Agri-environmental policy decentralization: theoretical analysis and application to abandoned wetland in Brittany

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Abstract:

In a context of reflections around the next Common Agricultural Policy (CAP) reform, the European Commission is considering the possibility to decentralize the provision of environmental goods towards lower level of governments. We examine the gains of such potential policy using a simple model of an economy constituted of homogeneous regions and considering that agriculture produces jointly local and global PGs (public goods). We assume that the central government faces lower deadweight losses than the local government but that the local government can better target their subsidies. Our analytical results present the differences of landscape structure (constituted of two areas) and welfare in three cases of governance: full-centralization (EU is in charge of environmental good provision), full-decentralization (local government is in charge of environmental good provision) and partial decentralization (EU allocates a share of its budget to the local government for the provision of environmental goods). We apply our theoretical model to the case of abandoned wetlands in Brittany. Based on this example and the actual CAP budget dedicated for environmental good provision, we illustrate the difference of welfare between the three cases of governance.

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1 Introduction

Agriculture jointly produces private agricultural goods (food and fibers) and public environmental goods (such as biodiversity, water quality, carbon sequestration), which both affect the welfare of the populations. Public goods (PG) can be distinguished according to the scale sensitivity of their beneficiaries. In case of global PG, the beneficiaries are localized all over the world. Local PG benefit to people in a delimited area around the provision locations.

The lack of market solutions for environmental PG justifies public regulator intervention. For example, in Europe, between 4 and 5 billion are allocated each year to the provision of environmental goods by farmers through the Agro-Environment-Climate Measures (AECM) in the context of the Common Agricultural Policy (CAP). Given its structure, design, objectives and budget, the AECM are largely decided and bargained at the EU level, with limited degree of freedom for local authorities.

Such a centralized control has been often debated given the high heterogeneity of agricultural and environmental contexts across EU. The heterogeneity of benefits and costs from PG provision (notably for local ones) lead to a potential spatial mismatch between supply and demand for PG produced by agriculture. The European Commission (EC) started addressed this issue with the communication COM(2017) 713 “The future of Food and farming”[1]. Discussing the future reform of the CAP, the EC claims that concerning environmental goal, that “Member States will need to define quantified targets which will ensure that the agreed environmental and climate objectives defined at EU level are achieved. Member States will have the flexibility to formulate strategic plans allowing for addressing climate and environmental needs at local level”.

The economic literature on environmental federalism addresses the issues of which level of government should design and implement environmental policy. Environmental federalism apply the “fiscal federalism” literature to environmental problems (Oates, 2001). The basic assumptions of these literatures are that *(i)* there are several levels of government (i.e. a federal system), *(ii)* local government can targeted more effectively public spending but *(iii)* faces more deadweight losses than the central government[2]. The literature examines the effectiveness of decentralization based on the trade-off between welfare losses due to uniform standards (uniform taxes or subsidies) and transaction costs. A large literature on this issue

[1] https://ec.europa.eu/agriculture/sites/agriculture/files/future-of-cap/future_of_food_and_farming_communication_en.pdf
[2] In other terms, the design of agri-environmental policies faces economies of scale.

has been developed based on Tiebout (1956).[3] However, contrary to Tiebout, most of the literature consider that there exist provision spillovers between jurisdictions. The conclusion of this literature is that instruments that generate benefits contained within the boundaries of local jurisdictions present a high interest for decentralized environmental management whereas global environmental problems require central government intervention (Tiebout and Houston, 1962).

In this paper, we examine how the decentralization of agri-environmental payments could improve their efficiency, taking into account the agricultural provision of both local and global PGs. We develop a theoretical model where we explicitly consider two levels of government (central and regional) which can both finance PG provision. The model is used to analyze what share of the budget dedicated to environmental good provision should be transferred from a central to a local government to maximize the efficiency of the expenditures. We apply our model to the case of abandoned wetland in Brittany. This application underlines the potential usefulness of our analytical results to the future financing of environmental goods in the CAP 2020-reform.

Our work shows that the decentralized governance reduces the global PG provision to the advantage of local one. Indeed, the total amount of financed lands decrease but that the PGs are produced on the most valuable lands. The effectiveness of decentralization compared to centralization depends on the value derived from local and global PGs produced on each unit of land, the additional deadweight losses incurred by the region and the PG cost function.

Some specific features of our model follow. First, we address the problem by assuming joint production of agricultural goods, global and local PG in case agricultural production is characterized by the risk of land abandonment, e.g. marginal land productivity is zero. While surely this approach limits its generalizability, land abandonment is common risk across Europe (Terres et al., 2015). This implies, differently from most of the fiscal federalism, but in accordance with Bougherara and Gaigné (2008), that the suppliers of PGs are not the public sector but a private (agricultural) sector. Moreover, the inclusion of both local and global PGs justifies the interest of both local and central government for agricultural lands. Second, we consider that both suppliers and consumers of PGs are immobile, i.e. that there is no competition between local jurisdictions. Like Tiebout and Houston (1962), we are more interested in how two levels of government should share a budget to insure the highest possible utility under a budget constraint. Indeed, we assume that the budget is exogenous. Indeed, constraints on budget do currently exist for environmental good provision from agriculture, notably due to European legislation. Thus, both governments cannot choose the budget they would allocate to PG provision. Fourth, we consider that the local and central governments face asymmetric information, the local one knowing the preference for local public good.

[3] Tiebout (1956) considers that local PGs are financed by local administration and can only benefit to the territory it represents. Its theory is that, if there were enough local administrations, individuals would choose to live in territories, revealing their true preference for PGs. This theory relies on the assumption of perfect residential mobility, which creates competition among territories: people can thus “vote with their feet”.

The article is organized as follows. The next section presents the theoretical model that analyzes the trade-offs between the centralized and the decentralized governments. Section 3 is devoted to the empirical applications of the analytical results. We discuss the theoretical and empirical results in the fourth section. Section 5 concludes.

2 Model

2.1 Setting

Imagine an economy composed by numerous regions. The utility of each region depends on the provision of a local PG and on a global PG. The local PG value is captured within the region where the production occurs but the value is heterogeneous. The global PG value is captured by the whole economy and the value is homogenous. Both PG are provided by the joint production of an agricultural sector on specific lands with null marginal productivity. In other term, the expansion of agriculture on these lands represents a net cost for the farmers.

The government has an exogenous budget to finance the provision of the PG in each region. We can interpret the budget as the sum of the 2014-2020 CAP Agri-Environment-Climate Measures (AECM) annual payments in each region. Currently these payments are largely decided centrally. Moreover, in accordance with the European Legal framework we assume that the regions cannot levy tax to finance agriculture.[4]

We consider that the budget can be managed centrally or delegated to the regional governments. We assume that the central government has perfect information on preferences for global PG but not for local PG. On the contrary, the regional government has perfect information on the preferences for local PG but ignores the utility derived from global PG provision by other regions. This implies a trade-off in the effectiveness of the decentralization of the budget management. On one hand, decentralization entails a more efficient allocation that addresses the heterogeneous provision of the local PG. On the other hand, the central government internalizes the impact of global PG production for all the regions. This is a common feature of the literature on fiscal federalism (Oates, 1972, 1999).

Based on welfare analysis, our theoretical model aims to examine the effectiveness of "deconcentration" of the agri-environmental budget.[5] The variable decisions are the proposed subsidies by the central and regional governments and the share of the agri-environmental budget that the central government gives to the regional government. We identify the required conditions of success of decentralization and the optimal share of the existing budget to decentralize towards regional governments. We compare the welfare in three different cases: the *partial-decentralization* case where both governments can finance the PG provision, the *full-centralization* case where all the budget goes to the central government, the *full-decentralization* case where the budget returns to the regional government.

[4] The first paragraph of article 107 of the Treaty on the Functioning of the European Union states that regional subsidies to private companies (including agricultural companies) are not allowed due to introduction of possible distortion of concurrence inside the EU common market. We discuss the potential compatible mechanisms between regional and European subsidies in the discussion section.

[5] We use the terms "deconcentration" and "decentralization" interchangeably.

2.2 Mathematical description of the problem

Assume an economy constituted of J homogenous regions and a centralized government. Considering that there is no mobility of inhabitants between each homogenous region, we can resolve this problem considering one region and the central government.

Public good production. Each region contains a farming sector, constituted of two farmers $i \in \{1;2\}$. Farmers own $\overline{X}_{ij}$ units of land that can be either abandoned or managed, the latter increasing the production of PG. We denote the managed lands as X_{ij}. These lands can be pastured lands in the mountains or agricultural wetlands depending on the regional conditions. The agricultural management of these lands is a net cost represented by the quadratic cost function $\frac{1}{2}cX_{ij}^2$. In this setting, the PG provision occurs only in case where X_{ij} is subsidized. Given a subsidy ρ_{ij}, the program of farmer i in region j for PG production is:

$$\Pi_{ij} = \rho_{ij} X_{ij} - \frac{1}{2}cX_{ij}^2 \tag{1}$$

The usual FOC yields:

$$X_{ij}^* = \frac{\rho_{ij}}{c} \tag{2}$$

Each farmer allocates lands to PG production until the costs she incurs from farming the last unit of land equals the subsidy. Here, we assume that the land constraint is not binding, i.e. that $\overline{X}_{ij} > \rho_{ij}/c$.

Region. The utility of the J regions depends on the provision of local and global PG. The utility of each of the J regions is given by:

$$U_j = \sum_i v_{ij} X_{ij} + w\sum_i X_{ij} + w\sum_{\substack{k=1 \\ k\neq j}}^{J} \left(X_{1j} + X_{2j}\right) \tag{3}$$

where v_i is the marginal utility derived from the consumption of the local PG on X_{ij} and w is the marginal utility derived by the inhabitants of region J from the provision of global PG. We assume that $v_1 > v_2$. For example, agricultural wetlands located downstream to a drinking-water-treatment plant are less valuable than ones located upstream to it. The $J-1$ other regions do not benefit from the local PG produced by the two farmers. Note that the utility derived from the global PG depends both on the lands inside and outside the considered region. For simplicity, we call $y=w\cdot(J-1)$ the marginal utility derived by other regions from the land allocated to PG in region j. The utilities of the region and the rest of the economy being linear, the choices of financed lands in other regions do not influence the behaviour of either the central or the regional government.

We examine the PG provision properties emerging in the three types of governance, namely the *full-centralization*, the *full-decentralization* and the *partial-decentralization* cases. Each government chooses ρ_i anticipating the farmers' supply response. In the *full-centralization* case, the central government is in charge of managing the whole agro-environmental budget of region *j* (we note it $\overline{B}$ for simplification). In the *full-decentralization* case, the regional government manages $\overline{B}$. In the *partial-decentralization* case, the governments share $\overline{B}$ to manage PG provision in the most efficient way. We assume $\overline{B}$ remains binding in the three cases. For each case, we provide the level of subsidies, the landscape structure and the welfare (labeled *W*).[6] We also provide the share δ of the budget $\overline{B}$ going to the regional government for the *optimal-decentralization* case. The region being homogenous, we perform the analysis for one region and thus remove the region index in the following.

2.3 Comparative statics: the full-centralization case

This case is the actual one regarding the financing of the PG provision from agriculture in Europe. The central government (the EU) decides how to spend the whole agri-environmental budget $\overline{B}$. The objective of the central government is to maximize the utility of the whole economy. However, there is an asymmetry of the information, the central government ignoring the heterogeneity of the preferences for local PG. It considers that the preferences for local PG are homogeneous, i.e. that the region derived the same marginal utility from the management of X_1 and X_2. On the opposite, it knows perfectly the utility derived from the consumption of the global PG, both in the region and the rest of the economy. The central government maximizes:

$$\max_{\mathbf{s}} U_{central} = \left(E(v) + w + y\right)\left(X_1 + X_2\right) \\ \overline{B} = s_1 X_1 + s_2 X_2 \tag{4}$$

where s_i is the vector of subsidy proposed to F_i and $E(v)$ is the central government's expected value of the utility derived by region J due to the provision of local PG inside the considered region. We have $E(v_1) = E(v_2) = E(v)$.

Introducing (2) into (4) leads to:

$$s_1 = s_2 = \sqrt{\frac{\overline{B}c}{2}} = s \tag{5}$$

The offered subsidies to F_1 and F_2 by the central government are homogenous. They increase with $\overline{B}$ and c. Introducing (5) in (2) leads to:

$$X_1^* = X_2^* = \sqrt{\frac{\overline{B}}{2c}} \tag{6}$$

The quantity of suitable lands allocated to PG provision are the same for famrers 1 and 2. They increase when $\overline{B}$ increases and decreases with c. In total, farmers in region *j* allocates

[6] The welfare is equal to $W = U_{region} + y\left(X_1 + X_2\right)$.

$\sqrt{2\overline{B}/c}$ units of land for the PG provision. The total welfare (labeled W) derived from the policy is equal to:

$$W^{centralization} = \sqrt{\frac{\overline{B}}{2c}}\left(\frac{v}{d_1}+\frac{v}{d_2}+2\left(w+y\right)\right) \tag{7}$$

Because the budget constraint is binding, the welfare does not depend on the expected value of the preferences for local PG.

2.4 Comparative statics: the full-decentralization case

In this case, we assess the outcome of a full decentralization of the budget management toward the regional government. This case is a theoretical case. Even if the discussions on CAP reform consider partial decentralization, it is unlikely that the CAP-2020 reform fully decentralizes the financing of PGs. The objective of the regional government is to maximize the utility of the region. The regional government has access to full information about the heterogeneity of the preferences for local PG. However, it does not take into account the externalities generated by the management of X_1 and X_2 on the utility of the other regions. The regional government maximizes:

$$\begin{aligned}&\max_{\mathbf{p}} U_{regional} = v_1 X_1 + v_2 X_2 + w\left(X_1 + X_2\right)\\&\overline{B} = \left(1+\tau\right)\left(p_1 X_1 + p_2 X_2\right)\end{aligned} \tag{8}$$

where p_1 and p_2 are the subsidy proposed to the farmers by the regional government and τ is the rate of additional transaction costs incurred by the regional government when being in charge of managing public money. Indeed, the literature on fiscal federalism considers that the highest levels of government face lower transaction costs, i.e. that public money management presents economies of scale (Ahmad, 2006). These economies of scale are explained by the marginal agency costs that decrease with the size of the agency. The economies of scale implies that the decentralization process presents $\tau \geq 0$. However, the central government could also face higher level of transaction costs than the regional government in the case when it assembles information on local PG preference. This feature has been discussed by Crémer et al. (1996) based on contract theory. For the authors, the information is endogenous and the central government can use its resources to obtain the information. In particular, the central government can coordinate with the region to get access to the information. As the information of local PG preferences from the central government is costly, the rate of additional transaction costs incurred by the regional government can be negative. The parameter τ is thus the addition of two forces: economies of scale and information costs (also called coordination costs here). The result being that τ can be either positive or negative. When τ is negative (positive), the regional (central) government is more efficient to manage public money.

Introducing the farmer response function (2) into the budget constraint (8) leads to:

$$\frac{p_1^2}{c}+\frac{p_2^2}{c}=\frac{\overline{B}}{1+\tau} \tag{9}$$

Which is equivalent to:

$$p_1=\sqrt{\frac{\overline{B}}{1+\tau}c-p_2^2} \tag{10}$$

Introducing relation (10) inside (8) leads to:

$$U_{region}=(v_1+w)\frac{\sqrt{\frac{\overline{B}}{1+\tau}c-p_2^2}}{c}+(v_2+w)\frac{p_2}{c} \tag{11}$$

The regional government then maximize (11) choosing p_2. First-order-conditions lead to:

$$\frac{\partial U_{region}}{\partial p_2}=-(v_1+w)\frac{p_2}{c\sqrt{\frac{\overline{B}}{1+\tau}c-p_2^2}}+(v_2+w)\frac{1}{c}=0$$

leading to:

$$p_2=\sqrt{\frac{\overline{B}c\left(v_2+w\right)^2}{\left[1+\tau\right]\left[\left(v_2+w\right)^2+\left(v_1+w\right)^2\right]}} \tag{12}$$

Introducing (12) in (10) leads to:

$$p_1=\sqrt{\frac{\overline{B}c\left(v_1+w\right)^2}{\left[1+\tau\right]\left[\left(v_2+w\right)^2+\left(v_1+w\right)^2\right]}} \tag{13}$$

The subsidies depend on the relative preference v_1 and v_2. The payment to farmer 2 (farmer 1) increases with v_2 (v_1) and decreases with v_1 (v_2). In other terms, p_1 increases and p_2 decreases with the heterogeneity of local PG preferences. The subsidy increases with $\overline{B}$ and c. The subsidies decrease with the additional transaction costs incurred by the regional government.

Introducing the optimal payments into the farmers' reaction functions yields:

$$X_i^*=\sqrt{\frac{\overline{B}(v_i+w)^2}{c[1+\tau]\left((v_2+w)^2+(v_1+w)^2\right)}}$$

The allocation of land by the two farmers decreases with the cost parameter and the additional deadweight losses but increases with the budget. X_1^* increases with v_1 but decreases with v_2 whereas X_2^* increases with v_2 but decreases with v_1. We can also verify that X_2^* increases with w and X_1^* decreases with w.[7] Contrary to the full-centralization case, the level of provision of X_1^* and X_2^* depends on the preferences of the city inhabitants for local and global PG.

The welfare of the economy in the case of full decentralization is:

$$W^{dec} = \frac{\sqrt{B}}{\sqrt{c[1+\tau]\left[(v_2+w)^2+(v_1+w)^2\right]}}\left((v_1+w)^2+(v_2+w)^2+y(v_1+v_2+2w)\right) \quad (14)$$

The regional government generates externalities to the rest of the economy equal to $\sqrt{By/c(1+\tau)\left[(v_2+w)^2+(v_1+w)^2\right]}$.

PROPOSITION 1: in case of null additional transaction costs, the full-decentralization leads to welfare gain if the spillovers from global PG provision are lower than the weighted curvature of preferences for local PG, i.e. if:

$$y \le \sqrt{\frac{(v_2+w)^2+(v_1+w)^2}{2}} \quad (15)$$

We obtain relation (15) thanks to comparison of welfare under centralization and the one under decentralization (relations (7) and (14) with τ being null). The choice between the centralized or decentralized provision involves a basic tradeoff between the gains from internalization of spillovers under centralization and the greater sensitivity of local outputs to heterogeneous preferences under decentralization (Oates, 2005).

PROPOSITION 2: the full-decentralization leads to welfare gain if the additional transaction costs faced by the regional government are lower than:

$$\tau \le 2\left(\frac{(v_1+w)+(v_2+w)+y}{(v_1+w)+(v_2+w)+2y}\right)^2 \frac{\left((v_1+w)+(v_2+w)\right)^2}{(v_2+w)^2+(v_1+w)^2} - 1 \quad (16)$$

The first ratio is lower than 1 because of the global PG externality. The second ratio is greater than 1 due to the convexity of the square function. Thus, the impact of additional transaction cost rate on the benefits of the full-decentralization depends on the values of local and global PG. The impact is more important when the externality is high and decrease when the heterogeneity of local PG value increases.

2.5 Comparative statics: the partial-decentralization case

Here, both governments can subsidize the farmers. The problem is equivalent than considering that the central government maximizes the welfare of the economy knowing both the preferences for local and global PG and the costs incurred by the farmers. The central

[7] $\frac{\partial X_2^*}{\partial w} = \sqrt{\frac{c\bar{B}(v_1+w)(v_1-v_2)}{[1+\tau](v_2+w)\left[(v_2+w)^2+c(v_1+w)^2\right]}} > 0$

government knows the local PG preferences thanks to the regional government. The program of the whole economy is:

$$\begin{aligned}&\operatorname*{Max}_{p_1,p_2,s} U_{economy} = U_{region} + U_{rest\_of\_the\_economy} = v_1X_1 + v_2X_2 + (w+y)(X_1+X_2)\\&s.t.\ \overline{B} = (1+\tau)(p_1X_1 + p_2X_2) + s(X_1+X_2)\end{aligned} \tag{17}$$

The subsidy s is proposed by the central government whereas the subsidies p_i are proposed by the regional government. By definition, this is the benchmark case, where the optimal amount of PG provision is reached. Farmers receive two subsidies for the same unit of land: a homogenous one and heterogeneous ones. The farmers allocate lands to the PG production such that:

$$X_i^* = \frac{p_i + s}{c} \tag{18}$$

Solving problem (17) with (18) in case of null transaction costs lead to an infinity of solutions. We are unable to differentiate the heterogeneous subsidies from the homogenous one in the optimal conditions. As a consequence, we fix p_2 to zero in the partial-decentralization case, meaning that the regional government proposes only a premium p to the most valuable lands (i.e. $p_1 = p$ and $p_2 = 0$). The consequence is that the regional government has no incentive to increase the level of X_2 and finances only closest suitable environmental quality lands X_1. Another possibility is to consider that the central government is indifferent to the source of financing for X_2 in case of null additional transaction costs.[8] Thus, program (17) is equivalent to:

$$\begin{aligned}&\operatorname*{Max}_{p,s} U_{economy} = v_1X_1 + v_2X_2 + (w+y)(X_1+X_2)\\&s.t.\ \overline{B} = (1+\tau)(pX_1) + s(X_1+X_2)\end{aligned} \tag{19}$$

The program states that the regional government finances the provision of X_1 only, giving a premium of p to F_1 for each additional unit of X_1. Here, the share of the budget δ going to the regional government is equal to $(1+\tau)(pX_1)/\overline{B}$. The central government chooses to give this share to the regional government for the financing of X_1. The farmers allocate lands to the PG production such that:

$$\begin{cases} X_1^* = \dfrac{p+s}{c} \\ X_2^* = \dfrac{s}{c} \end{cases} \tag{20}$$

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[8] In that case, p_2 would be positive and we would have $p = p_1 - p_2$. We would reach $p_2 + s = \sqrt{\dfrac{\overline{B}c(v_2+w+y)^2}{(v_2+w+y)^2 + (v_1+w+y)^2}}$ and $p_1 + s = \sqrt{\dfrac{\overline{B}c(v_1+w+y)^2}{(v_2+w+y)^2 + (v_1+w+y)^2}}$.

We solve (19) in two case. In a first case, we assume no additional transaction costs for the regional government ($\tau = 0$), leading to easily interpretable analytical solutions. In the second case, we solve (19) with positive transaction costs. The analytical solutions are more complex but we give some intuitions behind them.

Null transaction costs

Using the budget constraint with null transaction costs leads to:

$$p(s) = \sqrt{\overline{B}c - s^2} - s \tag{21}$$

The premium decreases with the initial subsidy proposed by the central government. We can write program (19) as:

$$\begin{aligned} &U_{economy} = (v_1 - v_2)\left(\frac{s}{c} + \frac{p(s)}{c}\right) + (w + y + v_2)\left(2\frac{s}{c} + \frac{p(s)}{c}\right) \\ &s.t.\, \overline{B} = p(s)X_1 + s(X_1 + X_2) \end{aligned} \tag{22}$$

Leading to (see appendix A1):

$$s^* = \sqrt{\frac{\overline{B}c(w + y + v_2)^2}{(w + y + v_1)^2 + (w + y + v_2)^2}} \tag{23}$$

And:

$$p^* = \sqrt{\frac{\overline{B}c}{(w + y + v_1)^2 + (w + y + v_2)^2}}[v_1 - v_2] \tag{24}$$

The subsidy and the premium have the same denominator: the sum of the marginal values from the provision of one unit of X_1 and X_2. The numerator of the subsidy highlights that the subsidy proposed by the central government depends only on the initial budget, the parameter of the cost function and the marginal value derived from the provision of X_2. The premium proposed by the local government depends on the additional local PG value of X_1 compared to X_2, the initial budget and the parameter of the cost function. Thus, the premium increases as the heterogeneity in the preference of the local PG provision increases. The subsidies s and p increase with the initial budget and cost parameter. They decrease as the preference parameters for global PG (w and y) increase.

We can deduce X_1^* and X_2^* from (20), (23) and (24):

$$X_1^* = \sqrt{\frac{\overline{B}(v_1 + w + y)^2}{c(v_1 + w + y)^2 + c(v_2 + w + y)^2}}$$

and

$$X_2^* = \sqrt{\frac{\overline{B}(v_2 + w + y)^2}{c(v_1 + w + y)^2 + c(v_2 + w + y)^2}}$$

We observe that X_1^* and X_2^* increase with the budget and decrease with c. X_1^* increases with v_1 but decreases with y, w and v_2. Similarly, we have X_2^* that decreases with v_1 but increases with y, w and v_2.

In the case of null deadweight losses, we have:

$$W = \sqrt{\frac{\overline{B}}{c}\left[(v_1 + w + y)^2 + (v_2 + w + y)^2\right]} \tag{25}$$

This relationship is the highest possible utility reached by the economy. In case of null transaction costs, the central government should allocate to the regional government:

$$\delta = \frac{v_1 - v_2}{(v_2 + w + y)\left(1 + \dfrac{v_2 + w + y}{v_1 + w + y}\right)} \tag{26}$$

We can verify that δ increases as the heterogeneity among the preferences for local PG increases but decreases with the preferences for global PG.

PROPOSITION 3: the share of the budget that should go to the regional government increases as the heterogeneity of the preferences for local PG increases. It decreases as the preferences for global PG increases.

This proposition captures the same features as the so-called "decentralization theorem" proposed by Oates (1972), but inside a given region.[9] The heterogeneity of the outcomes inside a region leads to higher level of decentralization. The decentralization level decreases if the spillovers (the externalities) are high, as it calls for internalization. We find the classical trade-off between heterogeneity and externalities (Besley and Coate ,2003).

Non-null transaction costs

In case of positive additional transaction costs, the decentralization may not be the best strategy compared to the fully-centralized case. Indeed, the losses of welfare due to additional transaction costs could be higher than the additional gains due to more precise targeted subsidy. The budget constraint in (19) leads to (see Appendix A2):

[9] Oates (1972) stated (p. 35): "For a public good—the consumption of which is defined over geographical subsets of the total population, and for which the costs of providing each level of the good are the same for the central or for the respective local government—it will always be more efficient (or at least as efficient) for local governments to provide Pareto–efficient levels of output for their respective jurisdictions than for the central government to provide any specified and uniform level of output across all jurisdictions".

$$p(s)=\frac{\sqrt{s^2\left(\tau^2-4\tau-4\right)+\overline{B}c(4+4\tau)}-s(2+\tau)}{2(1+\tau)} \qquad (27)$$

We can verify that (20) is similar to (14) in case of positive transaction costs. Solving (18) using (27) leads to (see Appendix A2):

$$s^*=\sqrt{\frac{A\overline{B}c(4+4\tau)}{\left(\tau^2-4\tau-4\right)\left(\tau^2-4\tau-4-A\right)}} \qquad (28)$$

With $A=\left[2(1+\tau)\frac{(v_2+w+y)}{(v_1+w+y)}+\tau\right]^2$

We can verify that (28) is similar to (23) in the case of positive transaction costs (see Appendix A2). The optimal subsidy paid by the central government depends on the additional transaction costs faced by the lower level of government. Introducing (28) in (27) leads to the optimal premium in presence of non-null transaction costs, i.e.:

$$p^*=\sqrt{\frac{\overline{B}c}{\left(\tau^2-4\tau-4-A\right)}}\left(\sqrt{\left(\tau^2-4\tau-4\right)}-\sqrt{\frac{A\left(\tau^2+4\tau+4\right)}{\left(\tau^2-4\tau-4\right)}}\right) \qquad (29)$$

We can also verify that (29) is equivalent to (24) in case of positive transaction costs (see Appendix A2). Compared to (23) and (24), the additional transaction costs decrease the level of the subsidy and the premium. We can deduce the optimal landscape structure in case of non-null transaction costs:

$$X_1^*=\sqrt{\frac{\overline{B}\left(\left(\tau^2-4\tau-4\right)^2-\tau^2A\right)}{c\left(\tau^2-4\tau-4\right)\left(\tau^2-4\tau-4-A\right)}}$$

$$X_2^*=\sqrt{\frac{\overline{B}A(4+4\tau)}{c\left(\tau^2-4\tau-4\right)\left(\tau^2-4\tau-4-A\right)}}$$

We have X_1^* and X_2^* increasing with the budget and decreasing with c and τ. Similar to the case of null additional transaction costs, we have X_1^* increasing with v_1 but decreasing with y, w and v_2. Similarly, we have X_2^* that decreases with v_1 but increases with y, w and v_2.

In case of non-null transaction costs, the central government should allocate to the local government the following budget share:

$$\delta=\frac{1}{\left(\tau^2-4\tau-4-A\right)}\left(1+\sqrt{\left(1-\left(\frac{\tau}{\left(\tau^2-4\tau-4\right)}\right)^2A\right)}-\sqrt{\frac{A}{\left(\tau^2+4\tau+4\right)}}\right) \qquad (30)$$

The share allocated to the local government decreases with τ. We can also verify that δ increases as the heterogeneity among the preferences for local PG increases but decreases with the preferences for global PG.

PROPOSITION 4: the share of the budget that should go to the regional government decreases as the rate of additional transaction costs faced by the regional government increases.

For the same levels of transaction costs, the level of decentralization depends on the heterogeneity of local PG preferences and size of spillovers (global public preference outside the region). However, this equilibrium depends also on the effectiveness of respective governments to manage public money and to have access to the information. A move towards higher economies of scale moves the equilibrium to the benefits of the central government. A move towards higher costs for local information moves the equilibrium to the benefits of the regional government.

3 Numerical application: abandonment of wetlands in Brittany

3.1 Provision of public goods from agricultural wetlands of the Odet watershed

In this section, we parameterized the theoretical model to the case study of wetland abandonment in the Odet watershed, in Brittany (France). The Odet watershed is a territory of 724 km², representing 2.64% of the size of the Brittany region (Figure 1). The territory is constituted of 27 municipalities and presents a density of 174 inhabitants per km². The main city of the watershed is Quimper, the third largest city of Brittany. Eight watercourses cross the watershed and they all group within the Odet coastal river. Agricultural wetlands represent 3,700 Ha, i.e. 5.1% of the watershed area. In 2014, 1,800 Ha of agricultural wetlands were abandoned in the Odet watershed (Figure 1).

The hydric and soil characteristics of agricultural wetlands provide a distinct ecosystem from other land types. Wetlands support the provision of several ecosystem functionalities contributing to water purification, flood control, biodiversity habitat and carbon sink. Based on benefit transfer functions and cost accounting, Bareille et al. (2017) find an estimated conservative value of 452 €/Ha for PG provided by agricultural wetlands at the watershed scale. This value is computed as the difference of between values of water filtration, fished salmon and trout, carbon sink and biodiversity habitat provided with and without agricultural management (Engel et al., 2008). Indeed, Bareille et al. (2017) consider that abandoned wetlands become afforested lands in the long run, which decrease PG provision compared to agricultural management of wetlands (e.g Pykälä 2003). This value is subdivided in 410 €/Ha for local PG (i.e. water quality and fishing) and 42€/Ha for global PG (i.e. carbon sink and biodiversity habitat).

The costs of agricultural production on wetlands incentivized farmers to turn them into arable lands through drainage works. Since drainage of wetlands has been forbidden in France in 1992, farmers are incited to sell or abandon their wetlands. In this context, farmers managing wetlands receive a payment of 120 €/ha thanks to an AECM (operation "Herbe_13" defined in Measure 10 of the 2014-2020 Rural Development Program for Brittany). Conditions of the AECM contract set that subsided areas should respect the maximum animal density of 1.4 per ha, a maximal nitrogen fertilization and the interdiction of pesticides and tillage. Despite this subsidy, abandonment of wetlands remains an issue in Brittany. Based on a wetland census of

2014 in Finistère (NUTS3 region), Bareille et al. (2017) have determined that 46% of the agricultural wetlands were not declared for CAP subsidies and thus assumed to be abandoned.

Here, we simulate the impact of decentralization on the rate of abandonment of wetlands inside the Odet watershed. The definition of the watershed as the empirical counterpart of the theoretical region makes sense since the benefits of the local PG (.e.g. water quality) are captured inside the watershed. The Brittany region is constituted of 110 watersheds. Each watershed is managed to improve water quality by local agencies, including regional government representatives, informing the Brittany government on the heterogeneity of the preferences and conditions inside each watershed.

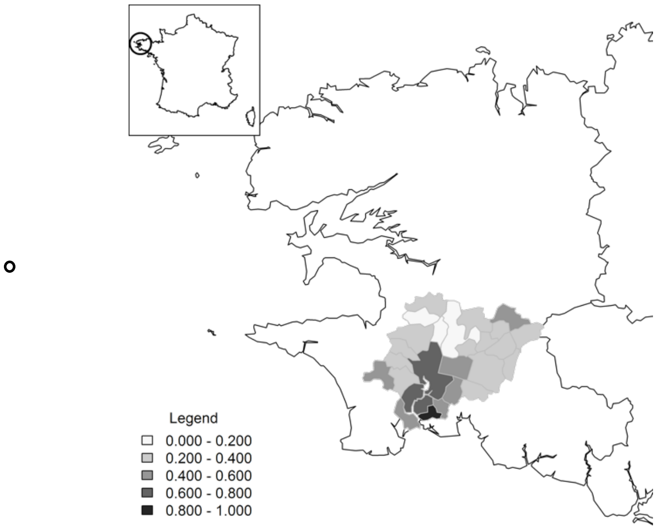

Figure 1: Wetland abandonment rate in the Odet watershed (source: Bareille et al., 2017)

3.2 Data and empirical model description

Contrary to theoretical part, we account for the heterogeneity in the opportunity cost of wetland management across municipalities, assuming that each of the 27 municipalities represents a single farm ($i \in [1;27]$). In the absence of detailed costs, we calibrate the individual cost parameter of wetland management from the current observed levels of wetland abandonment (Figure 1) and the Herbe_13 homogenous subsidy of 120€. Hence, given the farmers profit function), the cost parameters are given by: $c_i = \rho^o / X_i^o$, where the superscript "o" denotes observed levels. This procedure leads to cost parameters whom levels decrease with the distance to the seacoast, which is coherent with theory (see appendices for the calibrated values).

In order to consider the heterogeneous contribution of the wetlands to the local PG value, we use the results from the distance-decay literature. This literature states that the value of the local PG decreases with the distance between the consumer and provision localization (see Pate and Loomis, 1997 for an application on wetlands). Utilization of distance-decay is an empirical counterpart of the PG scale issue (e.g. Ostrom et al., 1961). Therefore, we write the utility of the watershed (i.e. the region) as:

$$U_{regional} = \int_0^{\bar{d}} \left[\left(\mathbf{1} \frac{v_{water}}{d_i} + \frac{v_{fishing}}{d_i} + w \right) X_i \right] dd_i$$

Where d_i is the distance in kilometers between the centroid of the municipality i to the centroid of Quimper, $\bar{d}$ is the distance between Quimper and the farthest municipality and **1** is an indicator function taking the value 1 (respectively 0) for municipalities located upstream (respectively downstream) Quimper.[10] Hence, all the wetlands of one municipality have the same value for the region. v_{water} and $v_{fishing}$ are local PG parameters, defined based on Bareille et al. (2017). We have:

$$v_{water} = 300 * 17 \Big/ \sum_{i=1}^{17} \frac{1}{d_i}$$

and

$$v_{fishing} = 80 * 27 \Big/ \sum_{i=1}^{27} \frac{1}{d_i}$$

yielding an average value for the local PG of 269 €/ha. The difference of average values between us and Bareille et al. (2017) is that they did not consider the different contribution between upstream and downstream wetlands.

In addition, we have for all wetlands (w+y)=42 €/ha. Under the assumption that each European region derives the same utility for global PG, we allocate the value between the region and the rest of the EU at the *pro rata* of inhabitants density, i.e. $w=0.009$ and $y=41.991$.

The budget level is assumed to be 666,344.40€, which represents the actual level of payment delivered to farms to manage wetland under the assumption that all managed wetlands are subsidized. The level of transaction costs is assumed to be 0; in section 0 we run a sensitivity analysis on this level.

The mathematical formulation of the empirical model is differentiated from the theoretical section only with respect to the increase in the number of farmers (from 2 to 27), with respect to the specification of heterogeneous costs and with the functional form for the heterogeneity of local PG.

3.3 Results

Table 1 presents the results of the empirical model in the three case: full-centralization, full-decentralization and the partial-decentralization case (with null transaction costs). The results clearly follow the theoretical analysis. The full-centralization case yields to a lower average

[10] As the water treatment factory is located in Quimper, the only valuable wetlands are located upstream to Quimper.

abandoned rate, and a more distributed one, while the full-decentralization and the partial-decentralization cases result in a more polarized landscape (Figure 2). Full-decentralization increases welfare by 15.3 %. The partial-decentralization case yields to an increase of welfare by15.4% and 0.1% with respect to the full-centralization and full-decentralization respectively. This suggests the deconcentration of the budget choices represent an option worth exploring, either partially or totally. This however must be further evaluated to observe whether such a result holds in the presence of transaction/coordination costs (see the sensitivity analysis in the next section). The share of the welfare captured by the region increases with the deconcentration due both to an increase of its utility caused by landscape reorganization and a decrease of the welfare of the rest of the economy caused by an increase in the abandonment rate. The small difference between the full-decentralization and the partial-decentralization is due to the relatively high value of the local PG with respect to the global one. The relative value of the two type of PG is a major driver of results. We provide a sensitivity analysis on that point in the next section.

The average subsidy from the region in the case of full-decentralization and in the partial-decentralization are respectively 95€/ha and 64 €/ha) but with a higher heterogeneity for the partial-decentralization (respectively, with a coefficient of variation of 0.71 and 0.97). In case of partial-decentralization, 76% of the budget is managed by the region. The budget deconcentration yields to a decrease in the average subsidy: the available budget is mostly spent on the most relevant municipalities, leaving the downstream municipalities with lower subsidy. Indeed, the local, spatially differentiated, PG is relatively more valuable than the homogenous PG and its value is concentrated in the upstream municipalities. Budget regional management favours farmers located upstream Quimper. This issue must be addressed in case the governments are inequality averse. As the farmers face an increasing marginal cost to manage wetlands, the concentration on valuable wetlands in case of decentralization decreases the total number of managed wetlands.

	full-centralization	full-decentralization	partial-decentralization
Region utility (€)	1,604,502	1,921,632	1,919,292
ROW utility (€)	233,171	197,411	201,996
Welfare (€)	1,837,672	2,119,044	2,121,288
subsidy from the EU (€/ha)	120	-	34
subsidy from region – average (€/ha)	-	95	64
subsidy from region - coeff of variation	-	0.71	0.97
Wetland abandonment rate - average	0.39	0.51	0.49
Wetland abandonment rat - st dev	0.18	0.30	0.29

Table 1. summary of results.

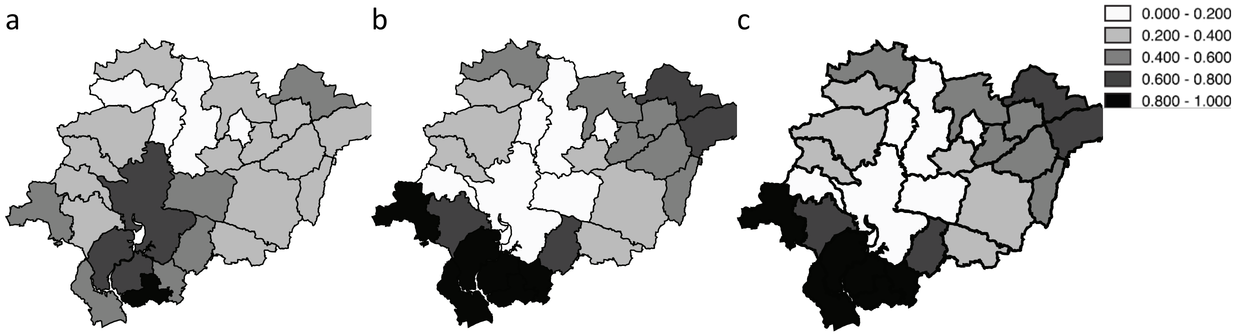

Figure 2: Results of simulations on (a) Full-centralization scenario ;(b)Full-decentralization scenario ; (c) optimal-decentralization with τ=0 (source: authors own computation)

3.4 Sensitivity analysis

3.4.1 Sensitivity analysis on transaction costs

Table 2 lists the summary of results of the sensitivity analysis on the transaction costs. The maps are relative to each transaction costs level are in the appendix. Note that we do not put the case where **τ** was negative, as all the budget goes to the regional government in this case. This is notably due to the relatively high value of local PG.

The case of **τ** = 0 represents the partial-decentralization scenario previously described, and it is repeated here to ease the comparisons. Clearly, an increase in the transaction costs result in a decrease in the total welfare due to the increase in the deadweight loss. However, the comparison with the full-centralization case shows that the deconcentration of the budget management it is still the most profitable option. This, again, must be carefully taken given the relatively high value of the local PG with respect to the global one.

Moreover, the regional subsidy and budget decrease not surprisingly with the increase in the transaction cost level. We find that only 33% of the budget should go to the regional government in case it would suffer from an additional transaction cost rate of 20%. Abandonment rate remains higher than in the full concentration case on average, but the partial deconcentration of the budget management enable to set heterogeneous payments that target the most valuable municipalities, hence resulting in higher welfare. This results is in line with quantification of welfare gains from a move towards more heterogeneous regulations, either from AES (van der Horst, 2007) or other instruments (Perino and Talavera, 2013).

	τ = 0	**τ** = 0.2	**τ** =0.4	**τ** = 0.6	**τ** = 0.8	**τ** = 1
Region utility (€)	1,919,292	1,815,442	1,758,530	1,721,711	1,696,081	1,677,252
ROW utility (€)	201,996	206,962	211,720	215,430	218,151	220,326
Welfare (€)	2,121,288	2,022,404	1,970,250	1,937,141	1,914,232	1,897,577
subsidy from the EU (€/ha)	33.57	81.24	94.14	100.97	104.94	107.75
subsidy from region – average	64.09	24.43	15.12	10.16	7.17	5.31

(€/ha)						
subsidy from region - coeff of variation	0.97	1.83	2.32	2.81	3.31	3.76
Regional share of the budget	0.76	0.33	0.21	0.14	0.10	0.08
Wetland abandonment rate - average	0.49	0.47	0.46	0.45	0.44	0.43
Wetland abandonment rat - st dev	0.29	0.21	0.18	0.16	0.16	0.16

Table 2. Summary of results for the transaction cost sensitivity analysis.

3.4.2 Sensitivity analysis on global public good value

In this section, we present the results on a sensitivity analysis on the global PG values. We modify the value by multiplying w and y by a coefficient $1 \le a \le 2$ with *0.1* steps. The maximum value for the global PG that we account for in the sensitivity analysis($2 \cdot (w+y)=84$ €/ha) is still much lower than the average local PG.

Table 3 shows the percentage increase in welfare of the full and partial decentralization cases with respect to the full-centralization case. The increase in the global PG value does not qualitatively affect the previous findings, namely that the deconcentration of the budget management is convenient. However, such an increase reduces the additional benefit from decentralization. For example, an increase in the global PG values of 100% causes a decrease in the percentage increase of welfare from 10% to 8% in case of **τ** = 0.2. Indeed, an increase in the global PG values decrease the relative heterogeneity of the municipalities with respect to the generation of PG values, explaining that an homogenous subsidy is relatively less damaging. The same pattern can be observed in the share of the budget delegated to the regional administration (see Table 4).

Despite these relatively small differences, the results suggest cautions in the decision regarding the decentralization of the budget, and a careful local-specific analysis.

	a=1.0	*a=1.1*	*a=1.2*	*a=1.3*	*a=1.4*	*a=1.5*	*a=1.6*	*a=1.7*	*a=1.8*	*a=1.9*	*a=2.0*
Full centralization	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Full decentralization	15%	15%	15%	14%	14%	13%	13%	13%	12%	12%	12%
partial decentralization	15%	15%	15%	14%	14%	14%	13%	13%	13%	13%	12%
τ = 0.2	10%	10%	10%	9%	9%	9%	9%	8%	8%	8%	8%
τ =0.4	7%	7%	7%	7%	6%	6%	6%	6%	6%	6%	5%
τ = 0.6	5%	5%	5%	5%	5%	5%	5%	4%	4%	4%	4%
τ = 0.8	4%	4%	4%	4%	4%	4%	3%	3%	3%	3%	3%
τ = 1	3%	3%	3%	3%	3%	3%	3%	3%	3%	2%	2%

Table 3. Percentage increase in welfare of full decentralization and partial decentralization cases with respect to the full centralization case.

	a=1.0	*a=1.1*	*a=1.2*	*a=1.3*	*a=1.4*	*a=1.5*	*a=1.6*	*a=1.7*	*a=1.8*	*a=1.9*	*a=2.0*
τ = 0	76%	75%	74%	73%	73%	72%	71%	70%	70%	69%	68%

τ = 0.2	33%	33%	32%	31%	31%	30%	30%	29%	29%	28%	28%
τ =0.4	21%	20%	20%	19%	19%	19%	18%	18%	18%	17%	17%
τ = 0.6	14%	14%	13%	13%	13%	13%	12%	12%	12%	11%	11%
τ = 0.8	10%	10%	10%	9%	9%	9%	9%	9%	8%	8%	8%
τ = 1	8%	7%	7%	7%	7%	7%	7%	6%	6%	6%	6%

Table 4. Share of the regional budget in different global PG value scenarios and transaction costs.

4 Discussion

Our analysis provides some theoretical background for a potential decentralization of the design of agri-environmental policies. The provision of PG from agriculture is a complex process that entails the joint production of local and global PG. The results of our model, albeit relatively simple, show that indeed a total or partial delegation of decisions to regional governments could improve the total welfare. The benefits of decentralization increase as the heterogeneity of preferences for local PG increases and when the spillovers (the global PG value) decrease. These results are coherent with the "Decentralization Theorem" proposed by Oates (1972), but within a given jurisdiction. A partial decentralization is the optimal strategy if the additional transaction costs do not significantly affect the budget. This result is in line with Tiebout and Houston (1962), who suggested to proceed to the integration of jurisdictions in order to create a multi-level government where provision of some PG would be in charge to the central government, other ones to states and others to lower levels of government. This is the spirit of the EC's communication COM(2017) 713 "The future of Food and farming".

Our empirical application provides a numerical illustration of the potential gains from such CAP reform. In a simple application on marginal lands that face a risk of abandonment (here, agricultural wetlands), the landscape resulting from either total or partial decentralization always improve the welfare compared to the centralized government. Partial decentralization results are in line with quantification of welfare gains from a move towards more heterogeneous regulations, either from AES (van der Horst, 2007) or other instruments (Perino and Talavera, 2013). Without any additional transaction costs, about 90% of the budget should go to the regional government. However, this share decreases quickly as transaction cost rate increases.

Our empirical results are however subject to some limitations.

First, the abandonment of wetlands is a specific example with the advantage that its agricultural management increases in the same time local and global PG provision. We can imagine cases where the subsidies would improve provision of one type of PG but decrease the other. Such a context could lead to a competition between the two governments, which is inexistent in our case. Second, our results hold under the assumption that the single source of revenue from wetlands is the subsidy. However, wetlands generate also market revenues for the farmers. Regarding their role of pasture, agricultural wetlands can benefit to farmers depending on milk and feed prices and fixed input dotation. More generally, extensive dairy farms can valorize these lands without any subsidies. As a result, our simulation leads to more contrasted landscapes than the ones that would emerge in reality. Third, the results depend on the valuation of the considered PGs, which are subject to their own limits (see Bareille et al., 2017 for a complete discussion). In particular, The spatialization of the local PG values is based on rough assumptions from distance-decay literature, which can bias our welfare quantification.

The main interest of this research is to use the fiscal federalism literature as a way to analyze the potential future reform of the CAP. We introduce two motives to model advantages and disadvantages of respective governments, namely the asymmetry of information and the economies of scale to manage public money. These two concepts are part of the second generation theories on fiscal federalism (Oates, 2005). The asymmetry of information explains partly why one government is more suitable to implement specific instruments (Boadway, 1997). In our framework, the knowledge of the heterogeneity of preferences lead to an advantage of the local government. Similarly, the knowledge of global PG preference by the central government allows internalizing externalities. In a sense, the asymmetry of information in the context of fiscal federalism gives the classical trade-off among the heterogeneity of the preferences and the spillovers as initially proposed by Oates (Besley and Coate, 2003).

The economies of scale for transaction costs is a common feature in the fiscal federalism literature, which give an advantage to the central government (Oates, 1999). However, we have here considered that the transaction costs are not only due to economies of scale, but also to information asymmetry. Indeed, as interestingly suggested by Crémer et al. (1996), the information asymmetry is not exogenous: the central government can spend resources to fill the information gap between the central and local governments. This is precisely the case of the existing CAP where the EC subsidies conjointly the farmers based on the average estimated opportunity costs with the region and the member state (see Beckmann et al., 2009).

Finally, here, we have studied the effectiveness of the deconcentration of the existing agro-environmental budget, leading to the assumption that the budget is exogenous. This is quite different from what it is studied in the fiscal federalism where local taxes are usually modelled. The different tax rates and resulting local PG levels expresses the heterogeneity of preferences between regions (Tiebout, 1956) and can lead to competition between regions. Future works could introduce local taxes (and expenses), making possible the study of strategic between regions and between government levels in a more decentralized context interactions (e.g. moral hazard and adverse selection - Epple and Nechyba, 2004). If such local expenses are not currently possible under public agencies, it could feat to public-private companies (like water purification factory or collective catering) in the framework of Payment for Environmental Services.

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Appendices

Appendix A1 : resolution of progam (24) with null transaction costs

The budget constraint in (24) is equivalent to:

$$0 = 2s^2 + 2sp + p^2 - \overline{B}c$$

This is a second-order polynomial, p being the variable. The determinant of the polynomial being $\Delta = -4s^2 + 4\overline{B}c$, the roots of the second-order polynomial are:

$$p^a = -\sqrt{\overline{B}c - s^2} - s$$

And

$$p^b = \sqrt{\overline{B}c - s^2} - s$$

The premium being positive, the optimal premium is $p^*(s) = \sqrt{\overline{B}c - s^2} - s$. We reintroduce the reaction function in program 1, leading to (27):

$$U_{economy} = \left(\frac{v}{d_1} - \frac{v}{d_2}\right)\left(\left(\frac{s}{c} + \frac{p^*(s)}{c}\right)\right) + \left(w + y + \frac{v}{d_2}\right)\left(2\frac{s}{c} + \frac{p^*(s)}{c}\right)$$

$$s.t.\, \overline{B} = p^*(s)\left(\frac{s}{c} + \frac{p^*(s)}{c}\right) + s\left(2\frac{s}{c} + \frac{p^*(s)}{c}\right)$$

Thus, the utility function of the whole economy is:

$$U_{economy} = \left(\frac{v}{d_1} - \frac{v}{d_2}\right)\left(\frac{\sqrt{\overline{B}c - s^2}}{c}\right) + \left(w + y + \frac{v}{d_2}\right)\left(\frac{s}{c} + \frac{\sqrt{\overline{B}c - s^2}}{c}\right)$$

The first-order condition of the utility on s gives:

$$\frac{\partial U_{economy}}{\partial s} = -\left(\frac{v}{d_1} - \frac{v}{d_2}\right)\left(\frac{s}{c\sqrt{\overline{B}c - s^2}}\right) + \left(w + y + \frac{v}{d_2}\right)\left(\frac{1}{c} - \frac{s}{c\sqrt{\overline{B}c - s^2}}\right) = 0$$

Which is equivalent to:

$$\left(w + y + \frac{v}{d_2}\right)\left(\frac{1}{c}\right) = \left(w + y + \frac{v}{d_1}\right)\left(\frac{s}{c\sqrt{\overline{B}c - s^2}}\right)$$

Leading to:

$$\frac{\left(w + y + \frac{v}{d_2}\right)}{\left(w + y + \frac{v}{d_1}\right)}\sqrt{\overline{B}c - s^2} = s$$

Or, alternatively:

$$\left(\frac{\left(w+y+\frac{v}{d_2}\right)}{\left(w+y+\frac{v}{d_1}\right)}\right)^2\left(\overline{B}c-s^2\right)=s^2$$

i.e.:

$$\left(\frac{\left(w+y+\frac{v}{d_2}\right)}{\left(w+y+\frac{v}{d_1}\right)}\right)^2\overline{B}c=s^2\left(1+\left(\frac{\left(w+y+\frac{v}{d_2}\right)}{\left(w+y+\frac{v}{d_1}\right)}\right)^2\right)$$

Leading to:

$$\frac{\left(\frac{\left(w+y+\frac{v}{d_2}\right)}{\left(w+y+\frac{v}{d_1}\right)}\right)^2}{\left(1+\left(\frac{\left(w+y+\frac{v}{d_2}\right)}{\left(w+y+\frac{v}{d_1}\right)}\right)^2\right)}\overline{B}c=s^2$$

And, finally, giving the optimal subsidy offered by the central government:

$$s^*=\sqrt{\frac{\overline{B}c\left(w+y+\frac{v}{d_2}\right)^2}{\left(w+y+\frac{v}{d_1}\right)^2+\left(w+y+\frac{v}{d_2}\right)^2}}$$

Using s^* and $p^*(s)$ we have:

$$p^*=\sqrt{\overline{B}c-\frac{\overline{B}c\left(w+y+\frac{v}{d_2}\right)^2}{\left(w+y+\frac{v}{d_1}\right)^2+\left(w+y+\frac{v}{d_2}\right)^2}}-\sqrt{\frac{\overline{B}c\left(w+y+\frac{v}{d_2}\right)^2}{\left(w+y+\frac{v}{d_1}\right)^2+\left(w+y+\frac{v}{d_2}\right)^2}}$$

Which is equivalent to:

$$p^* = \sqrt{\frac{\overline{B}c}{\left(w + y + \frac{v}{d_1}\right)^2 + \left(w + y + \frac{v}{d_2}\right)^2}}\left[\frac{v}{d_1} - \frac{v}{d_2}\right]$$

Appendix A2: Solution of progam (24) with positive transaction costs

Program (24) is equivalent to:

$$U_{economy} = \frac{v}{d_1} X_1 + \frac{v}{d_2} X_2 + (w+y)(X_1 + X_2)$$

$$s.t..\overline{B} = (1+\tau)p\left(\frac{p+s}{c}\right) + s\left(\frac{p+s}{c} + \frac{s}{c}\right)$$

It leads to the following second-order polynomial:

$$(1+\tau)p^2 + (2+\tau)sp + 2s^2 - \overline{B}c = 0$$

The determinant is:

$$\Delta = s^2\tau^2 + (4+4\tau)(\overline{B}c - s^2)$$

The two roots of the polynomial are:

$$p^a = \frac{-(2+\tau)s + \sqrt{s^2\tau^2 + (4+4\tau)(\overline{B}c - s^2)}}{2(1+\tau)}$$

And

$$p^b = \frac{-(2+\tau)s - \sqrt{s^2\tau^2 + (4+4\tau)(\overline{B}c - s^2)}}{2(1+\tau)}$$

Because the premium p and the subsidy s are positive, the only possible solution is:

$$p^*(s) = \frac{-(2+\tau)s + \sqrt{s^2\tau^2 + (4+4\tau)(\overline{B}c - s^2)}}{2(1+\tau)}$$

We introduce this relation in the utility function, leading to:

$$U_{economy} = \left(\frac{v}{d_1} - \frac{v}{d_2}\right)\left(\frac{s}{c} + \frac{\sqrt{s^2\tau^2 + (4+4\tau)(\overline{B}c - s^2)} - (2+\tau)s}{2(1+\tau)c}\right) + \left(\frac{v}{d_2} + w + y\right)\left(2\frac{s}{c} + \frac{\sqrt{s^2\tau^2 + (4+4\tau)(\overline{B}c - s^2)} - (2+\tau)s}{2(1+\tau)c}\right)$$

The first order condition on s is:

$$\frac{\partial U_{economy}}{\partial s} = 0 = \left(\frac{v}{d_1} - \frac{v}{d_2}\right)\left(\frac{1}{c} - \frac{s(\tau^2 - 4\tau - 4)}{2(1+\tau)c\sqrt{s^2\tau^2 + (4+4\tau)(\overline{B}c - s^2)}} - \frac{(2+\tau)}{2(1+\tau)c}\right)$$
$$+ \left(\frac{v}{d_2} + w + y\right)\left(\frac{2}{c} - \frac{s(\tau^2 - 4\tau - 4)}{2(1+\tau)c\sqrt{s^2\tau^2 + (4+4\tau)(\overline{B}c - s^2)}} - \frac{(2+\tau)}{2(1+\tau)c}\right)$$

Which is equivalent to:

$$\frac{\partial U_{economy}}{\partial s}=0=\left(\frac{v}{d_1}-\frac{v}{d_2}\right)\left(\frac{\tau}{2(1+\tau)c}-\frac{s(\tau^2-4\tau-4)}{2(1+\tau)c\sqrt{s^2\tau^2+(4+4\tau)(\overline{B}c-s^2)}}\right)$$
$$+\left(\frac{v}{d_2}+w+y\right)\left(\frac{1}{c}+\frac{\tau}{2(1+\tau)c}-\frac{s(\tau^2-4\tau-4)}{2(1+\tau)c\sqrt{s^2\tau^2+(4+4\tau)(\overline{B}c-s^2)}}\right)$$

Or:

$$\frac{\partial U_{economy}}{\partial s}=0=\frac{\left(\frac{v}{d_2}+w+y\right)}{c}+\frac{\left(\frac{v}{d_1}+w+y\right)}{2(1+\tau)c}\left(\tau-\frac{s(\tau^2-4\tau-4)}{\sqrt{s^2\tau^2+(4+4\tau)(\overline{B}c-s^2)}}\right)$$

We can isolate s such that:

$$\left(2(1+\tau)\frac{\left(\frac{v}{d_2}+w+y\right)}{\left(\frac{v}{d_1}+w+y\right)}+\tau\right)^2=A=\frac{s^2\left((\tau^2-4\tau-4)\right)^2}{s^2\tau^2+(4+4\tau)(\overline{B}c-s^2)}$$

Which is equivalent to:

$$s^2(\tau^2-4\tau-4)(\tau^2-4\tau-4-A)=A\overline{B}c(4+4\tau)$$

And finally:

$$s^*=\sqrt{\frac{A\overline{B}c(4+4\tau)}{(\tau^2-4\tau-4)(\tau^2-4\tau-4-A)}}$$

Introducing s^* in the reaction function of the city leads to:

$$p^*=\frac{\sqrt{\frac{A\overline{B}c(4+4\tau)}{(\tau^2-4\tau-4)(\tau^2-4\tau-4-A)}}(\tau^2-4\tau-4)+\overline{B}c(4+4\tau)-(2+\tau)\sqrt{\frac{A\overline{B}c(4+4\tau)}{(\tau^2-4\tau-4)(\tau^2-4\tau-4-A)}}}{2(1+\tau)}$$

Noticing that $\sqrt{4+4\tau}=2(1+\tau)$, we have:

$$p^*=\sqrt{\frac{A\overline{B}c}{(\tau^2-4\tau-4-A)}}+\overline{B}c-(2+\tau)\sqrt{\frac{A\overline{B}c}{(\tau^2-4\tau-4)(\tau^2-4\tau-4-A)}}$$

Which is equivalent to:

$$p^*=\sqrt{\frac{\overline{B}c(\tau^2-4\tau-4)}{(\tau^2-4\tau-4-A)}}-\sqrt{\frac{A\overline{B}c(\tau^2+4\tau+4)}{(\tau^2-4\tau-4)(\tau^2-4\tau-4-A)}}$$

Giving relation (34):

$$p^* = \sqrt{\frac{\overline{B}c}{(\tau^2 - 4\tau - 4 - A)}}\left(\sqrt{(\tau^2 - 4\tau - 4)} - \sqrt{\frac{A(\tau^2 + 4\tau + 4)}{(\tau^2 - 4\tau - 4)}}\right)$$

We can verify that s^* and p^* gives (28) and (29) in case where $\tau = 0$. Indeed, we have:

$$A = 4\left(\frac{\left(\frac{v}{d_2} + w + y\right)}{\left(\frac{v}{d_1} + w + y\right)}\right)^2$$

and

$$s^* = \sqrt{\frac{4A\overline{B}c}{(-4)(-4 - A)}}$$

i.e.

$$s^* = \sqrt{\frac{A\overline{B}c}{(4 + A)}}$$

Or:

$$s^* = \sqrt{\frac{4\left(\frac{\left(\frac{v}{d_2} + w + y\right)}{\left(\frac{v}{d_1} + w + y\right)}\right)^2 \overline{B}c}{\left(4 + 4\left(\frac{\left(\frac{v}{d_2} + w + y\right)}{\left(\frac{v}{d_1} + w + y\right)}\right)^2\right)}}$$

Giving (28):

$$s^* = \sqrt{\frac{\overline{B}c\left(w + y + \frac{v}{d_2}\right)^2}{\left(w + y + \frac{v}{d_1}\right)^2 + \left(w + y + \frac{v}{d_2}\right)^2}}$$

Similarly, we have in case where $\tau = 0$:

$$p^* = \sqrt{\frac{\overline{B}c}{(-4 - A)}}\left(\sqrt{(-4)} - \sqrt{\frac{4A}{(-4)}}\right)$$

Or :

$$p^* = \sqrt{\frac{\overline{B}c}{(4+A)}}\left(\sqrt{4} - \sqrt{A}\right)$$

Meaning :

$$p^* = \sqrt{\frac{\overline{B}c}{\left(1 + \left(\frac{\left(\frac{v}{d_2} + w + y\right)}{\left(\frac{v}{d_1} + w + y\right)}\right)^2\right)}}\left(1 - \left(\frac{\left(\frac{v}{d_2} + w + y\right)}{\left(\frac{v}{d_1} + w + y\right)}\right)\right)$$

Leading to :

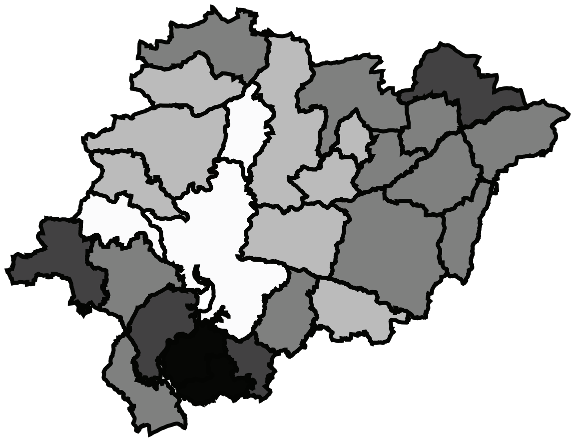
$$p^* = \sqrt{\frac{\overline{B}c\left(\frac{v}{d_1} + w + y\right)^2}{\left(\left(\frac{v}{d_1} + w + y\right)^2 + \left(\frac{v}{d_2} + w + y\right)^2\right)}}\left(1 - \left(\frac{\left(\frac{v}{d_2} + w + y\right)}{\left(\frac{v}{d_1} + w + y\right)}\right)\right)$$

Finally giving (29) :

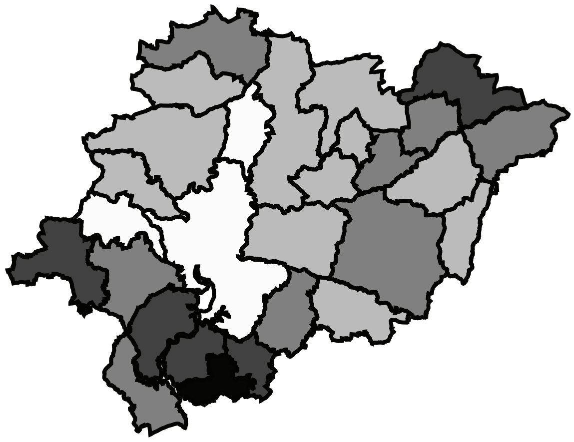
$$p^* = \sqrt{\frac{\overline{B}c}{\left(w + y + \frac{v}{d_1}\right)^2 + \left(w + y + \frac{v}{d_2}\right)^2}}\left[\frac{v}{d_1} - \frac{v}{d_2}\right]$$

Appendix A3: Maps of the case study area for the sensitivity analysis on transaction costs.

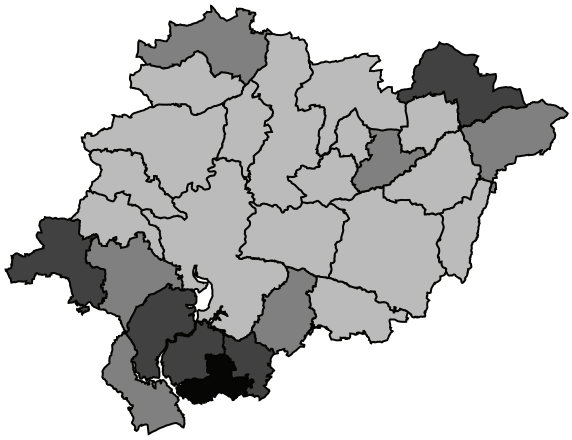
τ = 0.2



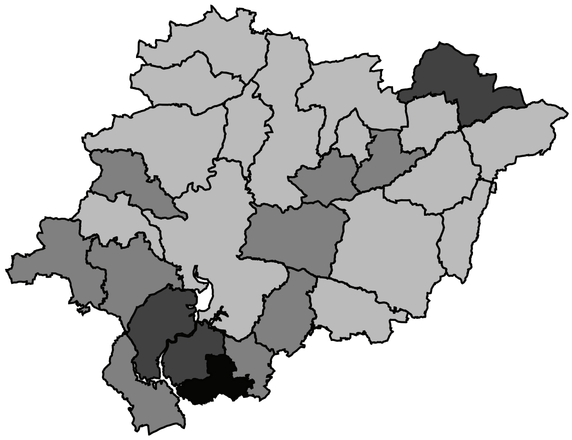
τ =0.4



τ = 0.6



τ = 0.8



τ = 1