC sequence in France aligned with the definitions and national guidance for each step. They analyzed 42 impact studies for projects between 2006 and 2016 in the territory of the Montpellier metropolis and contiguous municipalities and found that in 60% of the cases, the qualifications of the ARC measures given in the impact study did not correspond to the national reference definitions. For example, the so-called avoidance measures in the impact studies were actually reduction measures according to the national reference definitions. They also found that this confusion had negative consequences on the ecological effectiveness of the ARC hierarchy. As Stevenson and Weber (2020) note, there is a temptation to skip to steps lower in the hierarchy that are easier or cheaper.

2.5 Conclusion

Biodiversity loss is one of the most important problems humanity faces today. The various benefits humans receive from a diversity of life and services supported by diverse ecosystems is not captured by markets, and so government intervention is necessary to reach a socially optimal provision. This literature review has focused on Payments for Environmental Services (PES), a policy tool that aims to internalize the positive externalities of environmental services to encourage their provision. The economic literature analyzes conditions and design choices that make PES more or less efficient, using both theoretical models and empirical studies of existing programs.

PES can take many forms, including auctions, programs with agglomeration bonuses, and mitigation banks, all of which face challenges and are imperfect solutions to a complex problem. A variety of ecosystems and policy contexts necessitates a variety of policy design options. Conservation auctions may perform best in one context, while standard fixed rate PES may be preferred in another. Therefore, policy makers should be prudent when designing PES schemes and gather information about their specific policy context. While this literature review has focused on efficiency, policy makers should also pay attention to equity and fairness concerns.

Although the literature on PES is extensive, knowledge gaps remain. In particular, the theoretical design of PES under imperfect competition has yet to be explored. Additionally, very few papers look at the interaction of PES and other environmental policies such as environmental taxes. Next, the social cost of public funds is largely excluded from analyses of PES programs. Finally, the literature on mitigation banking lacks an economic analysis of the rationality of the ARC sequence. The remainder of this thesis aims to contribute to the existing literature by filling in these gaps.

Chapter 3

Payment for Environmental Services and environmental tax under imperfect competition

This paper designs the second-best Payment for Environmental Services (PES) when it interacts with a Pigouvian tax under imperfect competition. We consider farmers who face a choice between producing a conventional or an organic agriculture good. The regulator sets a Pigouvian tax on conventional agriculture as it generates environmental damages, as well as a PES on uncultivated land as buffer strips favor biodiversity. The conventional agriculture sector is perfectly competitive, unlike the organic agriculture sector, which is organized under an oligopoly. We show that the second-best level of the Pigouvian tax is higher than the marginal damage whereas the PES is lower than the marginal benefit. We then introduce the marginal social cost of public funds (MCF) and show that the Pigouvian tax increases with the MCF while the PES decreases with the MCF provided that demand for the conventional agriculture good is inelastic. We thus highlight a contributory component of the environmental incentive tax. This paper also identifies specific cases where the PES is ineffective in promoting biodiversity.[1]

Keywords: Biodiversity Conservation · Payment for Environmental Services · Pigouvian Tax · the Marginal Social Cost of Public Funds · Market Power

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[1] This chapter is joint work with Sonia Schwartz: Krautkraemer A., S. Schwartz (2023) Payment for environmental services and environmental tax under imperfect competition, document de recherche du LEO, DR LEO 2023-12, available at: https://hal.science/hal-04160411

3.1 Introduction

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

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

One of the most widely cited definitions of PES comes from Wunder (2005). He defines PES as a voluntary transaction where a well-defined ES or a land-use that is likely to produce that service is bought by a (minimum one) ES buyer from a (minimum one) ES provider if and only if the ES provider secures ES provision. Other definitions as given by Muradian et al. (2010) include the possibility of in-kind payment. Wunder's definition is broad enough to include in particular a Coasean negotiation or a public buyer. For instance, if the PES involves private agents, this type of PES can be related to Coasean negotiations[2]. Others PES include certain types of government intervention that reflect a Pigouvian subsidy (Sattler and Matzdorf, 2013; Pigou, 1920). This type of PES is common in practice and is

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[2] One example of a Coasean PES is the Vittel PES in north-eastern France, where Nestle reached an agreement with local farmers to prevent nitrate contamination in aquifers (Sattler and Matzdorf, 2013; Bingham, 2021).

the focus of this article.

Some examples of PES funded by public authorities can be mentioned. Following France's National Biodiversity Plan of 2018 (MTES, 2021), French water agencies are experimenting with their own PES schemes. They have been allocated 150 million euros of the French national budget, with the objective to maintain or create good ecological practices, such as lowering pesticide use or planting cover crops (MTES, 2019). While both maintaining and creating good practices will be remunerated, creating good practices will receive much higher compensation (up to 676 euros/ha/year compared to up to 66 euros/ha/year for maintenance). A new program in Paris involves setting up a PES between the water agency Eau de Paris and farmers located in the water catchment area (CPES, 2020). Farmers will benefit from the PES if they commit to limiting the use of fertilizers and pesticides, or if they establish grasslands, which are considered a better filter for water than wheat or maize fields. A wheat farmer who converts to organic farming will be able to get €450 per year per hectare for the first five years and €220 for the next two years. Farmers will only receive the full payment if a target level for nitrate concentration in groundwater is reached. This PES was created thanks to the validation of a state aid scheme (n°SA.54810) by the European Commission. This type of PES is therefore considered as a public subsidy. Regarding the Pigouvian subsidy promoting positive externalities, it should correspond to the marginal environmental benefit.

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

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

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

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

The relevance of competitive organic farming market can be questioned. According to Nguyen-Van et al. (2021), the development of organic agriculture can be very heterogeneous over a territory. For instance, out of 34259 municipalities in metropolitan France (excluding overseas territories) with at least one farmer, only 418 (1.2%) are 100% organic, and 52.4% of municipalities do not have an organic farmer.[3] The non-uniform distribution of organic farming across the country and transport constraints for organic products can limit competition in organic product market, resulting in local markets for organic farming where some producers have market power. Indeed, while we did not find empirical work on the presence of market power in the organic sector, as Sexton (2013) points out, in reality probably no agricultural markets are perfect examples of competitive markets, for reasons including the emphasis on dimensions of product quality and differentiation, which could apply to organic products. Thus, it can be interesting to see what happens theoretically to the welfare-maximizing PES payment in the presence of market power.

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

The focus of our theoretical paper is to analyze the second-best PES design combined with environmental taxes under imperfect competition and taking into account distortions from contributory taxation. To do this, we assume a farmer chooses to produce a conventional or an organic good. Whereas the conventional agriculture

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[3] Spatial factors explain the gaps in organic development between territories, such as the quality of the soil (Wollni and 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 and Blekesaune, 2013).

good market is perfectly competitive, the organic good market is organized under an oligopoly. Farmers can produce conventional agriculture goods, which causes environmental damages, or an organic production which we are assuming will have a neutral impact on the environment. If the farmer leaves fallow buffer strips, this favors biodiversity. In order to simultaneously favor biodiversity and reduce environmental damages, the regulator sets a PES on fallow land and a Pigouvian tax on conventional agriculture production.

In our framework, the Pigouvian tax decreases the conventional good production level. The PES on the fallow land area reduces organic and conventional production levels. Under market power, we show that the second-best level of the Pigouvian tax is higher than the marginal damage – contrary to Barnett (1980) – and the PES is lower than the marginal benefit. The organic good production level is too low because of the market power and the PES further reduces this production level. In order to mitigate the reduction due to market power, the regulator sets a PES lower than the marginal benefit. The conventional good level is reduced with both the PES and the Pigouvian tax. As the PES is not high enough, the regulator sets a Pigouvian tax above the marginal damage in order to reach the correct level of conventional agriculture. The environmental policies are used in a complementary way to take into account the distortion induced by the market power. We also analyze the particular case where farmers never choose buffer strips, which occurs when productions are profitable enough. In this case the PES is useless and the regulator can only regulate environmental damages. This time, market power in organic agriculture favors conventional agriculture production. So a way to reduce environmental damages is to set the Pigouvian tax above the marginal damage.

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

The assumption of a neutral impact of organic agriculture can be controversial. On the one hand, several empirical studies found a positive relationship between organic farming and biodiversity (Batáry et al., 2015; Freemark and Kirk, 2001;

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

This paper is organized as follows. Section 3.2 presents our model. Section 3.3 examines second-best environmental policies and Section 3.4 introduces the MCF. Finally, Section 3.5 concludes.

3.2 The model

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

3.2.1 Assumptions

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

The cost of implementing organic agriculture is higher than that of conventional agriculture, $c_1(x_{1i}) < c_2(x_{2i})$. Both $c_1(x_{1i})$ and $c_2(x_{2i})$ are increasing and convex[4], $\forall i = 1, ..., n$. The quantity of land left uncultivated only incurs an opportunity cost of not producing. For simplicity, we set the cost of entry into the organic market at zero, which corresponds to an absence of barriers to entry[5]. We assume a linear demand for both agricultural goods. The inverse demand function for each agricultural product is given by $p_1(X_1)$ and $p_2(X_2)$ for conventional and organic agriculture, respectively.

The organic agricultural good can be considered as a good with few substitutes, contrary to the conventional agriculture good. For example, transport constraints for organic products can limit competition in the organic product market. We are assuming that the conventional good is one that is traded on the global market (e.g. wheat) while the organic good is one that is traded locally, is difficult to transport long distances, and is not taking prices from the global market (e.g. baby leaf lettuce). So, we assume perfect competition on the conventional agriculture good market and imperfect competition on the organic agriculture good market, which is organized in the form of oligopoly.

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

3.2.2 The benchmark

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

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

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

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

Maximizing profit yields the following conditions:

$$p_1 - c_1'(x_{1i}) - \lambda = 0 \tag{3.1}$$

$$p_2'\big(X_2\big)x_{2i} + p_2\big(X_2\big) - c_2'(x_{2i}) - \lambda = 0 \tag{3.2}$$

$$\lambda(T_i - x_{1i} - x_{2i}) = 0 \tag{3.3}$$

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

Farmer i considers all other farmers' decisions in the organic product market in order to maximize his profit. To see how the production level of farmer i responds to the production level of farmer j, we use Equation (3.2) and apply the implicit function theorem. When the farmer leaves uncultivated land ($\lambda = 0$), we find:

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

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

For the case where there is no uncultivated land ($\lambda > 0$), using equations (3.1), (3.2) and (3.3), we set $N(x_{2i}, x_{2j}) = p_1 - c_1'(T_i - x_{2i}) - p_2'(X_2)x_{2i} - p_2(X_2) + c_2'(x_{2i})$.

Applying the implicit function theorem we find:

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

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

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

3.2.3 The first-best

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

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

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

$$p_1(X_1^*) - c_1'(\frac{X_1^*}{n}) - B_y - D'(\frac{X_1^*}{n}) - \lambda = 0 \tag{3.4}$$

$$p_2(\frac{X_2^*}{n}) - c_2'(\frac{X_2^*}{n}) - B_y - \lambda = 0 \tag{3.5}$$

$$\lambda(T - X_1^* - X_2^*) = 0 \tag{3.6}$$

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

Consider a first-best policy. In this case, the pigouvian tax must be equal to the marginal damage i.e. $t^* = D'(\frac{X_1^*}{n})$ and the PES must be set at the marginal environmental benefit level i.e. $s^* = B_y$ if $\lambda > 0$ and must be nonexistent if $\lambda = 0$.

However, it is easy to see that these levels of environmental policy would not lead to the first-best (equations 3.4, 3.5, 3.6). Environmental policies would correct environmental externalities, but another distortion would remain: market power. The regulator must therefore designate second-best policies.

3.3 Second-best environmental policies

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

3.3.1 The farmer's behavior

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

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

Maximizing profit yields the following conditions:

$$p_1 - c_1'(x_{1i}) - t - s - \lambda = 0 \tag{3.7}$$

$$p_2'\big(X_2\big)x_{2i} + p_2\big(X_2\big) - c_2'(x_{2i}) - s - \lambda = 0 \tag{3.8}$$

$$\lambda(T_i - x_{1i} - x_{2i}) = 0 \tag{3.9}$$

We can see how production levels change with environmental policies. When the farmer leaves uncultivated land ($\lambda = 0$), we use Equations (3.7) and (3.8), and apply the implicit function theorem. We find:

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

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

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

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

If the farmer leaves no uncultivated land ($\lambda > 0$), we obtain, after using Equations (3.7), (3.8) and (3.9) and applying the implicit function theorem:

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

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

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

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

3.3.2 Second-best level of environmental tax and PES

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

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

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

$$\frac{\partial X_1}{\partial s}[p_1(X_1(s)) - c_1'\left(\frac{X_1(s)}{n}\right) - B_y - D'(X_1(s))] + \frac{dX_2}{ds}[p_2(X_2(s)) - c_2'\left(\frac{X_2(s)}{n}\right) - B_y] = 0 \tag{3.10}$$

$$\frac{\partial X_1}{\partial t}[p_1(X_1(t)) - c_1'\left(\frac{X_1(t)}{n}\right) - B_y - D'(X_1(t))] = 0 \tag{3.11}$$

with $\frac{\partial X_1}{\partial s} < 0$, $\frac{\partial X_1}{\partial t} < 0$, and $\frac{dX_2}{ds} < 0$ obtained in the previous section and $B_y = B'(y)$. Using equations (3.7) and (3.8), we rearrange the profit maximization conditions to obtain the following:

$$p_1 - c_1'\left(\frac{X_1}{n}\right) = t + s \tag{3.12}$$

$$p_2(X_2) - c_2'\left(\frac{X_2}{n}\right) = -p_2'(X_2)\frac{X_2}{n} + s \tag{3.13}$$

Next, we plug equations (3.12) and (3.13) into equations (3.10) and (3.11) to obtain the following equations:

$$\frac{\partial X_1}{\partial s}[t + s - B_y - D'(X_1(s))] + \frac{dX_2}{ds}[-p_2'(X_2(s))\frac{X_2}{n} + s - B_y] = 0 \tag{3.14}$$

$$\frac{\partial X_1}{\partial t}[t + s - B_y - D'(X_1(t))] = 0 \tag{3.15}$$

We can now solve (3.15) for t, and plug that into (3.14) to solve for s and t. We find:

$$s = B_y + p_2'(X_2)\frac{X_2}{n} \tag{3.16}$$

$$t = D'(X_1) - p_2'(X_2)\frac{X_2}{n} \tag{3.17}$$

Here, the PES is based on the marginal environmental benefit from the grass strip rather than the opportunity cost for the farmer, in contrast to typical agri-environmental contracts. It appears that the second-best PES is lower than the marginal benefit, whereas the second-best tax is higher than the marginal damage. This result differs from Barnett (1980) who shows that in the presence of market power, the Pigouvian tax must be lower than the marginal damage. In our study, production of the organic agriculture good is lower than its first best level because of market power. As the PES reduces the level of organic agriculture, a way to not further decrease this level is to set a lower PES. But this PES will not sufficiently reduce the production from conventional agriculture. Thus the environmental tax is higher than its first best level in order to get the right level of conventional agriculture. Replacing the value of environmental policy tools in (3.7) and (3.8), we find first-best quantities (given by (3.4) and (3.5)). Finally, we can see that if the number of firms increases and approaches infinity, both environmental policy tools reach their first best level: the marginal benefit for the PES and the marginal damage for the environmental tax.

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

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

Maximizing this welfare equation yields the following first order condition:

$$\frac{dX_2}{dt}[-p_1(T - X_2) + p_2(X_2) + c_1'\left(\frac{T - X_2}{n}\right) - c_2'\left(\frac{X_2}{n}\right) + D'(T - X_2)] = 0 \quad (3.18)$$

Using the profit first order conditions (3.7) and (3.8), we find that:

$$-p_1 + c_1'\left(\frac{T - X_2}{n}\right) + p_2(X_2) - c_2'\left(\frac{X_2}{n}\right) = -t - p_2'(X_2)\frac{X_2}{n} \quad (3.19)$$

Plugging (3.19) into (3.18) yields:

$$t = D'(T - X_2) - p_2'(X_2)\frac{X_2}{n} \tag{3.20}$$

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

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

3.4 The marginal social cost of public funds

The public PES needs to be financed, which means taxing taxpayers in other ways. There are two ways to introduce the distortions induced by the tax system into our theoretical model. The first is to consider a general equilibrium model that explicitly introduces the tax system. The problem is the complexity of the model, making its results difficult to interpret. The second is to introduce into a partial equilibrium model the marginal social cost of public funds (MCF), which summarizes the fiscal distortions. In order to enrich our results, we choose this second path. We denote by ϵ the MCF. Each euro raised by the environmental tax will enable to reduce distortionary contributory taxes of $(1 + \epsilon)$ euros. Conversely, implementing a PES means a requirement for additional government revenue through increased contributory taxes, which will come at a cost to society. So, each euro allocated to the PES costs $(1 + \epsilon)$ euros to society.[6] We modify the welfare function given in Section 3.3 in order to take into account the taxation effects. In the case where the

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

farmers leave uncultivated land, the welfare reads as:

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

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

$$\begin{aligned}&\frac{\partial X_1}{\partial s}[p_1(X_1(s)) - c_1'\left(\frac{X_1(s)}{n}\right) - B_y - D'(X_1(s)) + \epsilon t + \epsilon s] \\ &+ \frac{dX_2}{ds}[p_2(X_2(s)) - c_2'\left(\frac{X_2(s)}{n}\right) - B_y + \epsilon s] - \epsilon(T - X_1(s) - X_2(s)) = 0\end{aligned} \tag{3.21}$$

$$\frac{\partial X_1(t,s)}{\partial t}[p_1(X_1(t,s)) - c_1'\left(\frac{X_1(t,s)}{n}\right) - B_y - D'(X_1(t,s)) + \epsilon t + \epsilon s] + \epsilon X_1(t,s) = 0 \tag{3.22}$$

with $\frac{\partial X_1(t,s)}{\partial s} < 0$, $\frac{\partial X_1(t,s)}{\partial t} < 0$, and $\frac{dX_2(s)}{ds} < 0$. Using Equations (3.21) and (3.22), and solving for s and t we find:

$$s^{MCF} = \frac{B_y + p_2'(X_2)\frac{X_2}{n}}{1+\epsilon} + \frac{\epsilon}{1+\epsilon}\left[\frac{T - X_1 - X_2}{\frac{dX_2}{ds}}\right] + \frac{\epsilon}{1+\epsilon}X_1\left[\frac{\frac{\partial X_1}{\partial s}}{\frac{dX_2}{ds}\frac{\partial X_1}{\partial t}}\right] \tag{3.23}$$

$$t^{MCF} = \frac{D'(X_1) - p_2'(X_2)\frac{X_2}{n}}{1+\epsilon} - \frac{\epsilon}{1+\epsilon}\left[\frac{\frac{\partial X_1}{\partial s}X_1}{\frac{dX_2}{ds}\frac{\partial X_1}{\partial t}} + \frac{T - X_1 - X_2}{\frac{dX_2}{ds}} + \frac{X_1}{\frac{\partial X_1}{\partial t}}\right] \tag{3.24}$$

The second-best PES and environmental tax are now defined taking into account their costs as far as public finance is concerned. Environmental policy tool design combines the direct effect on the environment and market power and indirectly the induced changes in several land uses computed to the MCF. Comparing (3.16) and (3.23) shows that $PES^{MCF} < PES$ whereas the comparison is not simple for t^{MCF} and t.

Contrary to the intuition, the effect of a change in ϵ in t^{MCF} and PES^{MCF} is not immediate (see Appendix C and D in Section 3.6 for full calculations). To investigate this point, we use (3.12) and (3.13) with $X_1(s(\epsilon), t(\epsilon))$ and $X_2(s(\epsilon))$. The variation of t^{MCF} and PES^{MCF} with respect to the MCF is mainly undetermined. Restricting conditions, we obtain:

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

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

Indeed if $e_{X_1/t} > -1$, the production level of conventional agriculture will not be significantly reduced after the implementation of the environmental tax. An increase in the marginal cost of public funds will increase the environmental tax, provided also that the impact of changes in production levels induced by the environmental tax and the PES are higher than a threshold given by ϖ. The environmental tax should reduce the level of conventional agricultural production more than the PES diminishes the level of organic production. In other words, the uncultivated land should be further to the detriment of conventional agriculture than to the detriment of organic agriculture. The introduction of the MCF leads the regulator to exploit a contributory component of the incentive tax while keeping in mind the objective of providing the right environmental incentives. Consequently, the environmental tax, which initially has an incentive objective (Bureau and Mougeot, 2005), would also have a contributory outcome when the MCF is taken into account .

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

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

Maximizing welfare yields this following first-order condition:

$$\frac{dX_2}{dt}[-p_1(T-X_2)+p_2(X_2)+c_1'(\frac{T-X_2}{n})-c_2'(\frac{X_2}{n})+D'(T-X_2)-\epsilon t]+\epsilon(T-X_2)=0 \tag{3.25}$$

Using equations (3.7) and (3.8) from the profit maximization gives:

$$-p_1+c_1'(X_1)+p_2(X_2)-c_2'(X_2)=-t-p_2'(X_2)\frac{X_2}{n} \tag{3.26}$$

We can then write equation (3.25) as:

$$\frac{dX_2}{dt}\left[-t-p_2'(X_2)\frac{X_2}{n}+D'(T-X_2)-\epsilon t\right]+\epsilon(T-X_2)=0 \tag{3.27}$$

Then, we solve equation (3.27) and we obtain the second-best environmental tax level:

$$t^{MCF}=\frac{D'(X_1)-p_2'(X_2)\frac{X_2}{n}}{1+\epsilon}+\frac{\epsilon}{1+\epsilon}\left(\frac{X_1}{\frac{dX_2}{dt}}\right) \tag{3.28}$$

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

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

Proposition 2 summarizes our results:

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

3.5 Conclusion

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

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

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

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

3.6 Appendices of Chapter 3

Appendix A. Welfare function concavity

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

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

where

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

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

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

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

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

After simplification, we obtain:

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

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

- Next, we look at the case where $\lambda > 0$, referring to (3.18):

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

Under our assumptions, we have:

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

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

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

- If $\lambda = 0$, we use (3.21) and (3.22) to create the Hessian matrix:

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

where

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

and

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

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

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

So the determinant is:

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

Simplifying, we find:

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

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

- If $\lambda > 0$, we refer to (3.25):

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

where

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

With our assumptions we can simplify this to:

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

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

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

According to (3.23), t and s depend on ϵ. Moreover t and s must satisfy conditions (3.21) and (3.22). We set:

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

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

- We differentiate (3.21) and (3.22) with respect to ϵ and rearrange the equations into the following matrix form:

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

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

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

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

$$\begin{bmatrix} \frac{ds}{d\epsilon} \\ \frac{dt}{d\epsilon} \end{bmatrix} = K^{-1} \begin{bmatrix} -\frac{\partial X_1}{\partial s}[t+s] - \frac{\partial X_2}{\partial s}s + (T - X_1 - X_2) \\ -\frac{\partial X_1}{\partial t}(t+s) - X_1 \end{bmatrix} \tag{3.29}$$

where

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

- We calculate $\det K$:

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

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

- We calculate $\frac{ds}{d\epsilon}$, using (3.29):

$$\begin{aligned}
\frac{\partial s}{\partial \epsilon} =& \frac{1}{\det}\Big\{[\frac{\partial X_1}{\partial t}[(q+B_{yy})\frac{\partial X_1}{\partial t}+2\epsilon]\Big\}\Big\{-\frac{\partial X_1}{\partial s}[t+s]-\frac{\partial X_2}{\partial s}s+(T-X_1-X_2)\Big\} \\
&+\frac{1}{\det}\Big\{-\frac{\partial X_1}{\partial s}[(q+B_{yy})\frac{\partial X_1}{\partial t}+2\epsilon+B_{yy}\frac{\partial X_2}{\partial s}]\Big\}\Big\{-\frac{\partial X_1}{\partial t}(t+s)-X_1\Big\} \\
\frac{\partial s}{\partial \epsilon} =& \frac{1}{\det}\Big\{-\frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s}qs+\frac{\partial X_1}{\partial t}^2 q(T-X_2)+\underbrace{\frac{\partial X_1}{\partial t}^2\frac{\partial X_2}{\partial s}tB_{yy}}_{>0}+\frac{\partial X_1}{\partial t}^2 B_{yy}(T-X_2) \\
&+\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}X_1B_{yy}-2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}s\epsilon+2\frac{\partial X_1}{\partial t}\epsilon(T-X_2)\Big\}
\end{aligned}$$

So $\dfrac{\partial s}{\partial \epsilon}<0$ if $\dfrac{\partial X_1}{\partial t}^2\dfrac{\partial X_2}{\partial s}tB_{yy}+\dfrac{\partial X_1}{\partial t}\dfrac{\partial X_2}{\partial s}X_1B_{yy}<0 \Leftrightarrow \dfrac{\partial X_1}{\partial t}\dfrac{\partial x_2}{\partial s}B_{yy}[\dfrac{\partial X_1}{\partial t}t+X_1]<0$

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

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

- We calculate $\frac{dt}{d\epsilon}$, using (3.29):

$$
\begin{aligned}
\frac{\partial t}{\partial \epsilon} =&\frac{1}{\det}\Big\{ -\frac{\partial X_1}{\partial t}\big[(q+B_{yy})\frac{\partial X_1}{\partial s}+B_{yy}\frac{\partial X_2}{\partial s}+2\epsilon\big]\big[-\frac{\partial X_1}{\partial s}(t+s)-\frac{\partial X_2}{\partial s}s\\
&+(T-X_1-X_2)\big]+\big[\frac{\partial X_1}{\partial s}[(q+B_{yy})\frac{\partial X_1}{\partial s}+2\epsilon+B_{yy}\frac{\partial X_2}{\partial s}]\\
&+\frac{\partial X_2}{\partial s}[(z+B_{yy})\frac{\partial X_2}{\partial s}+B_{yy}\frac{\partial X_1}{\partial s}+2\epsilon]\big]\big[-\frac{\partial X_1}{\partial t}(t+s)-X_1\big]\Big\}\\
\frac{\partial t}{\partial \epsilon} =&\frac{1}{\det}\Big\{\frac{\partial {X_1}^2}{\partial t}\frac{\partial X_2}{\partial s}qs-\frac{\partial X_1}{\partial t}\frac{\partial {X_2}^2}{\partial s}zs-\frac{\partial X_1}{\partial t}\frac{\partial {X_2}^2}{\partial s}zt-\frac{\partial {X_1}^2}{\partial t}qT-\frac{\partial {X_2}^2}{\partial s}zx_1\\
&+\frac{\partial {X_1}^2}{\partial t}qx_2-\frac{\partial {X_1}^2}{\partial t}\frac{\partial X_2}{\partial s}tB_{yy}-\frac{\partial X_1}{\partial t}\frac{\partial {X_2}^2}{\partial s}tB_{yy}-\frac{\partial {X_1}^2}{\partial t}TB_{yy}\\
&-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}TB_{yy}-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}X_1B_{yy}-\frac{\partial {X_2}^2}{\partial s}X_1B_{yy}+\frac{\partial {X_1}^2}{\partial t}X_2B_{yy}\\
&+\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}X_2B_{yy}-2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}t\epsilon-2\frac{\partial X_1}{\partial t}T\epsilon-2\frac{\partial X_2}{\partial s}X_1\epsilon+2\frac{\partial X_1}{\partial t}X_2\epsilon\Big\}\\
\frac{\partial t}{\partial \epsilon} =&\frac{1}{\det}\Big\{\frac{\partial {X_1}^2}{\partial t}\frac{\partial X_2}{\partial s}qs-\frac{\partial {X_1}^2}{\partial t}q(T-X_2)-\frac{\partial {X_1}^2}{\partial t}B_{yy}(T-X_2)-2\frac{\partial X_1}{\partial t}\epsilon(T-X_2)\\
&-\frac{\partial {X_1}^2}{\partial t}\frac{\partial X_2}{\partial s}tB_{yy}-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}X_1B_{yy}-\frac{\partial X_1}{\partial t}\frac{\partial {X_2}^2}{\partial s}zs-\frac{\partial X_1}{\partial t}\frac{\partial {X_2}^2}{\partial s}zt\\
&-\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}B_{yy}(T-X_2)-\frac{\partial {X_2}^2}{\partial s}X_1B_{yy}-2\frac{\partial X_2}{\partial s}X_1\epsilon-\frac{\partial {X_2}^2}{\partial s}zX_1\\
&-2\frac{\partial X_1}{\partial t}\frac{\partial X_2}{\partial s}t\epsilon-\frac{\partial X_1}{\partial t}\frac{\partial {X_2}^2}{\partial s}tB_{yy}\Big\}
\end{aligned}
$$

We know that

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

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

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

We use (3.25) and we set: $J(t,\epsilon) = \frac{dX_2}{dt}[-p_1(T-X_2)+p_2(X_2)+c_1'(\frac{T-X_2}{n})-c_2'(\frac{X_2}{n})+D'(T-X_2)-\epsilon t]+\epsilon(T-X_2)$. Applying the implicit function theorem we find:

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

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

Chapter 4

Are Additionality-Based Payments for Environmental Services Efficient?

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. This paper aims to study the efficiency of additionality-based PES. We consider a farmer who allocates 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 farmer distorts his behavior in the initial period, in order to obtain more payment in the final period. The second-best PES to limit this behavior equals the discounted difference of the marginal environmental benefits obtained in each period. The second-best value of environmental taxes in the presence of this PES 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.[1]

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[1] This chapter is joint work with Sonia Schwartz: Krautkraemer, A., S. Schwartz (2023). Are additonality-based PES efficient, document de recherche du LEO, DR LEO 2023-01, available at `https://univ-orleans.hal.science/hal-04152591/`

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4.1 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 schemes (AES). They consist of offering financial compensation to farmers for voluntary commitment on their part, over several years, to implement practices or production. For example, some AES contracts are offered for a period of five years, and compensate the farmer for the decrease in profit associated with adopting environmental practices. 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 (Wunder, 2005; Kaczan et al., 2017), and the consequences in terms of new technology development (Pates and 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 and 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 and 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.[2] The non-uniform distribution of organic farming across the country and transport constraints for organic products could limit competition in the organic product market, resulting in local markets for organic farming where some producers could have market power. Indeed, while we did not find empirical work on the

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[2] Spatial factors explain the gaps in organic development between territories, such as the quality of the soil (Wollni and 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 and Blekesaune, 2013).

presence of market power in the organic sector, as Sexton (2013) points out in reality probably no agricultural markets are perfect examples of competitive markets, for reasons including the emphasis on dimensions of product quality and differentiation, which could apply to organic products. Thus, it can be interesting to see what happens theoretically to the welfare-maximizing PES payment in the presence of 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 4.2 provides a review of the literature on additionality in PES schemes. In Section 4.3 we specify the assumptions of our model and analyze a benchmark and first-best scenario. Next, Section 4.4 examines the policy levels of a PES and tax and their resulting production levels, assuming perfect competition. In Section 4.5 we introduce imperfect competition in the organic sector. Finally, Section 4.6 concludes.

4.2 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 and 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 and 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 and

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 and 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 and 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.

4.3 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.

4.3.1 Assumptions

In order to analyze the additionality issue, we construct a model with two periods, $t = 0, 1$. For example, the initial period is before the PES contract, while the final period is during the PES contract. 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). 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 4.5, 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 and convex, 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 look at the case where 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.

4.3.2 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:

$$\pi(x_1^0, x_2^0, x_1^1, x_2^1) = p_1^0 x_1^0 + p_2^0 x_2^0 - c_1(x_1^0) - c_2(x_2^0) + \beta\{p_1^1 x_1^1 + p_2^1 x_2^1 - c_1(x_1^1) - c_2(x_2^1)\} \tag{4.1}$$

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.

4.3.3 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.

$$W(x_1^0,x_2^0,x_1^1,x_2^1) = \int\limits_0^{x_1^0} p_1^0(u)du + \int\limits_0^{x_2^0} p_2^0(v)dv - c_1(x_1^0) - c_2(x_2^0) + B(T - x_1^0 - x_2^0) - D(x_1^0)$$

$$+\beta\Big\{ \int\limits_0^{x_1^1} p_1^1(w)dw + \int\limits_0^{x_2^1} p_2^1(z)dz - c_1(x_1^1) - c_2(x_2^1) + \psi(y^0)B(T - x_1^1 - x_2^1) - D(x_1^1)\Big\}$$

Taking the first order conditions we obtain:

$$\frac{\partial W}{\partial x_1^0} = p_1^0(x_1^{0*}) - c_1'(x_1^{0*}) - B_{y^{0*}} - \beta\psi'(y^{0*})B(y^{1*}) - D'(x_1^{0*}) = 0 \tag{4.2}$$

$$\frac{\partial W}{\partial x_2^0} = p_2^0(x_2^{0*}) - c_2'(x_2^{0*}) - B_{y^{0*}} - \beta\psi'(y^{0*})B(y^{1*}) = 0 \tag{4.3}$$

$$\frac{\partial W}{\partial x_1^1} = \beta\big[p_1^1(x_1^{1*}) - c_1'(x_1^{1*}) - \psi(y^{0*})B_{y^{1*}} - D'(x_1^{1*})\big] = 0 \tag{4.4}$$

$$\frac{\partial W}{\partial x_2^1} = \beta\big[p_2^1(x_2^{1*}) - c_2'(x_2^{1*}) - \psi(y^{0*})B_{y^{1*}}\big] = 0 \tag{4.5}$$

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[3] may lead the regulator to integrate the principle of additionality in the PES, by remunerating only the environmental benefits induced by the PES.

4.4 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 farmer is aware of the PES policy implementation and is able to adjust his initial period quantities beforehand. 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.

4.4.1 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.

4.4.1.1 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 $[y^1 - y^0]$

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

We maximize the profit in the final period in order to define the subgame-perfect

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[3] One possibility would be to try to finance the PES payment with the environmental tax. However, when trying to include this in the model it became intractable.

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:

$$\frac{\partial \pi^1}{\partial x_1^1} = p_1^1 - c_1'(x_1^{1c}) - t^1 - s = 0 \tag{4.6}$$

$$\frac{\partial \pi^1}{\partial x_2^1} = p_2^1 - c_2'(x_2^{1c}) - s = 0 \tag{4.7}$$

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 (4.6) and (4.7) we can investigate how the production levels change in response to the environmental policies. We obtain:

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

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.

4.4.1.2 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:

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

$$\frac{\partial \pi}{\partial x_1^0} = p_1^0 - c_1'(x_1^{0c}) - t^0 + \beta s = 0 \tag{4.8}$$

$$\frac{\partial \pi}{\partial x_2^0} = p_2^0 - c_2'(x_2^{0c}) + \beta s = 0 \tag{4.9}$$

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 (4.8) and (4.9) to see how production levels change in response to the environmental policies. We find:

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

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.

4.4.2 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:

$$W(x_1^0(s,t^0), \underset{s,t^0,t^1}{x_2^0(s)}, x_1^1(s,t^1), x_2^1(s)) = \int\limits_0^{x_1^0(s,t^0)} p_1(u)du + \int\limits_0^{x_2^0(s)} p_2(v)dv - c_1(x_1^0(s,t^0)) - c_2(x_2^0(s))$$

$$+ B(T - x_1^0(s,t^0) - x_2^0(s)) - D(x_1^0(s,t^0)) + \beta\Bigg\{ \int\limits_0^{x_1^1(s,t^1)} p_1(w)dw + \int\limits_0^{x_2^1(s)} p_2(z)dz - c_1(x_1^1(s,t^1))$$

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

Taking the first order conditions we obtain:

$$\frac{\partial W}{\partial t^0} = \frac{\partial x_1^0}{\partial t^0}\Bigg[p_1^0 - c_1'(x_1^0) - B_{y^0} - \beta\psi'(y^0)B(y^1) - D'(x_1^0)\Bigg] = 0 \tag{4.10}$$

$$\frac{\partial W}{\partial t^1} = \frac{\partial x_1^1}{\partial t}\beta\Bigg[p_1^1 - c_1'(x_1^1) - \psi(y^0)B_{y^1} - D'(x_1^1)\Bigg] = 0 \tag{4.11}$$

$$\begin{aligned}\frac{\partial W}{\partial s} = \frac{\partial x_1^1}{\partial s}\beta\Big[p_1^1 - c_1'(x_1^1) - \psi(y^0)B_{y^1} - D'(x_1^1)\Big] + \frac{dx_2^1}{ds}\beta\Big[p_2^1 - c_2'(x_2^1) - \psi(y^0)B_{y^1}\Big] \\ + \frac{\partial x_1^0}{\partial s}\Big[p_1^0 - c_1'(x_1^0) - B_{y^0} - \beta\psi'(y^0)B(y^1) - D'(x_1^0)\Big] \\ + \frac{dx_2^0}{ds}\Big[p_2^0 - c_2'(x_2^0) - B_{y^0} - \beta\psi'(y^0)B(y^1)\Big] = 0\end{aligned} \tag{4.12}$$

We find the following expression for the second-best additionality-based PES payment (see Appendix A in section 4.7 for calculations):

$$s = \frac{\frac{1}{c_2''(x_2^1)}\psi(y^0)B_{y^1} - \frac{1}{c_2''(x_2^0)}[B_{y^0} + \beta\psi'(y^0)B(y^1)]}{[\frac{1}{c_2''(x_2^1)} + \frac{\beta}{c_2''(x_2^0)}]} \tag{4.13}$$

The PES depends on the values of the marginal benefit in each period, as well as the production costs in each period. In the following, for ease of reading, we consider the particular case where c'' is constant, such as with quadratic equations, which gives:

$$s^c = \frac{\psi(y^{0c})B_{y^{1c}} - (B_{y^{0c}} + \beta\psi'(y^{0c})B(y^{1c}))}{1+\beta} \tag{4.14}$$

The second-best PES based on additionality is equal, in this case, 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. This is in contrast to actual AES contracts, which base payments off of foregone profits from adopting environmental practices. 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 in Section 4.7 for full calculations and the general case). Starting with the tax in the initial period we obtain:

$$t^{0c}(y^{0c}, y^{1c}) = t^{0*} + \frac{B_{y^{0c}} + \beta[\psi'(y^{0c})B(y^{1c}) + \psi(y^{0c})B_{y^{1c}}]}{1+\beta} \tag{4.15}$$

Then, for the final period tax we find:

$$t^{1c}(y^{0c}, y^{1c}) = t^{1*} + \frac{B_{y^{0c}} + \beta[\psi'(y^{0c})B(y^{1c}) + \psi(y^{0c})B_{y^{1c}}]}{1+\beta} \tag{4.16}$$

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.

4.4.3 Calculated quantities

We now calculate the levels of conventional and organic agriculture that will result from the policies. We take the equations (4.14), (4.15) and (4.16), and plug these into the profit FOCs (4.6), (4.7), (4.8), and (4.9). 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 (see Appendix A in Section 4.7 for calculations).

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.

4.5 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 are assuming that the conventional good is one that is traded on the global market (e.g. wheat) while the organic good is one that is traded locally, is difficult to transport long distances, and is not taking prices from the global market (e.g. baby leaf lettuce). 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.

4.5.1 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.

4.5.1.1 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:

$$\frac{\partial \pi^1}{\partial x_1^1} = p_1^1 - c_1'(x_1^{1m}) - t^1 - s = 0 \tag{4.17}$$

$$\frac{\partial \pi^1}{\partial x_2^1} = p_2^{1\prime}(x_2^{1m})x_2^{1m} + p_2^1(x_2^{1m}) - c_2'(x_2^{1m}) - s = 0 \tag{4.18}$$

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 (4.17) and (4.18), 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.

4.5.1.2 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:

$$\frac{\partial \pi}{\partial x_1^0} = p_1^0 - c_1'(x_1^{0m}) - t^0 + \beta s = 0 \tag{4.19}$$

$$\frac{\partial \pi}{\partial x_2^0} = p_2^{0\prime}(x_2^{0m})x_2^{0m} + p_2^0(x_2^{0m}) - c_2'(x_2^{0m}) + \beta s = 0 \tag{4.20}$$

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 (4.19) and (4.20), 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.

4.5.2 Tax and PES designs

We will now define the second-best environmental policies. Let's assume $s = -\frac{p_2^{0\prime}(x_2^{0m})x_2^{0m}}{\beta}$. From (4.20), 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.

We obtain the PES value, s^m (see Appendix B in Section 4.7 for calculations and the general case):

$$s^m = s^*(y^{0m}, y^{1m}) + \frac{p_2'(x_2^{1m})x_2^{1m} - p_2'(x_2^{0m})x_2^{0m}}{1+\beta} \tag{4.21}$$

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 $p' < 0$. 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.

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 4.21), 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 in Section 4.7 for calculations and the general case):

$$t^{0m}(y^{0m}, y^{1m}) = t^{0c} + \frac{\beta[p_2'(x_2^{1m})x_2^{1m} - p_2'(x_2^{0m})x_2^{0m}]}{1+\beta} \tag{4.22}$$

$$t^{1m}(y^{0m}, y^{1m}) = t^{1c} + \frac{-p_2'(x_2^{1m})x_2^{1m} + p_2'(x_2^{0m})x_2^{0m}}{1+\beta} \tag{4.23}$$

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.

4.5.3 Calculated quantities

We now seek to calculate the production levels of conventional and organic agriculture that will result from the policies. We take equations (4.21), (4.22), and (4.23) and plug them into the profit FOCs (4.17), (4.18), (4.19), and (4.20). 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 (see Appendix B in Section 4.7 for calculations).

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.

4.6 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. This is in contrast to actual schemes which allocate payments based on foregone profits from adopting environmental practices. 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.

4.7 Appendices of Chapter 4

Appendix A. The second-best environmental policies under perfect competition

Determination of s^c

From the profit FOCs given by (4.6), (4.7), (4.8), and (4.9), 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 (4.10), (4.11), and (4.12), we obtain:

$$\frac{\partial x_1^0}{\partial t^0}\Big[t^0 - \beta s - B_{y^0} - \beta\psi'(y^0)B(y^1) - D'(x_1^0)\Big] = 0 \tag{4.24}$$

$$\frac{\partial x_1^1}{\partial t^1}\beta\Big[t^1 + s - \psi(y^0)B_{y^1} - D'(x_1^1)\Big] = 0 \tag{4.25}$$

$$\begin{aligned}
&\frac{\partial x_1^1}{\partial s}\beta\Big[t^1 + s - \psi(y^0)B_{y^1} - D'(x_1^1)\Big] + \frac{dx_2^1}{ds}\beta\Big[s - \psi(y^0)B_{y^1}\Big] \\
&+ \frac{\partial x_1^0}{\partial s}\Big[t^0 - \beta s - B_{y^0} - \beta\psi'(y^0)B(y^1) - D'(x_1^0)\Big] + \frac{dx_2^0}{ds}\Big[-\beta s - B_{y^0} - \beta\psi(y^0)B_{y^1}\Big] = 0
\end{aligned} \tag{4.26}$$

We can then solve (4.24) and (4.25) for t^0 and t^1:

$$t^0 = \beta s + B_{y^0} + \beta\psi'(y^0)B(y^1) + D'(x_1^0) \tag{4.27}$$

$$t^1 = -s + \psi(y^0)B_{y^1} + D'(x_1^1) \tag{4.28}$$

We plug these values into (4.26):

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

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

$$s=\frac{\frac{1}{c_2''(x_2^1)}\psi(y^0)B_{y^1}-\frac{1}{c_2''(x_2^0)}[B_{y^0}+\beta\psi'(y^0)B(y^1)]}{\frac{1}{c_2''(x_2^1)}+\frac{\beta}{c_2''(x_2^0)}} \tag{4.29}$$

After assuming a constant c'', we obtain equation (4.14).

Determination of t^{0c}

Replacing s in (4.27), we have:

$$t^{0c}=\beta\left[\frac{\frac{1}{c_2''(x_2^1)}\psi(y^0)B_{y^1}-\frac{1}{c_2''(x_2^0)}[B_{y^0}+\beta\psi'(y^0)B(y^1)]}{\frac{1}{c_2''(x_2^1)}+\frac{\beta}{c_2''(x_2^0)}}\right]+B_{y^0}+\beta\psi'(y^0)B(y^1)+D'(x_1^0)$$

Simplifying:

$$t^{0c}=\frac{\frac{(1-\beta)(B_{y^0}+\beta\psi'(y^0)B(y^1))+\beta\psi'(y^0)B(y^1))}{c_2''(x_2^1)}+\frac{\beta[B_{y^0}+\beta\psi'(y^0)B(y^1))]}{c_2''(x_2^0)}}{\frac{1}{c_2''(x_2^1)}+\frac{\beta}{c_2''(x_2^0)}}+D'(x_1^0)$$

After rearranging and taking the case where c_2'' is constant, we obtain Equation (4.15).

Determination of t^{1c}

Replacing s in (4.28), we have:

$$t^1=-\left\{\frac{\frac{1}{c_2''(x_2^1)}\psi(y^0)B_{y^1}-\frac{1}{c_2''(x_2^0)}[B_{y^0}+\beta\psi'(y^0)B(y^1)]}{\frac{1}{c_2''(x_2^1)}+\frac{\beta}{c_2''(x_2^0)}}\right\}+\psi(y^0)B_{y^1}+D'(x_1^1)$$

Simplifying:

$$t^1 = D'(x_1^1) + \frac{\frac{1}{c_2''(x_2^0)}\left[B_{y^0} + \beta\psi'(y^0)B(y^1) + \psi(y^0)B_{y^1}\right]}{\frac{1}{c_2''(x_2^1)} + \frac{\beta}{c_2''(x_2^0)}}$$

After rearranging and taking the case where c_2'' is constant, we obtain Equation (4.16).

Determination of calculated quantities

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:

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

Appendix B. The second-best environmental policies under imperfect competition

Welfare equation with market power

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:

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

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

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

The first order conditions are the following:

$$\frac{\partial W}{\partial t^0} = \frac{\partial x_1^0}{\partial t^0}\left[p_1 - c_1'(x_1^0) - B_{y^0} - \beta\psi'(y^0)B(y^1) - D'(x_1^0)\right] = 0 \tag{4.30}$$

$$\frac{\partial W}{\partial t^1} = \frac{\partial x_1^1}{\partial t}\beta\left[p_1 - c_1'(x_1^1) - \psi(y^0)B_{y^1} - D'(x_1^1)\right] = 0 \tag{4.31}$$

$$\begin{aligned}\frac{\partial W}{\partial s} = &\frac{\partial x_1^1}{\partial s}\beta\left[p_1 - c_1'(x_1^1) - \psi(y^0)B_{y^1} - D'(x_1^1)\right] + \frac{dx_2^1}{ds}\beta\left[p_2 - c_2'(x_2^1) - \psi(y^0)B_{y^1}\right]\\ &+ \frac{\partial x_1^0}{\partial s}\left[p_1 - c_1'(x_1^0) - B_{y^0} - \beta\psi'(y^0)B(y^1) - D'(x_1^0)\right]\\ &+ \frac{dx_2^0}{ds}\left[p_2 - c_2'(x_2^0) - B_{y^0} - \beta\psi'(y^0)B(y^1)\right] = 0\end{aligned} \tag{4.32}$$

Determination of s^m

We rearrange all of the profit FOCs, (4.17), (4.18), (4.19), and (4.20) 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 (4.30), (4.31), and (4.32), we obtain:

$$\frac{\partial x_1^0}{\partial t^0}\left[t^0 - \beta s - B_{y^0} - \beta\psi'(y^0)B(y^1) - D'(x_1^0)\right] = 0 \tag{4.33}$$

$$\frac{\partial x_1^1}{\partial t^1}\beta\left[t^1 + s - \psi(y^0)B_{y^1} - D'(x_1^1)\right] = 0 \tag{4.34}$$

$$\begin{aligned}&\frac{\partial x_1^1}{\partial s}\beta\left[t^1 + s - \psi(y^0)B_{y^1} - D'(x_1^1)\right] + \frac{dx_2^1}{ds}\beta\left[s - p_2'(x_2^1)x_2^1 - \psi(y^0)B_{y^1}\right]\\ &+ \frac{\partial x_1^0}{\partial s}\left[t^0 - \beta s - B_{y^0} - \beta\psi'(y^0)B(y^1) - D'(x_1^0)\right]\\ &+ \frac{dx_2^0}{ds}\left[-\beta s - p_2'(x_2^0)x_2^0 - B_{y^0} - \beta\psi(y^0)B_{y^1}\right] = 0\end{aligned} \tag{4.35}$$

We can then solve (4.33) and (4.34) for t^0 and t^1.

$$t^0 = \beta s + B_{y^0} + \beta\psi'(y^0)B(y^1) + D'(x_1^0) \tag{4.36}$$

$$t^1 = -s + \psi(y^0)B_{y^1} + D'(x_1^1) \tag{4.37}$$

We plug these values into (4.35) in order to obtain the value of s:

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

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

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

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

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

Assuming c_2'' is constant and demand is linear, we find Equation (4.21).

Determination of t^{0m}

Plugging the value of s into (4.36), we have:

$$\begin{aligned} t^0 =& \beta\left[\frac{\frac{1}{2p_2'(x_2^1) - c_2''(x_2^1)}[p_2'(x_2^1)x_2^1 + \psi(y^0)B_{y^1}] - \frac{1}{2p_2'(x_2^0) - c_2''(x_2^0)}[p_2'(x_2^0)x_2^0 + B_{y^0} + \beta\psi'(y^0)B(y^1)]}{\frac{1}{2p_2'(x_2^1) - c_2''(x_2^1)} + \frac{\beta}{2p_2'(x_2^0) - c_2''(x_2^0)}}\right] \\ &+ B_{y^0} + \beta\psi'(y^0)B(y^1) + D'(x_1^0) \end{aligned}$$

Simplifying:

$$t^0 = \frac{\frac{B_{y^0} + \beta\psi'(y^0)B(y^1) + \beta(p_2'(x_2^1)x_2^1 + \psi(y^0)B_{y^1})}{2p_2'(x_2^1) - c_2''(x_2^1)} - \frac{\beta(p_2'(x_2^0)x_2^0)}{2p_2'(x_2^0) - c_2''(x_2^0)}}{\frac{1}{2p_2'(x_2^1) - c_2''(x_2^1)} + \frac{\beta}{2p_2'(x_2^0) - c_2''(x_2^0)}}$$

When we look at the case where c'' is constant, we obtain Equation (4.22).

Determination of t^{1m}

Plugging s^m into (4.37), we find:

$$t^1 = -\left\{ \frac{\frac{1}{2p_2'(x_2^1)-c_2''(x_2^1)}[p_2'(x_2^1)x_2^1 + \psi(y^0)B_{y^1}] - \frac{1}{2p_2'(x_2^0)-c_2''(x_2^0)}[p_2'(x_2^0)x_2^0 + B_{y^0} + \beta\psi'(y^0)B(y^1)]}{\frac{1}{2p_2'(x_2^1)-c_2''(x_2^1)} + \frac{\beta}{2p_2'(x_2^0)-c_2''(x_2^0)}} \right\}$$
$$+ \psi(y^0)B_{y^1} + D'(x_1^1)$$

Simplifying:

$$t^1 = D'(x_1^1) + \frac{\frac{p_2'(x_2^1)x_2^1+B_{y^0}+\beta\psi(y^0)B_{y^1}+\beta\psi'(y^0)B(y^1)}{2p_2'(x_2^0)-c_2''(x_2^0)} - \frac{p_2'(x_2^1)x_2^1}{2p_2'(x_2^1)-c_2''(x_2^1)}}{\frac{1}{2p_2'(x_2^1)-c_2''(x_2^1)} + \frac{\beta}{2p_2'(x_2^0)-c_2''(x_2^0)}}$$

After rearranging and taking the case where c'' is constant, we obtain Equation (4.23).

Determination of calculated quantities

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:

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

Chapter 5

On the efficiency of the mitigation hierarchy

This article focuses on the avoid, reduce, compensate (ARC) sequence that accompanies the no net loss policy. It studies the behavior of a developer in the face of this policy. Under perfect information, it appears that this policy is a policy of environmental standards, whose objectives are difficult to transpose into a microeconomic decision model. Moreover, we show that the demand for compensation does not depend on its price. We then assume that the regulator does not share the same information as the developer on the environmental damage of the project. In this case, the developer strategically uses this asymmetric information. Using the backward induction reasoning, he simultaneously defines his demand for offsets and the level of environmental damage reduction based on the offset price. In the end, the project choice is made by also taking into account the price of the offset. This article shows that the mitigation hierarchy is ineffective under asymmetric information, making the safeguarding of biodiversity inefficient.[1]

Keywords: biodiversity conservation · avoid reduce compensate sequence · mitigation banking · mitigation hierarchy

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[1] This chapter is joint work with Sonia Schwartz.

5.1 Introduction

The collapse of biodiversity is a well-documented phenomenon, which is likely to worsen with climate change (Dasgupta, 2021; Díaz et al., 2019; Ruckelshaus et al., 2020). A leading cause of the decline in biodiversity is the loss of various habitats due to land use change (Lewis et al., 2011; Bamière et al., 2013). According to Dasgupta (2021), an estimated 20% of species could become extinct in the next several decades, perhaps twice as many by the end of the century.

One concept that aims to halt biodiversity loss is mitigation banking, the idea behind which started in the context of declining wetland area in the United States, which was often the result of land use shifts to urban development projects and agriculture (Burgin, 2010; Dahl, 1990). Wetlands act as habitat for many species and also provide many environmental services, including water filtration and flood management. The Ramsar Convention in 1971 established an international treaty for the conservation and sustainable use of wetlands, especially as habitat for birds. In order to address the loss of wetland area, the US Clean Water Act of 1972 introduced a permitting program that requires following a mitigation hierarchy to obtain a permit for a development project. The mitigation hierarchy lists the steps to be taken by major development projects to achieve the goal of no net loss of wetland area: avoid, reduce, and compensate (ARC). Consider a plan for a development project that will damage at least part of a wetland. First, the developer must avoid as much damage as possible, for example by relocating the project or reducing its size. Second, if some damage remains, it should be reduced as much as possible, using pollution abatement technologies or other methods. And finally, if there is any remaining damage, there are two options to compensate for said damage: either re-establish a similar wetland, on site or at another location, or purchase credits from a mitigation bank. A mitigation bank buys credits from restoration projects and sells them to developers who need to offset their residual impacts that could not be avoided or reduced.

In France, the mitigation hierarchy was introduced by the founding law for the Protection of Nature of 1976. The effectiveness of the mitigation hierarchy is measured via impact studies, which are required when obtaining a permit for development projects of a certain nature or size that are likely to affect protected species or habitats (Bigard et al., 2018; Levrel et al., 2018). It applies to projects, plans and programmes subject to environmental assessment as well as to projects subject to various administrative authorization procedures under the Environmental

Code, such as environmental authorization, derogations for species protection or Natura 2000 impact assessment. The ARC sequence is widely practiced in European Union environmental policy and EU Directives, such as the Habitats Directive, have been a major driver in the reinforcement of the ARC sequence in France (Quétier et al., 2014). France's Law 2010-788 of July 12, 2010 led to important reforms concerning the mitigation of development impacts on biodiversity, including reforms on the requirements for impact assessments and enforcement capabilities (Quétier et al., 2014). Governmental guidance from 2012 states that compensatory actions should last as long as impacts, but there is little guidance about design, duration, or frequency of monitoring efforts (Quétier et al., 2014). The 2016 Biodiversity Law resulted in compensation becoming mandatory for residual impacts (Levrel et al., 2018) and introduced the use of natural compensation sites to anticipate future compensation demands (Aubry et al., 2021).

The idea of natural compensation sites first materialized in France with the pilot project on the Cossure site in the Bouches-du-Rhône department. This site was created in 2009 by the organization CDC Biodiversité, with the support of the Ministry of Ecology and Sustainable Development (MEDD) (Dutoit et al., 2018). The idea behind natural compensation sites is to create a supply of compensation credits by restoring larger connected areas, in order to avoid the time lag between damaging habitats and restoring compensation areas.

The economic literature has examined the efficacy of restoration policies to protect biodiversity. From an ecological point of view, the results of various monitoring studies show that the goal of restoring herbaceous vegetation has been successful so far, and that its maintenance should be upheld thanks to the re-establishment of pastoral practices in the area (Dutoit et al., 2018). However, the final ecological assessment of the restoration actions can only be carried out with a longer time span, as varying weather conditions can lead to different invasive species thriving, as happened in 2014 when a particularly rainy summer allowed an invasive species to proliferate (Dutoit et al., 2018). Campbell et al. (2002) compare natural and created wetlands in the state of Pennsylvania, looking at variables related to soil and plant quality and found that even the oldest created wetlands had few similarities with their natural counterparts. Tillman et al. (2022) looked at wetland mitigation banks that have aged past the required 5-year management and monitoring periods and found that plant communities in wetland banks have greater conservation value than the lowest quality, degraded natural wetlands, but were not close to the same value as high-quality, reference natural wetlands. Reiss et al. (2009) studied wetland mitigation banks in Florida and found that while most banks were deemed successful in terms of permit criteria, the permit criteria were not explicitly tied to ecological criteria, and so the functional performance provided by the wetland banks remains unclear. While the natural compensation site has demonstrated the possibility to restore some parts of a natural habitat, it has also demonstrated the limitations of compensation actions to fully restore lost ecosystems (Dutoit et al., 2018).

Another part of the literature questions the feasibility of the compensation step. There is an issue of finding compensation areas that equate to the damaged areas, which is seen as one of the main challenges of mitigation banking (de Muelenaere, 2011). Often, criteria may be simplified in order to allow for more participation in compensation markets. There is also a potential issue of displacing wetlands or other natural environments from more urban to more rural areas due to differing land prices, making it more cost-effective for restoration projects to occur in more rural areas because of the lower land prices.

While the compensation step of the sequence has arguably received the most attention in the literature, many studies regarding the mitigation hierarchy also highlight that the first step, avoidance, is the most important but is “more often ignored than implemented” (Clare et al., 2011). Avoidance is the most certain and effective way to limit impacts on biodiversity, as it does not engender the same problems as compensation, such as restoration time lags, limitations to what can be offset, and negative social implications from taking away biodiversity in one area and improving it in another (Phalan et al., 2018). A few papers describe different reasons for which the avoidance step is not properly implemented. Clare et al. (2011) identify five key factors that lead decision-makers to fail to prioritize wetland impact avoidance and reduction above compensation in the US and Canada, namely a lack of consensus on what constitutes avoidance, a failure of land-use planning approaches to identify high-priority wetlands in advance of development, an economic undervaluation of wetlands, a "techno-arrogance" associated with wetland creation and restoration that results in wetland loss, and finally inadequate enforcement of compensation requirements. Similarly, Phalan et al. (2018) identify five challenges for effective impact avoidance: political will, legislation quality and its implementation in practice, process, capacity (informational and transaction costs), and technical knowledge. Finally, Levrel et al. (2018) identify five drifts that undermine the additionality of the ARC sequence in France, which relate to a diversion of resources from existing conservation actions toward compensation measures and the pursuit of rents and cost minimization by different stakeholders.

Bigard et al. (2018) sought to evaluate how the execution of the ARC sequence in France aligned with the definitions and national guidance for each step. They analyzed 42 impact studies for projects between 2006 and 2016 in the territory of the Montpellier metropolis and contiguous municipalities and found that in 60% of the cases, the qualifications of the ARC measures given in the impact study did not correspond to the national reference definitions. For example, the so-called avoidance measures in the impact studies were actually reduction measures according to the national reference definitions. They also found that this confusion had negative consequences on the ecological effectiveness of the ARC hierarchy. As Stevenson and Weber (2020) note, there is a temptation to skip to steps lower in the hierarchy that are easier or cheaper. The aim of this paper is to define the operational contents of the sequence and to identify the cases where the sequence is inoperative.

While the economic literature has focused on the efficiency of the sequence in protecting biodiversity or on the realization of the different stages of the sequence, the essence of the policy is unclear. It appears a confusion between not net loss policies based on the ARC sequence and a market-based biodiversity conservation policy. Mitigation banking can be considered a type of PES scheme, as both instruments involve providing payment for the restoration, preservation, and/or management of biodiversity and ecosystems (Bureau, 2010; Combe, 2020). However, a PES is a market mechanism. The not-net-loss policy is an environmental standard, accompanied by the implementation of three successive standards: avoid, reduce and compensate. However, this possibility of compensation can lead to the development of an offset supply. The simultaneity of norms, prices and the supply of offsets can lead to an amalgam of the ARC sequence with a market instrument. One of the objectives of this article is to clarify this point.

The economic literature has identified various factors contributing to the failure to meet the no net loss objective have been widely discussed. However, to our knowledge, there has not yet been an attempt to model the developer's behavior in the face of various incentives to comply or not with the different steps of the mitigation hierarchy. The objective of this paper is not to analyze the efficiency of the ARC sequence in protecting biodiversity as this question is better suited to biological or ecological analysis. The idea of this article is to analyze how a developer behaves when faced with the ARC sequence.

To answer this question, we will mobilize two informational contexts: perfect information and asymmetric information. Under perfect information, it is assumed that the regulator has all the information about the developer's projects, both on the level of possible damage and the possibilities of damage reduction. Second, we assume that this information is only held by the developer. Under both assumptions, we seek to characterize the behavior of a developer in the face of the ARC sequence and the no net loss policy. We first highlight the difficulties of transposing the sequence into an economic decision model with perfect information. Moreover we show that the demand for compensation does not depend on its price. Under asymmetric information, the developer uses information strategically to achieve the no net loss objective by circumventing the ARC sequence. We show that, using the backward induction reasoning, the developer first defines his demand for offsets based on their price. In the end, the project chosen is the one that is most profitable given the compensation expense. Under asymmetric information, the price of compensation is therefore a key variable, unlike in the situation of perfect information. The no net loss policy accompanied by the ARC sequence is a policy of environmental standards and not an economic instrument. In the real world, asymmetric information seems the most likely hypothesis. In this case, the ARC sequence is inoperative, with the consequence that it is ineffective in protecting biodiversity. The generalization of the ARC sequence and the creation of a public agency for the preservation of biodiversity may allow the problem of asymmetric information to be overcome, thus making the sequence more operative.

The article is structured as follows. Section 5.2 outlines the assumptions of our model. Then, Section 5.3 integrates the ARC sequence into a decision model under perfect information and Section 5.4 under asymmetric information. Finally, discussion and conclusion are presented in Section 5.5.

5.2 Assumptions

We assume a developer wants to invest in a project v_i, $i = 0, 1$. The net economic benefit without taking into account the environmental damages is given by $B(v_i)$. Each project causes environmental damages in the amount of $D(v_i)$. We assume that the project v_1 generates fewer benefits but less environmental damage than the project v_0. So we have: $B(v_1) < B(v_0)$ and $D(v_1) < D(v_0)$. The regulator imposes the no net loss principle and the ARC sequence in order to help the developer achieve this environmental policy goal. Thus, each developer must sequentially avoid, reduce and compensate for its environmental losses.

Damage reduction is achieved by choosing a damage level $D^{\min}(v_i)$ lower than the initial damage, such as: $r = D(v_i) - D^{\min}(v_i)$. Damage reduction imposes an additional cost on the company given by $C(r)$ with $C'(r) > 0$ and $C''(r) > 0$. The remaining environmental damage must be compensated. Offset banks offer offset credits. The offset credit market is assumed to be atomistic so that the price of the credits, p, is a competitive price.

5.3 Perfect and symmetric information

We first assume perfect and symmetric information. In this case, the regulator and the developer share the same information about the environmental damages and the different costs of reducing the damages. The regulator can monitor whether the developer follows the ARC procedure. Under this assumption, the developer can only respect, step by step, the sequence. We follow the French definitions from the MEDD for each step of the sequence.

The avoidance stage For the avoidance stage, the definition of the MEDD emphasizes that the design of a project "*must first of all seek to avoid impacts on the environment, including the fundamental choices related to the project (the nature of the project, location, even opportunity)*". We interpret this definition as the fact that the developer must avoid the environmental impacts of the project as much as possible. In our framework, he chooses the project v_1, which causes the least environmental damage ($D(v_1) < D(v_0)$).

The reduction stage The MEDD gives the following definition for the reduction stage: "*These impacts must then be sufficiently reduced (...) at a reasonable cost, to constitute only the smallest possible residual negative impacts.*" This step lacks operational content. Indeed, what does *sufficiently reduced* mean? What is *a reasonable cost*? If the level of damage reduction has to be the lowest level achievable by the developer, it is possible that the cost of reduction is such that the developer's profit is negative. Here, we clarify the desired requirement at this stage as keeping the level of damage reduction as high as possible, while remaining consistent with a non-negative profit. If the level of damage chosen is positive, this constraint must include the necessary cost of compensation, which is included in step 3. We note $D^{\min}(v_1)$ this level of damage. So $r = D(v_1) - D^{\min}(v_1)$, with $D^{\min}(v_1) < D(v_1)$. So $D^{\min}(v_1)$ has to solve $B(v_1) - C(D(v_1) - D^{\min}(v_1)) = 0$. If there is no damage level satisfying this condition, the developer chooses $D^{\min}(v_1)$ such as:

$B(v_1) - C(D(v_1) - D^{\min}(v_1)) - pD^{\min}(v_1) = 0$. Despite the developer's efforts to minimize damage, there may be no possibility of complete damage reduction compatible with the non-negative profit constraint. In this case, a positive level of damage is implied.

The compensation stage The compensation stage only appears if the damage level is positive, i.e. $D^{\min}(v_1) > 0$. The not net loss principle imposes a necessary damage compensation. This compensation is only permitted by the regulator if the ARC sequence has been previously scrupulously followed by the developer. The demand for offsets is therefore determined in a residual manner. This observation allows us to make this proposition:

Proposition 1. *Under perfect information, the offset demand does not depend on the offset price.*

The compensation cost is given by $pD^{\min}(v_1)$ if $D^{\min}(v_1) > 0$ and 0 if $D^{\min}(v_1) = 0$.

In the end, by applying the rules of the ARC sequence under perfect information, the developer chooses the project v_1, opts for an environmental reduction level compatible with a non negative profit and compensates for the residual damage. The sequence is respected at each level, which allows for the best protection of biodiversity. The price of compensation does not influence the developer's behavior. The ARC sequence coupled with the no net loss policy is a succession of environmental standards.

5.4 Asymmetric Information

We now assume that only the developer has information about the different projects he wants to carry out, including the environmental damage of each project, $D(v_i)$, and the possibilities of damage reduction given by the function $C(r)$. The information between the regulator and the developer is therefore asymmetric. The assumption of asymmetric information leads to two differences compared to the situation of perfect information. On the one hand, the regulator cannot know whether the developer has respected the ARC sequence. On the other hand, the developer – as an homo economicus – will not consider the sequence separately, that is, in a myopic way. The developer can be expected to behave strategically while respecting the no net loss requirement. He will adopt backward induction reasoning in order to choose the level of reduction and compensation. In the end, the rational developer will choose the project that offers the greatest profit.

Assuming that the developer chooses the project v_i, he decides the amount of reduction and thus the level of compensation by minimizing the total environmental conformity cost:

$$\begin{aligned} \text{Min } TC_{D\tilde{v}_i} &= C(Dv_i - D\tilde{v}_i) + pD\tilde{v}_i \\ -C'(Dv_i - D\tilde{v}_i) + p &= 0 \end{aligned} \tag{5.1}$$

According to Equation (5.1), the developer chooses the level of damage reduction $[Dv_i - D\tilde{v}_i]$ such that the marginal cost of environmental damage reduction is equal to the offset price. If $D\tilde{v}_i$ is equal to zero, there is no damage and no need for compensation. If $D\tilde{v}_i > 0$, the developer has to buy offset credits in order to compensate for the environmental damage at a cost $pD\tilde{v}_i$.

Therefore, what will explain the compensation level is the shape and limits of the damage reduction curves and the price of the offset credits. Compensation occurs if $C'(Dv_i)$ has a finite limit in $D\tilde{v}_i = 0$ such that the offset price is lower than this limit or if $C'(Dv_i)$ satisfies Inada's condition in $D\tilde{v}_i = 0$. However, there is never compensation if $C'(Dv_i)$ has a finite limit in $D\tilde{v}_1 = 0$ such that the offset price is higher than this limit.

Proposition 2. *Under asymmetric information, the demand for compensation is based on the offset price.*

Thus, the level of compensation is no longer residual as required by law (step 2 of the ARC sequence), but results from an economic calculation. Homo economicus uses the asymmetric information to maximize its profit. Finally, the profit obtained with the project v_i is written as:

$$\Pi(v_i) = B(v_i) - C(D(v_i) - D(\tilde{v}_i)) - pD(\tilde{v}_i)$$

In the end, the developer chooses the project that gives the higher level of profit. He will choose the project v_1 if:

$$\Pi(v_1) > \Pi(v_0)$$

Which can also be written as:

$$B(v_1) - C(D(v_1) - D(\tilde{v}_1)) - pD(\tilde{v}_1) > B(v_0) - C(D(v_0) - D(\tilde{v}_0)) - pD(\tilde{v}_0) \quad (5.2)$$

As $C'(Dv_0 - D\tilde{v}_0) = p = C'(Dv_1 - D\tilde{v}_1)$, we have: $Dv_0 - D\tilde{v}_0 = Dv_1 - D\tilde{v}_1$, and $C(D(v_1) - D(\tilde{v}_1)) = C(D(v_0) - D(\tilde{v}_0))$. Replacing in (5.2), we obtain:

$$B(v_1) - B(v_0) > p[D(\tilde{v}_1) - D(\tilde{v}_0)]$$

A project v_1 is chosen if the difference in benefit between projects v_1 and v_0 is greater than the difference in expenditure between the projects on compensation.

Proposition 3. *The project choice only depends on the project benefit and on the offset price.*

Thus, the offset price determines the compensation level and thus the level of the environmental damage reduction. The offset price is also the determining factor in the choice of project. At no point does the avoidance stage play a role in the behavior of homo economicus. The reduce and compensate stages are not sequential but simultaneous. In the end, the ARC sequence is inoperative under asymmetric information. The developer makes decisions based on the compensation price. In this case, the not net loss policy can be considered as a market-based instrument.

5.5 Discussion and conclusion

The ARC sequence appeared in the United States in 1972, then in 1976 in French law. In France, the definitions of the Avoidance, Reduction, and Compensation measures were introduced in 2012, followed by the not net loss of biodiversity objective in its Biodiversity Law of 2016. The study of this sequence in the economic literature is most often done by taking into account its impact on biodiversity conservation (Brown and Land, 1999; Quétier et al., 2014; Calvet et al., 2019). Some studies, such as Bigard et al. (2018), highlight the difficulties of translating the concepts of the ARC sequence into practice. According to the authors, the qualifications given in the impact studies often do not correspond to the national reference definitions. In particular, they note a confusion between avoidance and reduction measures.

Following Bigard et al. (2018), our work sought to analyze the operational dimension of the ARC sequence, but mobilizing another angle of study. We sought to incorporate the ARC sequence into an economic decision model. The objective of this paper is to investigate the rationality of the ARC sequence. To do so, we assumed the hypotheses of perfect and asymmetric information.

Using the perfect information hypothesis, we first highlighted the difficulties of transposing the imperatives of the sequence into an economic decision model. The ARC sequence corresponds to the implementation of three standards: avoid, reduce, and compensate. We selected the project that caused the least environmental damage, at the avoidance stage, which implies the existence of several projects or project modalities. The reduction stage raises the question of the meaning of "sufficiently reduced" (...) at "a reasonable cost". This point is difficult to transpose into an economic model. Here we have chosen the highest level of damage reduction that can be accounted for with a non-negative profit. We have shown that when the sequence is respected, the demand for compensation does not depend on its price. Under symmetric information, the ARC sequence is an environmental standard.

The environmental economics literature notes the importance of information in the implementation of environmental standards as a means of pollution control. However, the sequence goes even further in requiring information than pollution standards because it involves sequential implementation. So, we then lift this assumption of perfect information by assuming that the regulator does not have all the information about the projects. In this case, we showed the information is used strategically by the developer and that the ARC sequence is inoperative. The developer will not behave in a myopic way, considering the different steps independently of each other. Rather, as an homo economicus, he will reason backwards in order to choose the most profitable project, under constraint of the no net loss policy. We show that the developer will simultaneously decide on the amount of the damage reduction and the compensation based on the offset price and that, in the end, the choice of project is established in particular on the offset price. In other words, establishing this sequence in the law involving the no net loss policy is inefficient when the information is asymmetric. Therefore, under asymmetric information, the no net loss policy is a market-based instrument.

However, our article has not taken into account the existence of another operator, the auditors. In fact, the ARC sequence is carried out through impact studies. The developer is responsible for the study, and can call on the services of consulting firms to draw up this document. The company pays for these services. In the face of the operational vagueness of the ARC sequence, one can imagine that the company can draft the impact study by evading certain information or minimizing certain impacts, which justifies our hypothesis of asymmetric information. One way to overcome this information problem would be to create a specialized public agency whose mission would be to conduct all these impact studies. This agency would benefit from the experience gained from one study to another and would be better able to apply the same interpretation of the ARC sequence to each project. The generalization of the sequence in France to all projects regardless of their location and size would allow for these economies of scale. In our article, we have considered several possible projects with different levels of damage. In reality, developers consider a single project, hence the difficulties in interpreting the avoidance stage. One could imagine that the developer would be obliged to communicate to this agency his different projects so that the ARC sequence is applied upstream of the decisions. In the end, the creation of this agency would tend to remove the asymmetry of information concerning the environmental damage of the project, thus allowing the ARC sequence to be implemented. The sequence would be a standards approach, not a market-based approach. The objective of no net loss is thus achieved, but not at the lowest cost.

In fact, our work highlights the different objectives of a biodiversity conservation policy, either strictly protecting biodiversity or implementing the least cost criterion. The ARC sequence coupled with the not net loss objective is a sequence of norms aimed at preserving biodiversity. The offset mechanism, by putting a price on the offset, can be seen as an economic incentive to compensate. If each developer reduces his damage by equating the marginal cost of reducing the damage to the price of the offset, biodiversity will be saved at lower costs. This result is not possible by applying the ARC sequence, but perhaps this is the price to pay for taking into account a very particular and difficult to measure good, biodiversity.

In this article, we have assumed an exogenous price for offsets. When the supply of offsets is not well developed, this assumption can be challenged. Future research should take into account the sequence when the price of the offset is established on an over-the-counter market.

Chapter 6

Conclusion

Biodiversity collapse is a well-documented problem that affects human well-being through the decline in provision of numerous ecosystem services. Terrestrial biodiversity loss is mainly due to land use changes, in particular conversion to and intensification of agricultural lands. This thesis, consisting of four chapters, has focused on the theoretical efficiency of one market-based policy instrument, payments for environmental services (PES), which aims to address the problem of biodiversity decline by financially incentivizing its provision. The first chapter reviewed the literature on PES while the other three chapters fill in gaps in the existing literature by examining specific aspects of imperfect competition and PES design and efficiency are impacted. Two chapters analyzed price-based PES and one chapter analyzed a quantity-based PES.

6.1 Main results

In the first article, we looked at a scenario where an environmental tax and a PES scheme are used to address pollution and biodiversity conservation, respectively. Our model looked at how several identical farmers choose to allocate their land between conventional agriculture production, organic agriculture production, and leaving grass buffer strips. We assumed that conventional production causes environmental damages, organic production has a neutral impact on the environment, and the grass buffer strips provide environmental benefits. We added an additional market distortion in the form of an oligopoly in organic agriculture production. We found that the second-best tax on conventional agriculture production is higher than the marginal damage from pollution, and the second-best PES for biodiversity is lower than the marginal benefit. In order to account for the fact that funds must be raised to finance a public PES, we then introduced the marginal social cost of public funds (MCF). The PES decreases with the MCF, whereas the Pigouvian tax increases with the MCF, provided that demand for the conventional agriculture good is inelastic and environmental policies provide buffer strips efficiently. The first article highlights a contributory component of the environmental incentive tax. We also identify cases where the PES is ineffective in promoting biodiversity.

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

Budgets for PES programs are often limited, and regulators may decide to condition payments on additional area of a biodiversity-friendly land use. We denote such a policy as additionality-based PES. The second paper looks at whether additionality-based PES achieve environmental efficiency. We used a model with two time periods and we considered the representative farmer's behavior. The regulator sets a PES that only pays 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, the second 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.

Turning to a quantity-based PES, we looked at mitigation banking, and in particular, the mitigation hierarchy or avoid, reduce, compensate (ARC) sequence in the third paper. Some studies, such as Bigard et al. (2018), highlight the difficulties of translating the concepts of the ARC sequence into practice. According to the authors, the qualifications given in the impact studies often do not correspond to the national reference definitions. In particular, they note a confusion between avoidance and reduction measures. Following Bigard et al. (2018), our work sought to analyze the operational dimension of the ARC sequence, but mobilizing another angle of study. We sought to incorporate the ARC sequence into an economic decision model, with the objective of investigating its rationality. To do so, we assumed the hypotheses of perfect and asymmetric information.

Using the perfect information hypothesis, we first highlighted the difficulties of transposing the imperatives of the sequence into an economic decision model. The ARC sequence corresponds to the implementation of three standards: avoid, reduce, and compensate. We selected the project that caused the least environmental damage, at the avoidance stage, which implies the existence of several projects or project modalities. The reduction stage raises the question of the meaning of "sufficiently reduced" (...) at "a reasonable cost". This point is difficult to transpose into an economic model. Here we have chosen the highest level of damage reduction that can be accounted for with a non-negative profit. We have shown that when the sequence is respected, the demand for compensation does not depend on its price. Under symmetric information, the ARC sequence is an environmental standard.

The environmental economics literature notes the importance of information in the implementation of environmental standards as a means of pollution control. However, the sequence goes even further in requiring information than pollution standards because it involves sequential implementation. So, we then lift this assumption of perfect information by assuming that the regulator does not have all the information about the projects. In this case, we showed the information is used strategically by the developer and that the ARC sequence is inoperative. The developer will not behave in a myopic way, considering the different steps independently of each other. Instead, as an homo economicus, he will reason backwards in order to choose the most profitable project, under the constraint of the no net loss policy. We show that the developer will simultaneously decide on the amount of the damage reduction and the compensation based on the offset price and that, in the end, the choice of project is based on the offset price. In other words, establishing this sequence in the law involving the no net loss policy is inefficient when the information is asymmetric. Therefore, under asymmetric information, the no net loss policy is a market-based instrument.

In fact, our work highlights the different objectives of a biodiversity conservation policy, either strictly protecting biodiversity or implementing the least cost criterion. The ARC sequence coupled with the not net loss objective is a sequence of norms aimed at preserving biodiversity. The offset mechanism, by putting a price on the offset, can be seen as an economic incentive to compensate. If each developer reduces his damage by equating the marginal cost of reducing the damage to the price of the offset, biodiversity will be saved at lower costs. This result is not possible by applying the ARC sequence, but perhaps this is the price to pay for taking into account a very particular and difficult to measure good, biodiversity.

6.2 Limitations and future research

Our theoretical analyses of PES policies, like all analyses, have limitations. While we explored some alternative assumptions in the first study, it could also be extended to consider differentiated demands for organic agriculture that occur for some level of market power. Another extension would be to look at the case where farmers are heterogeneous and analyze the definition of PES when the conventional good production has negative externalities on the organic good production and these externalities cannot be directly internalized. Additionally, the first study employs a relatively simple model, where the only way to increase biodiversity benefits is by leaving grass strips. This management action is assumed to only incur opportunity costs of not producing. Indeed, existing programs remunerate several different land management actions, some of which incur other costs, such as planting cover crops. Future research could explore how the farmer chooses which management action(s) to undertake and how this impacts the level of environmental service provision.

Regarding the second study, it turns out that basing the PES on the additional environmental benefits obtained by the payment is not easy to characterize in a simple perfect information setting with two time periods. However, the second study could be extended by considering an infinite time horizon, in order to see how the results hold up. This would mean modeling strategic behavior in an optimal control model. In the same vein as Barnett (1980), we defined the second-best environmental policies 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.

The third study examined the rationality of the ARC sequence. However, our study has not taken into account the existence of another operator, the auditors. In fact, the ARC sequence is carried out through impact studies. The developer is responsible for the study, and can employ consulting firms to draw up this document, which entails another cost for the developer. In the face of the operational vagueness of the ARC sequence, one can imagine that the consulting firm can draft the impact study by evading certain information or minimizing certain impacts, which justifies our hypothesis of asymmetric information. One way to overcome this information problem would be to create a specialized public agency whose mission would be to conduct all of these impact studies. This agency would benefit from the experience gained from one study to another and would be better able to apply the same interpretation of the ARC sequence to each project. The generalization of the sequence in France to all projects regardless of their location and size would allow for these economies of scale.

In our study, we have considered several possible projects with different levels of damage. In reality, developers consider a single project, hence the difficulties in interpreting the avoidance stage. One could imagine that the developer would be obliged to communicate to the specialized public agency his different projects so that the ARC sequence is applied upstream of the decisions. In the end, the creation of the specialized public agency would tend to remove the asymmetry of information concerning the environmental damage of the project, thus allowing the ARC sequence to be implemented. The sequence would be a standards approach, not a market-based approach. The objective of no net loss is thus achieved, but not at the lowest cost.

Finally, we have assumed an exogenous price for offsets. When the supply of offsets is not well developed, this assumption can be challenged. This work can be extended by taking into account the sequence when the price of the offset is established on an over-the-counter market.

CHAPTER 7

Résumé extensif en français: Paiements pour services environnementaux et concurrence imparfaite

Ce résumé extensif de la thèse est structuré comme suit. La section 7.1 définit les notions de la biodiversité et les services environnementaux. La section 7.2 introduit le concept de paiements pour les services environnementaux. Les motivations de la thèse sont exposées dans la section 7.3 et la section 7.4 présente les principaux résultats. Enfin, la section 7.5 discute des pistes de recherche futures.

7.1 De la biodiversité aux services environnementaux

La Convention sur la Diversité Biologique définit la biodiversité comme "la variabilité des organismes vivants de toute origine y compris, entre autres, les écosystèmes terrestres, marins et autres écosystèmes aquatiques et les complexes écologiques dont ils font partie ; cela comprend la diversité au sein des espèces et entre espèces ainsi que celle des écosystèmes" (Convention on Biological Diversity, 2010). La diversité de la vie et des écosystèmes permet diversifier les services environnementaux. Dasgupta (2021) les compare aux portefeuilles financiers : si la diversité des investissements permet d'atténuer les risques, la biodiversité permet à la nature d'être plus productive, résiliente et adaptable.

Le déclin de la biodiversité est un phénomène bien documenté, qui risque de s'aggraver avec le changement climatique (Díaz et al., 2019; Ruckelshaus et al., 2020; Dasgupta, 2021). L'une des principales causes de ce déclin est la perte de divers habitats due au changement d'affectation des sols (Lewis et al., 2011; Bamière et al., 2013). En effet, une grande partie de la perte de biodiversité terrestre provient de la transformation des sols en terres agricoles. L'intensification de l'usage des terres et l'augmentation de la taille des exploitations agricoles ont transformé et fragmenté les habitats naturels, entrainant le déclin de nombreuses espèces. Selon Dasgupta (2021), on estime que 20 % des espèces pourraient disparaître au cours des prochaines décennies, et peut-être le double d'ici la fin du siècle.

L'expression "services de la nature" est apparue pour la première fois en 1977 dans la littérature académique dans un article de Walter Westman (Westman, 1977). Elle a été suivie du terme "services écosystémiques", évoqué en 1981 par Costanza et al. (2017). Toutefois, ce n'est qu'à la fin des années 1990, lorsqu'un article paru dans Nature a estimé que la valeur totale de tous les services écosystémiques de la biosphère se situait entre 16 et 54 billions de dollars américains, que la notion de services écosystémiques a gagné en popularité en tant que sujet de recherche (Costanza et al., 1997).

L'évaluation des écosystèmes pour le millénaire définit les services écosystémiques comme les avantages que les agents retirent des écosystèmes. Il s'agit notamment des *services d'approvisionnement* tels que la nourriture, l'eau, le bois et les fibres ; des *services de régulation* qui affectent le climat, les inondations, les maladies, les déchets et la qualité de l'eau ; des *services culturels* qui fournissent des avantages récréatifs, esthétiques et spirituels ; et des *services de soutien ou services de support* qui permettent la production d'autres services tels que la formation des sols, la photosynthèse et le cycle des nutriments (Reid et al., 2005).

La littérature économique fait la distinction entre les services écosystémiques et les services environnementaux (SE). Le terme "services écosystémiques" fait référence aux bénéfices fournis par les écosystèmes tandis que le terme "services environnementaux" renvoie a la protection de ces écosystèmes par l'homme et a la notion d'externalités induites par les activités humaines. Par exemple, l'Organisation des Nations Unies pour l'alimentation et l'agriculture (FAO) propose une définition des SE en termes de services écosystémiques. Pour l'agriculture, les SE sont définis comme la sous-partie des services écosystémiques qui peuvent être qualifiés d'externalités, c'est-a-dire tous les services écosystémiques a l'exception des services d'approvisionnement (Lugo, 2007). La notion de SE peut être utilisée pour faire référence à la production de services par les agriculteurs pour protéger l'environnement. Nous pouvons citer plusieurs exemples. Les rotations longues de cultures améliorent les services écosystémiques tels que les services de soutien grâce à l'amélioration de la qualité des sols. La diversité des activités productives d'une exploitation favorise les interactions bénéfiques entre les cultures et le bétail, et la gestion des éléments du paysage tels que les bandes enherbées, les pentes, les haies ou les cours d'eau. Elle contribue au fonctionnement écologique des agroécosystèmes.

Toutes ces définitions permettent de justifier la rémunération de ces SE comme une internalisation des externalités. Cela laisse place à une intervention publique visant à encourager leur fourniture optimale, comme la mise en place de paiements pour services environnementaux (PSE). Les PSE sont un outil utilisé aujourd'hui pour la conservation et la restauration des écosystèmes et des services qu'ils fournissent (Dasgupta, 2021).

7.2 Paiements pour services environnementaux

L'une des définitions les plus largement citées du PSE est celle de Wunder (2005). Il définit le PSE comme une transaction volontaire dans laquelle un SE bien défini ou une utilisation des terres pouvant produire ce service est acheté par (au moins) un acheteur de SE à (au moins) un fournisseur de SE si et seulement si le fournisseur de SE garantit la fourniture du SE. Cette conditionnalité peut être compliqué à évaluer dans les mécanismes de PSE basés sur les résultats, car certains SE sont difficiles à mesurer. Dans la pratique, il est beaucoup plus courant de mettre en place des mécanismes de PSE basés sur des actions qui sont conditionnées à des pratiques spécifiques d'utilisation ou de gestion des terres.

La définition ci-dessus illustre le théorème de Coase, selon lequel une externalité peut être internalisée par une négociation privée. Dans ce cas, l'allocation optimale des SE peut être obtenue, indépendamment de l'allocation initiale des droits de propriétés, en supposant des coûts de transaction suffisamment faibles et des droits de propriété bien définis (Coase, 1960). Un exemple de PSE coasien est le PSE de Vittel, dans le nord-est de la France. L'entreprise, subissant la pollution des aquifères par les nitrates, a conclu un accord avec les agriculteurs locaux. Il s'agissait de les indemniser pour qu'ils réduisent leur utilisation d'engrais (Bingham, 2021).

Cette définition des PSE peut être élargie pour inclure certains types d'interventions gouvernementales qui reflètent une subvention pigouvienne (Pigou, 1920; Sattler and Matzdorf, 2013). Ce type de PSE est beaucoup plus courant dans la pratique qu'un PSE coasien. Par exemple, les programmes agro-environnementaux européens sont financés par des fonds publics et le gouvernement agit en tant qu'intermédiaire entre les acheteurs de SE (le public) et les vendeurs de SE (les agriculteurs qui reçoivent les PSE). Les systèmes de PSE coasiens et pigouviens suivent tous les deux le principe du beneficiaire-payeur.

Une autre définition fournie par Muradian et al. (2010) décrit les PSE comme un transfert de ressources entre acteurs, visant à créer des incitations pour aligner les décisions individuelles et/ou collectives d'utilisation des terres sur l'intérêt social en matière de gestion des ressources naturelles. Cette définition est plus souple que celle de Wunder (2005) et reflète mieux la pratique actuelle des PSE. Ainsi, les paiements ne sont pas nécessairement monétaires, mais peuvent constituer des transferts en nature.

De nombreuses formes de PSE ont été mises en œuvre tant dans les pays en développement que dans les pays développés. Aux États-Unis, le Conservation Reserve Program est en place depuis 1985 (Hellerstein, 2017). Le Costa Rica est l'un des premiers pays à avoir adopté, en 1997, un programme national de PSE (Pagiola, 2008). En Chine, le programme de conversion des terres en pente et le programme de conservation des forêts naturelles ont investi plus de 50 milliards USD entre 2000 et 2009 (Salzman et al., 2018). Le programme REDD+, conceptualisé en 2007, met en lien les pays développés et les pays en développement. Il vise à réduire les émissions de carbone dues à la déforestation et à la dégradation des forêts. Plus précisément, il incite les pays en développement à préserver leurs forêts grâce à des paiements financés par les pays développés (Chiroleu-Assouline et al., 2018). Les politiques de protection de la biodiversité se concentrent souvent sur les terres agricoles, comme les Mesures Agro-Environnementales et Climatiques (MAEC) en Europe, que les États membres sont tenus d'appliquer depuis 1992. Les MAEC sont des PSE qui rémunèrent les agriculteurs pour les actions volontaires qu'ils entreprennent en vue de préserver et d'améliorer l'environnement. Dans l'Union européenne, la préservation de la biodiversité passe essentiellement par la mise en œuvre des PSE appliqués dans le cadre de la politique agricole commune (PAC) (Herzon et al., 2018). Les pratiques adoptées comprennent la réduction des engrais et/ou des pesticides, l'établissement de bandes enherbées notamment près des rivières et le recours à la rotation de cultures. Plus récemment, dans le cadre du Plan National pour la Biodiversité 2018 adopté en France, les agences de l'eau peuvent mettre en place leurs propres programmes de PSE. Elles ont reçu 150 millions d'euros du budget national français, avec pour objectif de maintenir ou de créer de bonnes pratiques écologiques, telles que la réduction des pesticides ou la plantation de couvert végétale. Ce nouveau programme vise des PSE basés sur les résultats annuels plutôt que sur les actions. Les actions de maintien ou de création de bonnes pratiques sont toutes les deux récompensées, mais la création de bonnes pratiques permet d'obtenir des paiements plus élevés (jusqu'à 676 euros/ha/an, contre 66 euros/ha/an pour le maintien des bonnes pratiques).

Il est difficile de classer ces différents mécanismes de PSE. Comme le soulignent Sattler et al. (2013), les PSE reposent sur une multitude d'approches qui diffèrent en termes de SE visés, de mécanismes de formation des prix, d'origines et de niveaux de paiement, de caractéristiques des acheteurs et des vendeurs ou de règles régissant le contrat entre les parties concernées. Selon Wunder (2005), les principaux SE visés par les PSE sont la séquestration et le stockage du carbone, la protection de la biodiversité, la protection des bassins versants et la beauté des paysages.

7.3 Motivation de la thèse

Malgré l'abondante littérature sur les PSE, de nombreuses questions de recherche restent inexplorées. Tout d'abord, il est nécessaire d'analyser la manière dont les PSE interagissent avec d'autres politiques environnementales telles que les taxes pigouviennes, et de définir dans ce contexte leur niveau optimal. Selon Bryan and Crossman (2013), l'interaction de multiples incitations financières visant la fourniture de services par les agro-écosystèmes peut réduire leur efficacité. Les mesures agroenvironnementales doivent donc tenir compte du fait que les politiques sont généralement des combinaisons de mesures et que les incitations financières pour différents services écosystémiques interagissent (Huber et al., 2017). Lankoski and Ollikainen (2003) fournissent un cadre théorique intéressant visant à définir le niveau optimal d'un PSE et d'une taxe pigouvienne dans le secteur agricole.

Une autre question peu développée dans la littérature est d'investiguer dans quelle mesure un pouvoir de marche peut modifier le niveau optimal des PSE. Ce point a largement été traite en ce qui concerne les taxes pigouviennes. En présence de pouvoir de marche, il est montre que la taxe optimale de second rang doit être inférieure au dommage marginal (Barnett, 1980; Ebert, 1991). Toutefois, aucune étude ne définit le niveau optimal des PSE en présence de concurrence imparfaite. Le pouvoir de marche conduit à un niveau de production sous-optimal, car les entreprises restreignent la production pour augmenter leurs profits. Étant donne que les taxes et les PSE influencent les niveaux de production, les PSE devraient également tenir compte des pouvoirs de marche afin de ne pas fausser davantage la production en l'éloignant du niveau socialement optimal.

En outre, lorsque les PSE sont financés par de l'argent public, il est nécessaire de lever des fonds par le biais de l'impôt, ce qui peut entraîner des distorsions dans l'économie. L'augmentation des impôts contributifs peut modifier l'allocation des ressources en influençant les décisions en matière de consommation, de travail ou d'investissement. Il semble donc important de prendre en compte le coût social des fonds publics dans notre analyse. Il s'agit d'une mesure de la perte de bien-être subie par la société du fait de la mobilisation de recettes supplémentaires pour financer les dépenses publiques. Par exemple, Browning (1976) estime le Coût Marginal Social des Fonds Publiques (MCF) de l'impôt sur le revenu du travail aux États-Unis entre 1,09 à 1,16 $ par dollar de recettes fiscales collectées. Selon Beaud (2008), ce coût est égal à 1,2 pour la France. Ainsi, lorsque l'État collecte un euro de taxe, cette dernière coûte finalement 1,2 euro à la société. Cet aspect ne doit donc pas être négligé dans la décision de mettre en place un PSE.

Un autre facteur important conditionnant l'efficacité économique des PSE est leur caractère additionnel ou non, c'est-a-dire s'ils impliquent la fourniture d'un SE qui n'aurait pas eu lieu en l'absence de tout paiement. Les premiers PSE n'exigeaient pas l'additionnalite. Il est vrai que le contrôle de l'additionnalite peut s'avérer très coûteux. Par exemple, dans le cas du programme national du Costa Rica, l'objectif est de reconnaître et de payer pour toute fourniture de SE indépendamment de son additionnalite. Ce n'est que plus récemment que l'évaluation de l'additionnalite des programmes de PSE est devenue une préoccupation. Ce caractère est toutefois essentiel pour qu'un mécanisme de PSE atteigne un objectif environnemental et économique, tout en maintenant la confiance des investisseurs (Bennett, 2010).

Enfin, les banques de compensation peuvent être considérées comme un PSE, car elles conduisent les agents à payer pour les actions de restauration, de préservation et/ou de gestion de la biodiversité et des écosystèmes (Bureau, 2010; Salzman et al., 2018). Dans ce cas, la persévération de la biodiversité repose sur un mécanisme quantité plutôt que basé sur les prix. En effet, les banques de compensation impliquent le recours à des permis négociables. Avant de pouvoir acheter des crédits auprès d'une banque de compensation, il faut, en théorie, suivre une hiérarchie des mesures d'atténuation dont l'objectif est l'absence de perte nette de biodiversité ou de services environnementaux. Lors de la conception d'un projet qui générera des dommages environnementaux, un aménageur doit d'abord éviter tout dommage possible en modifiant le projet. Ensuite, les dommages qui ne peuvent être évités doivent être réduits. Enfin, tout dommage résiduel après évitement et réduction doit être compense, soit par la restauration d'une autre zone naturelle équivalente, soit par l'achat de permis auprès d'une banque de compensation. Cependant, dans la réalité, la hiérarchie des mesures d'atténuation n'est pas correctement respectée, affectant ainsi l'efficacité de ces PSE.

7.4 Principaux résultats

L'objectif de cette thèse est d'analyser ces différentes questions, afin d'approfondir les connaissances sur les PSE. Elle se compose d'une revue de la littérature sur les PSE et de trois articles originaux dans lesquels sont introduits chacun de ces points inexplorés jusqu'à présent dans la littérature économique.

La revue de la littérature analyse l'efficacité des mécanismes de PSE. De nombreux articles traitent de l'asymétrie d'information qui existe entre les acheteurs et les vendeurs de services environnementaux. Cette asymétrie remet en question l'additionnalité des PSE. Afin d'y remédier, une partie de la littérature analyse les enchères de conservation. D'autres facteurs limitant l'efficacité des PSE sont également abordés, comme les coûts de transaction, la durée des contrats, et les motivations à la conservation. Le principe d'un bonus d'agglomération est considéré afin d'améliorer l'efficacité environnementale. Finalement, les études des banques de compensation montrent que la séquence des mesures d'atténuation des dommages est difficilement respectée, affectant l'efficacité de la politique de préservation de la biodiversité.

Dans le premier article, nous avons étudié un scénario dans lequel une taxe environnementale et un système de PSE sont utilisés pour lutter contre la pollution et préserver la biodiversité, respectivement. Ce modèle examine comment des agriculteurs choisissent de répartir leurs terres entre une production agricole conventionnelle, une production agricole biologique et la mise en place de bandes enherbées. Il est supposé que la production conventionnelle cause des dommages environnementaux, que la production biologique a un impact neutre sur l'environnement et que les bandes enherbées permettent de promouvoir la biodiversité. Une distorsion supplémentaire a été ajoutée en supposant que le marché agricole biologique est organisé en oligopole. Il est montre que la taxe de second rang sur la production agricole conventionnelle est supérieure au dommage marginal causé par la pollution, et que le PSE de second rang est inférieur au bénéfice marginal de la biodiversité.

Afin de tenir compte du fait que des fonds doivent être collectés pour financer un PSE public, le MCF a été ensuite été introduit. Le PSE de second rang diminue avec le MCF, tandis que la taxe environnementale de second rang augmente avec le MCF, a condition que la demande pour le bien agricole conventionnel soit inélastique et que les politiques environnementales fournissent des bandes enherbées de manière efficace. Le premier article met en évidence une composante contributive de la taxe incitative. Nous identifions également des cas ou le PSE est inefficace pour promouvoir la biodiversité.

Ce premier article a été prolongé par l'examen d'hypothèses alternatives. Tout d'abord, nous avons remis en question le postulat d'un impact neutre de l'agriculture biologique sur la biodiversité, et nous avons supposé que les bandes enherbées produisent plus de biodiversité que l'agriculture biologique. Dans ce cas, deux PSE doivent être mis en place. Le niveau d'agriculture biologique serait alors soumis à deux effets : un effet négatif induit par l'incitation à la production des bandes enherbées et un effet positif induit par la subvention à la production. Sous nos hypothèses, le premier effet l'emporterait sur le second et les mécanismes mis en évidence dans le premier article resteraient pertinents.

Deuxièmement, maintenant nos postulats de départ, nous avons modifié les outils de politique environnementale en envisageant deux systèmes de PSE - l'un portant sur les terres non cultivées et l'autre sur l'agriculture biologique - mais sans taxe environnementale. Dans ce cas, le PSE rémunérant l'agriculture biologique tient compte du pouvoir de marche et est supérieur au bénéfice marginal de la production biologique, tandis que le PSE sur les terres non cultivées est égal au bénéfice marginal de la biodiversité et ne s'ajuste plus pour intégrer le pouvoir de marche.

Enfin, nous avons modifié l'hypothèse selon laquelle il n'y a pas d'externalités négatives de la production agricole conventionnelle sur le niveau de la production biologique. Lorsque c'est le cas, l'agriculteur internalise lui-même cet impact négatif et les niveaux de PSE et de taxes environnementales ne diffèrent pas de ceux du scénario principal expose dans la thèse.

Les budgets des programmes des PSE sont souvent limités et les régulateurs peuvent décider de conditionner les paiements aux bénéfices environnementaux additionnels obtenus en termes de biodiversité. Nous qualifions cette politique de PSE additionnels. Le deuxième article examine si ces PSE additionnels permettent d'atteindre l'efficacité environnementale. Pour ce faire, nous avons utilisé un modèle a deux périodes, dans lequel un agriculteur affecte ses terres entre une production conventionnelle génératrice de dommages environnementaux, une agriculture biologique et des bandes enherbées favorisant la biodiversité. Une taxe environnementale est appliquée sur la production traditionnelle et un PSE sur les bandes enherbées, ne rémunérant que les bénéfices environnementaux supplémentaires résultant du PSE.

Nous montrons que ce PSE base sur l'additionnalite introduit une distorsion dans le comportement de l'agriculteur au cours de la période initiale. L'agriculteur augmente ses niveaux de production afin d'obtenir un paiement plus important au cours de la période finale. Le PSE de second rang doit corriger cette distorsion tout en prenant en compte les bénéfices et les dommages environnementaux. Au final, le PSE de second rang est égal a la différence actualisée des bénéfices environnementaux marginaux obtenus a chaque période. Les taxes environnementales de second rang pour chaque période ne sont plus égales au dommage marginal. Elles sont ajustées pour corriger les distorsions induites par le PSE.

Nous avons ensuite introduit une position dominante sur le marché de l'agriculture biologique. Si le pouvoir de marche réduit le niveau de production biologique dans la période finale, il limite la distorsion dans la période initiale. Selon l'ampleur de ces deux effets, le PSE additionnel de second rang augmente ou diminue par rapport au scénario sans pouvoir de marche. Les taxes sont ajustées pour tenir compte des effets indirects du pouvoir de marche sur le niveau de la production agricole conventionnelle.

Finalement, cette deuxième étude a montré que le caractère additionnel des PSE ne permet pas d'atteindre l'efficacité environnementale, même sous des hypothèses de concurrence parfaite. Elle permet également de mieux comprendre les interactions entre les différents types de politiques environnementales.

S'agissant d'un PSE basé sur la quantité, nous avons examiné les banques de compensation et, en particulier, la hiérarchie d'atténuation ou la séquence "éviter, réduire, compenser" (ERC) dans le troisième étude. Bigard et al. (2018) soulignent les difficultés à traduire les concepts de la séquence ERC dans la pratique. Selon ces auteurs, les qualifications données dans les études d'impact ne correspondent pas, la plupart du temps, aux définitions nationales de référence. Ils notent notamment une confusion entre les mesures d'évitement et de réduction. À la suite de Bigard et al. (2018), notre travail a analysé la dimension opérationnelle de la séquence ERC, mais en mobilisant un autre angle d'étude. Nous avons cherché à intégrer la séquence ERC dans un modèle de décision économique, avec l'objectif d'étudier sa rationalité. Pour ce faire, nous avons posé les hypothèses d'information parfaite et asymétrique.

Nous avons d'abord mis en évidence les difficultés de transposer les impératifs de la séquence dans un modèle de décision économique. La séquence ERC correspond à la mise en œuvre successive de trois normes : éviter, réduire et compenser. À l'étape “éviter”, le projet le moins dommageable pour l'environnement doit être selectionné, ce qui implique l'existence de plusieurs projets ou modalités de projet. L'étape “réduire” pose la question de la signification de "suffisamment réduit" à "un coût raisonnable" que l'on trouve dans la définition de la séquence. Tel quel, ce point est donc difficilement modélisable. Nous avons défini cette étape comme le niveau le plus élevé de réduction des dommages compatible avec un bénéfice de l'aménageur non négatif. Nous montrons qu'en information parfaite, la séquence ERC est forcément respectée. Dans ce cas, la demande de compensation ne dépend pas de son prix.

La littérature en l'économie de l'environnement souligne l'importance de l'information dans la mise en œuvre des normes environnementales en tant que moyen de lutte contre la pollution. Cependant, la séquence va encore plus loin dans l'exigence d'information que les normes de pollution car elle implique une mise en œuvre séquentielle. Nous levons l'hypothèse d'information parfaite en supposant que le régulateur ne dispose pas de toutes les informations sur les projets. Dans ce cas, nous montrons que l'information est utilisée de manière stratégique par l'amenageur et que la séquence ERC est inopérante. L'amenageur ne se comportera pas de manière myope en considérant les différentes étapes indépendamment les unes des autres. Au contraire, en tant qu'homo-œconomicus, il effectura un raisonnement à rebours afin de choisir le projet le plus rentable, sous la contrainte de la politique d'absence de perte nette de biodiversité. Nous montrons que l'amenageur décidera simultanément du montant de la réduction des dommages et de la compensation en se basant sur le prix de la compensation et que, finalement, le choix du projet dépendra aussi de ce prix. En d'autres termes, l'introduction de la séquence ERC dans la loi impliquant la politique d'absence de perte nette est inefficace lorsque l'information est asymétrique.

Cette troisième étude met en évidence les différents objectifs d'une politique de conservation de la biodiversité, soit la protection stricte de la biodiversité, soit la mise en œuvre du critère du moindre coût. La séquence ERC couplée à l'objectif de "pas de perte nette" est une séquence de normes visant à préserver la biodiversité. Le mécanisme de compensation, en fixant un prix pour la compensation, peut être considéré comme une incitation économique à compenser. Si chaque aménageur réduit ses dommages en égalisant le coût marginal de la réduction des dommages au prix de la compensation, la biodiversité sera sauvegardée à moindre coût. Ce résultat n'est pas atteignable en appliquant la séquence ERC, mais c'est peut-être le prix à payer pour protéger un bien très particulier et difficilement mesurable, la biodiversité.

7.5 Limites et pistes de recherche futures

Nos analyses théoriques des politiques de PSE présentent des limites, comme toutes études. Bien que nous ayons déjà exploré certaines hypothèses alternatives dans le modèle de la première étude, celui-ci pourrait également être étendu pour prendre en compte des demandes différenciées pour les biens agricoles. Une autre extension consisterait à examiner le cas où les agriculteurs sont hétérogènes. Les PSE auraient aussi pu être définis lorsque la production de biens agricoles conventionnels induit des externalités négatives sur la production de biens agricoles biologiques sans que ces dernières puissent être directement internalisées. En outre, cette première étude utilise un modèle relativement simple, dans lequel le seul moyen d'augmenter les bénéfices de biodiversité est de mettre en place des bandes enherbées. Cette mesure est supposée n'entraîner que des coûts d'opportunité liés a l'absence de production. Toutefois, les PSE existants rémunèrent d'autres moyens de protéger la biodiversité, générant leur propre coût. On peut citer l'exemple de plantation de couverts végétaux. De futures recherches pourraient étudier la manière dont l'agriculteur choisit la ou les pratiques de conservation et l'impact de ces mesures sur le niveau de fourniture de services environnementaux.

En ce qui concerne la deuxième étude, la caracterisation des PSE basés sur les avantages environnementaux supplémentaires obtenus par le paiement s'avère complexe dans un cadre simple d'information parfaite avec deux périodes de temps. Cependant, elle pourrait être étendue en considérant un horizon temporel infini, afin d'analyser si les résultats sont maintenus sous cette nouvelle hypothèse. Il s'agirait alors de modéliser le comportement stratégique dans un modèle de contrôle optimal. Pars ailleurs, dans la même veine que Barnett (1980), nous avons défini les politiques environnementales de second rang en information parfaite, ce qui suggère que le régulateur connaît les coûts de production de l'entreprise. En mobilisant la théorie de l'agence, ces travaux pourraient être étendus lorsque l'information est asymétrique, ce qui permettrait de prendre en compte l'aléa moral. Enfin, le modèle pourrait être enrichi en introduisant le MCF.

La troisième étude a examiné la rationalité de la séquence ERC. Cependant, cette analyse n'a pas pris en compte l'existence d'un autre opérateur, les auditeurs. En effet, la séquence ERC est réalisée par le biais d'études d'impact. Ces dernières sont à la charge du promoteur, qui peut faire appel à des bureaux d'études pour rédiger ce document entraîneant ainsi un coût supplémentaire. Face au flou opérationnel de la séquence ERC, on peut imaginer que le bureau d'études mène l'étude d'impact en éludant certaines informations ou en minimisant certains impacts, ce qui justifie notre hypothèse d'asymétrie d'information. Une façon de surmonter ce problème d'information serait de créer une agence publique spécialisée dont la mission serait de réaliser l'ensemble de ces études d'impact. Cette agence bénéficierait de l'expérience acquise d'une étude à l'autre et serait plus à même d'appliquer la même interprétation de la séquence ERC à chaque projet. La généralisation de la séquence en France à tous les projets quels que soient leur localisation et leur taille permettrait ces économies d'échelle.

Dans notre étude, nous avons considéré plusieurs projets possibles avec différents niveaux de dommages. Dans la réalité, les aménageurs ne considèrent qu'un seul projet, d'où les difficultés d'interprétation de l'étape "éviter". On pourrait imaginer que l'amenageur soit obligé de communiquer à cette agence publique spécialisée ses différents projets afin que la séquence ERC soit appliquée en amont des décisions. Au final, la création de cette agence permetrait de rendre opérante la séquence ERC.

Enfin, nous avons supposé un prix exogène pour la pratique de la compensation. Lorsque l'offre de compensation n'est pas suffisamment développée, cette hypothèse peut être remise en cause. Ce travail peut être étendu en introduisant un prix de la compensation établi sur un marché de gré à gré.

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