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# Ecological compensation: how much and where?

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# Ecological compensation: how much and where?

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**Abstract**

We propose a spatial framework to study ecological compensation. The policy-maker implements a No Net Loss policy that meets the No Worse-Off principle as well as a location constraint on the offset. This determines both the location and the level of compensation that minimize the total cost of restoration. We describe the additional ecological cost induced by the No Worse-Off principle and how the spatial distribution of individuals, the environment and land costs affect the compensation location. The location constraint is shown to introduce a trade-off between the compensation cost and inequality.

Keywords: Ecological compensation, no net loss policy, welfare, inequality

JEL Codes: I3; Q5; R1

## 1 Introduction

Local and national economic development programs are often accompanied by ecological damages. Policy makers have designed mitigation measures in line with the 'polluter pays' principle to address the adverse impacts

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of development projects. These measures usually focus on the ecological dimension of the compensation as exemplified by the so-called No Net Loss (NNL) policy. This ecological approach to compensation has socio-economic drawbacks as it neglects the welfare consequences that the compensation has on the impacted population.

In our paper we develop an environmental compensation policy that meets both NNL and No Worse-Off (NWO) objectives so that the well-being of individuals is integrated to the NNL policy. The design of our compensation policy consists of both the location and the level of ecological compensation that minimize the total cost of restoration.

Nowadays, development projects have to put in place mitigation measures that offset the negative impacts of land developments. These compensation measures are perceived as a mean to reconcile development with conservation. While these practices originated in the United States, they now widely spread to other countries like Australia, New-Zealand, Canada, China, European countries, or even South America. Restoration designs can be either voluntary or compulsory by law. Compensation applies to a wide range of sectors including mining, wind power, hydropower, oil and gas, property development, agriculture, etc. As a priority, developers should avoid and minimize any impacts on biodiversity. When residual impacts cannot be avoided, creation and restoration of natural habitats are considered to achieve NNL (or even a net gain) of biodiversity. This mitigation sequence, referred to as 'mitigation hierarchy', cannot be bypassed.[1]

Biodiversity offset programs involve controversial issues which are still the source of debate in many countries (Clare et al. (2011), Gordon et al. (2015)). An important critique is that offsets are usually considered from an environmental perspective only and therefore omit other relevant dimen-

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[1] If a developer cannot afford the restoration cost, the development project will not be approved.

sions such as the quality of life, social values, and economic well-being. As the NNL policy focuses exclusively on the ecological cost, it leaves aside any welfare consideration. Governments usually justify the implementation of development projects by arguing that any impact to biodiversity can be compensated. However the corresponding mitigation measures may underestimate the social harm of the project (Githiru et al., 2015). This means that traditional mitigation planning may have detrimental consequences for people. This calls for offsets that address the welfare of individuals on top of the ecological cost associated with the NNL objective. As defined by Griffiths et al. (2019), the NWO principle states that "the social gains associated with the changes in biodiversity caused by development and accompanying offsets must at least equal any social losses". In our framework, we impose a no welfare loss so that social gains and losses compensate each other.

Individual welfare gains and losses depend on the distances of individuals from both the damage and offset sites (Mandle et al., 2015). Many countries have limited requirements regarding the spatial location of offsets. In general, the choice of the offset location is at the discretion of the proponent of the project. In practice it is driven by land availability and price. De facto, land developers are likely to seek cheap land, inducing the displacement of offsets away from development sites. Moving ecological resources across space has welfare implications. A good illustration of such a relocation of nature is the U.S. wetland mitigation programs. These programs require the developers to provide compensatory mitigation to aquatic resources in compliance with Federal, State and Tribal regulations. In many cases, the impacts on aquatic resources must be mitigated at a minimum acreage ratio of "an acre for an acre" but can be relocated. In practice, these programs frequently reroute the benefits people get from wetlands away from urbanized areas because it is less costly to undertake mitigation in less dense areas. This results in a loss of public access, amenity and ecosystem service benefits to some communities, in particular those close to development sites (Ruhl and Salzman, 2006; BenDor et al., 2008).

A strict implementation of the NNL principle would require compensation at the damage location. In other words, in environmental and territorial justice perspectives, population directly impacted by the damage should reap the benefits of the compensation. However, due to the lack of available or suitable land, on-site compensation is not always feasible. Therefore the need for some flexibility is required. An issue is then about where to locate offsets within a reasonable distance from the damage site. As ecological compensation practices gain importance in many countries, the location choice of offsets is also becoming a growing issue (Womble and Doyle, 2012). Once off-site compensation is allowed, offsets should presumably be implemented within some geographical area around the damage site.

These practical concerns are not new and have been studied in the recent literature. Some studies have shown that the distance between the site and compensation sites significantly influences individual preferences for compensation measures (Borrego, 2010; Burton et al., 2017). Empirical analyses on the North Carolina's ecosystem enhancement Program by BenDor and Stewart (2011), the wetland mitigation banking in Florida by Ruhl and Salzman (2006) and the Chicago's one by BenDor et al. (2007) highlighted the role of offset location constraints and property values on the compensation policy. A softer location constraint on offsets (North Carolina case) may relocate compensation sites away from urbanized areas due to the availability of cheaper land outside cities. This can induce social impacts on the communities located nearby the damage. These growing concerns have been recently highlighted through an in-depth interviews analysis of stakeholders in England (Taherzadeh and Howley, 2018) and also deeply discussed in Griffiths et al. (2019). Despite of this growing empirical evidence, the economic principles underlying the compensation design remain a matter of concern (Calvet et al., 2015). An economic approach to environmental compensation in a spatial context is mostly missing. Welfare impacts of compensation measures are an often-overlooked issue. Exceptions are Zafonte and Hampton (2007), Flores and Thacher (2002), Gastineau and Taugourdeau (2014). These papers are considering the consequences on welfare of alternative types of compensation (ecological or monetary compensation schemes). Zafonte and Hampton (2007) suggest that a pure ecological compensation based on the ecological equivalence principle may provide an acceptable approximation of wealth compensation. A different result is shown by Flores and Thacher (2002) who find that ecological equivalence specified in biophysical equivalents could fail to provide a satisfactory compensation from a welfare perspective. Finally, Gastineau and Taugourdeau (2014) explore the possibility to complement the ecological equivalence by a monetary compensation in order to restore the social welfare after the damage. Recently, Mandle et al. (2015) use an ecosystem service modeling framework to describe how the impacts of development (Pucallpa-Cruzeiro do Sul road, Peruvian Amazon) and the benefits of mitigation are spatially distributed.

To the best of our knowledge, no research addressing welfare issues of ecological compensation in a spatial context is available in the literature. This paper is an attempt to fill this gap. Based on the empirical evidence by BenDor et al. (2007), BenDor and Stewart (2011) and Ruhl and Salzman (2006), we develop a theoretical framework that integrates the spatial dimension of ecological compensation. By doing so, we introduce the location choice of offsets in a compensation policy that meets both NNL and NWO objectives. In our model the local policy-maker decides on the level and location of the ecological compensation so as to minimize the total cost of restoration. When doing so, the policy maker complies with both ecological and welfare constraints on top of geographical restrictions on the offset location.

First, we show how the individual willingness to accept the ecological compensation depends on his distance to the damage or restoration sites. This means that agents in different locations are impacted differently by the restoration policy. This is because both ecological costs and benefits decay with spatial distance. Second, when the mitigation ratio is low, the minimal ecological compensation meeting the NNL condition cannot satisfy the NWO objective. An additional ecological compensation is needed to meet this NWO objective. In the absence of land cost, we show that the ecological cost is minimized in the gravity center of marginal utilities of environmental consumption. This means that the location of offsets matters a lot. Compensating in another location is of course possible but would require a larger ecological offset. Third, we show that in the presence of land costs, the compensation relocates towards cheaper land areas. When this happens, the level of ecological compensation increases as it is getting away from the gravity center of marginal utilities of environmental consumption but the total restoration cost falls as cheaper land costs more than offsets the increase in ecological cost. Fourth, we show that on-site compensation is welfare neutral. A soft constraint on offset location allows a lower restoration cost because more sites become available, but it introduces inequality across agents. This establishes a trade-off between the compensation cost and inequality.

This paper is organized as follows. Section 2 determines and characterizes the willingness to accept the ecological compensation. It introduces the planner's program and characterizes the optimal offset. In Section 3 we study the additional ecological cost induced by the NWO. We also describe the role of land costs and the location constraint on the optimal offset. The final section summarizes discussions and concludes.

# 2 Model

We consider a two-period spatial economy. Individuals $i \in \{1, ..., N\}$ are distributed along a segment of unit length $\mathcal{S} = [0, 1]$. They consume an environmental good also distributed along the segment $\mathcal{S}$ according to the distribution $q_1(z)$ in period 1 (*resp.* $q_2(z)$ in period 2), $z \in \mathcal{S}$.

Individual $i$ located in $s_i \in \mathcal{S}$ has the following preferences:

$$U_i(s_i) = u_{i1}(X_{i1}, Q_1(s_i)) + \delta u_{i2}(X_{i2}, Q_2(s_i))$$

where $X_{it}$ represents his income at period $t$, $\delta$ the rate of time-preference and $Q_t\,(s)$ the effective level of the environmental good available in location $s$ at time $t$

$$\begin{aligned} Q_1(s) &= \int_{\mathcal{S}} [1 - \tau(s-z)^2] q_1(z) \mathrm{d}z \\ Q_2(s) &= \int_{\mathcal{S}} [1 - \tau(s-z)^2] q_2(z) \mathrm{d}z \end{aligned}$$

where parameter $\tau > 0$ reflects that the benefit from the environmental good decays over distance. We assume $\tau$ to be sufficiently small so that $1 - \tau(s-z)^2$ remains positive.

As agents are assumed to lend and borrow in a perfect capital market, the intertemporal budget constraint faced by individual $i$ is given by $W_i = X_{i1}(1 + r) + X_{i2}$, with $W_i$ being the intertemporal income of agent $i$ and $r$ the interest rate, so that his indirect utility can be written as $V_i(s_i) = v_i[W_i, Q_1(s_i), Q_2(s_i)]$. The aggregate welfare is given by the sum of individual utilities $\mathcal{W} = \sum_{i=1}^{N} V_i\,(s_i)$.

The economy faces an ecological damage $dq_1 < 0$ at period 1. We assume this damage to be small and to occur in the central location $z = 1/2$. The environmental compensation policy designed by the local decision-maker (the planner) consists of an ecological compensation $dq_2 > 0$ to be implemented in location $y$ at period 2.

## 2.1 Willingness to accept the ecological compensation

The impact of the ecological damage $dq_1$ and the environmental compensation policy $(dq_2, y)$ on the utility $V_i$ of individual $i$ is given by

$$dV_i = \frac{\partial v_i}{\partial Q_1}\left[1-\tau\left(s_i - 1/2\right)^2\right] dq_1 + \frac{\partial v_i}{\partial Q_2}\left[1-\tau\left(s_i - y\right)^2\right] dq_2 \tag{1}$$

This allows us to define individual $i$'s Willingness To Accept (WTA) the ecological compensation for the damage as the minimum ecological compensation $dq_2$ that leaves his utility $V_i$ unchanged:

$$WTA_i = dq_2|_{dV_i=0} = \frac{v'_{i,1}}{v'_{i,2}} \frac{1-\tau\left(s_i - 1/2\right)^2}{1-\tau\left(s_i - y\right)^2}(-dq_1) \tag{2}$$

where $v'_{i,t}$ denotes the marginal utility of the environmental good $\frac{\partial v_i}{\partial Q_t}$.

From expression (2), it appears that individuals in different locations are impacted differently by both the damage and the restoration because they value them differently (i.e. the marginal utilities of the environmental good are different) or because their distance to them is different. So their compensation requests in different locations are also different.

In order to better understand why the WTA of an individual varies with his location, we differentiate expression (2),

$$\begin{aligned}\frac{\partial WTA_i}{\partial s_i} =& \left[\frac{-2\tau(s_i - 1/2)}{1-\tau\left(s_i - 1/2\right)^2} + \frac{2\tau(s_i - y)}{1-\tau\left(s_i - y\right)^2} + \frac{1}{s_i}\left(\varepsilon_{v'_{i,1}} - \varepsilon_{v'_{i,2}}\right)\right] \\ & \times \frac{1-\tau(s_i - 1/2)^2}{1-\tau\left(s_i - y\right)^2}\frac{v'_{i,1}}{v'_{i,2}}(-dq_1)\end{aligned} \tag{3}$$

where $\varepsilon_{v'_{i,t}}$ refers to the elasticity of marginal utility of the environmental good with respect to location in period $t$, i.e. $\varepsilon_{v'_{i,t}} = (s_i/v'_{i,t})(dv'_{i,t}/ds_i)$.

The above expression (3) illustrates two impacts of location on the individual WTA. While the first two terms into the brackets describe the effect of the distance with respect to the damage or the restoration site, the elasticities of marginal utilities show the influence of the distance to the environment distribution in both periods.

The closer the damage to an individual, the larger its impact, and therefore a higher compensation is needed to maintain the individual utility unchanged. Similarly, the closer the compensation is implemented to an individual, the higher his benefit from the restoration, and thus the smaller the required compensation. On the other hand, an individual located closer to the center of the environment distribution $q_1$ (*resp.* the center of the environment distribution $q_2$) benefits from a higher effective level of the environmental good $Q_1$ (*resp.* the environmental good $Q_2$). As a result, her valuation of the damage in period 1 (*resp.* the restoration in period 2) is lower, which implies a smaller (*resp.* higher) corresponding compensation.

We define the society Willingness To Accept (WTA) the ecological compensation for the damage as the minimum ecological compensation $dq_2$ that leaves the aggregate utility unchanged $d\mathcal{W} = \sum_{i=1}^{N} dV_i = 0$

$$WTA = dq_2|_{d\mathcal{W}=0} = \frac{\sum_i \frac{\partial v_i}{\partial Q_1}\left[1-\tau\left(s_i-1/2\right)^2\right]}{\sum_i \frac{\partial v_i}{\partial Q_2}\left[1-\tau\left(s_i-y\right)^2\right]}(-dq_1) \tag{4}$$

The society WTA depends on agents' heterogeneity coming from their spatial distribution and their individual preferences of the environmental good (in both periods).

In order to better understand how the location of an agent affects his WTA, we now abstract from heterogeneous environmental valuations by considering identical separable utility functions and identical distributions of the environmental good across periods. In this case, the utility function of agent $i$ in location $s_i$ can be written as

$$U_i(s_i) = u_i(X_1) + w_i(Q_1(s_i)) + \delta u_i(X_2) + \delta w_i(Q_2(s_i))$$

From the intertemporal budget constraint, consumption smoothing in periods 1 and 2 leads to private consumption $X_{i,1}$ and $X_{i,2}$ in terms of $W_i$, $r$ and $\delta$. So the indirect utility $V_i$ can be written as

$$V_i = R_i + w_i(Q_1(s_i)) + \delta w_i(Q_2(s_i)) \tag{5}$$

where $R_i$ depends on $W_i$, $r$ and $\delta$. As utility functions and environmental distributions are assumed to be identical in both periods, marginal valuations of the environment cancel out and the elasticities of marginal utilities are equal so that Equation (3) reduces to

$$\frac{\partial WTA_i}{\partial s_i} = \left( \frac{-2\tau(s_i - 1/2)}{1 - \tau\left(s_i - 1/2\right)^2} + \frac{2\tau(s_i - y)}{1 - \tau\left(s_i - y\right)^2} \right) \frac{1 - \tau(s_i - 1/2)^2}{1 - \tau\left(s_i - y\right)^2} \left( \frac{-dq_1}{\delta} \right) \tag{6}$$

Expression (6) confirms that the change in WTA with respect to location is driven only by the distances to the damage and restoration sites.

**Proposition 1**

*For identical separable utility functions and identical distributions of the environmental good in both periods,*

*(i) on-site restoration leads to the same WTA for all agents,* $WTA_i = -dq_1/\delta, \quad \forall i = 1, ..., N$

*(ii) the WTA of an agent located between the damage and restoration sites decreases (resp. increases) when getting closer to the restoration site (resp. the damage); the WTA of an agent located away from the zone defined by the damage and the restoration site decreases (resp. increases) when getting closer to that zone if the restoration site (resp. the damage) is the furthest away from the agent.*

*(iii) a compensation policy that maintains the aggregate utility unchanged* ($d\mathcal{W} = 0$) *separates spatially the agents that are better off with the policy from those that are worse off.*

**Proof 1**

*(i) Directly from Expression (2) as* $v'_{i,1} = v'_{i,2}/\delta$ *for identical distributions of the environmental good.*

*(ii) Directly from Expression (6).*

*(iii) As the restoration given by the society WTA maintains the aggregate utility constant, some agents will benefit from the compensation policy, while others will lose. Under the conditions of Proposition 1, the WTA of agent $i$ is strictly monotone with respect to his location $s_i$. This is immediate from (ii). This means that implementing the restoration given by the society WTA leads $dV_i$ to be strictly monotone with respect to $s_i$. In other words, there is a unique location $s^\star$ such that $dV_i(s^\star) = 0$, which separates winners from losers.*

On-site restoration is usually advocated to compensate prioritarily the impacted population around the damage area. Proposition 1 (i) shows a desirable implication of on-site restoration. It is welfare neutral as it treats all agents equally in terms of welfare, addressing equity concerns that the policy-maker may have. Proposition 1 (ii) allows to determine how the WTA depends on location along the segment and therefore to compare the WTA of agents in different locations. For instance, when the restoration is implemented to the right of the damage (i.e. $y > z = 1/2$), the individual WTA decreases when the individual relocates from left to right meaning that the agent located to the right of another has a lower WTA.

In order to illustrate the WTA concept and the result of Proposition 1 (iii), consider the following example.

**Example** The economy consists of three individuals located in $s_1 = 0, s_2 = 0.7, s_3 = 1$ and the environment distribution $q(z = 0.4) = q(z = 0.5) = q(z = 0.6) = 1000$ in both periods, see Figure 1.

The damage occurs in $z = 1/2$ at period 1 and we consider a restoration implemented in $y = 0.6$ at period 2. We assume logarithmic preferences $U_i = \alpha \ln X_1 + (1-\alpha) \ln Q_1(s_i) + \delta\alpha \ln X_2 + \delta(1-\alpha) \ln Q_2(s_i)$, where $\alpha$ is

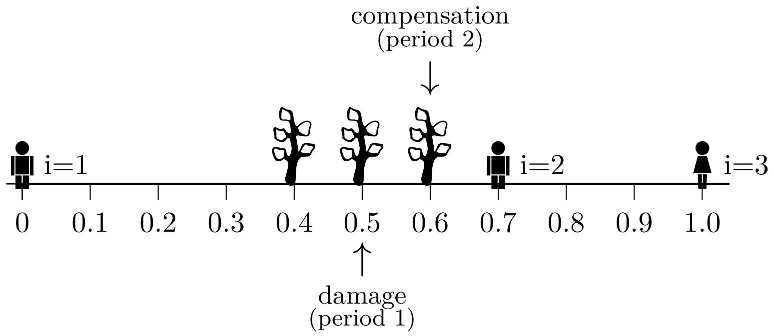

Figure 1: An economy consisting of three individuals and an environment distributed over three locations around the damage site

the weight of private consumption.

The effective level of the environmental good for individual $i$ writes

$$Q(s_i) = \sum_z [(1 - \tau(s_i - z)^2)q(z)]$$

As agents have the same income, the intertemporal budget constraint reduces to $W = X_1\,(1 + r) + X_2$. Consumption smoothing across periods 1 and 2 gives $X_2/X_1 = \delta\,(1 + r)$ leading to the following indirect utility

$$\begin{aligned} V_i = & \alpha \ln\left(\frac{W}{(1+\delta)\,(1+r)}\right) + (1-\alpha)\ln Q_1\,(s_i) + \delta\alpha\ln\left(\frac{\delta}{(1+\delta)}W\right) \\ & + \delta(1-\alpha)\ln Q_2\,(s_i) \end{aligned} \tag{7}$$

We use the following set of parameters for the numerical simulations: $W = 400{,}000$ (intertemporal income), $\alpha = 0.8$ (weight of private consumption), $\delta = 0.67$ (rate of time-preference), $\tau = 0.8$ (distance-decay parameter), $q_1(z) = 1000$ (environmental distribution in period 1), $q_2(z) = 1000$ (environmental distribution in period 2), $dq_1 = -200$ (environmental damage in period 1).

The WTA of agents are derived from expression (2) $WTA_1 = 335.402$; $WTA_2 = 291.286$; $WTA_3 = 273.86$. So compensating individuals in different locations implies different levels of compensation (e.g. individual 1 requires the highest compensation). The compensation that maintains the aggregate utility constant is given by expression (4),

$$WTA = \frac{\sum_i \frac{1}{Q_1(s_i)}\left[1-\tau\left(s_i-1/2\right)^2\right]}{\sum_i \frac{\delta}{Q_2(s_i)}\left[1-\tau\left(s_i-y\right)^2\right]}(-dq_1) = 298.34 \tag{8}$$

As the society WTA is higher than the individual WTA of agents 2 and 3 and lower than that of agent 1, individuals 2 and 3, the winners from the compensation policy, are indeed separated from agent 1 who loses out, as stated by Proposition 1 (iii).

## 2.2 Optimal environmental compensation policy

In this Section we describe the design of the environmental compensation policy. The objective of the local policy maker is to minimize the total cost of the compensation policy. In general the total restoration cost consists of the ecological cost and the land cost associated with the implementation of the ecological compensation. The ecological cost $C_1\left(dq_2\right)$ depends on the ecological compensation $dq_2$ expressed in units of the environmental good with $\partial C_1/\partial dq_2 > 0$. The land cost $C_2\left(dq_2, y\right)$ depends on both the location of compensation $y$ and the quantity of restored good $dq_2$ with $\partial C_2/\partial dq_2 > 0$.

The policy maker selects an optimal environmental compensation policy by choosing an ecological compensation $dq_2$ and a location $y$ where to implement it. When making this choice, the policy-maker faces three constraints. The No Net Loss (NNL) condition imposes a minimal ecological compensation $-\sigma dq_1$, where $\sigma$ is the mitigation ratio. The No Worse-Off (NWO) principle prevents the economy from experiencing a decrease in aggregate welfare. The location constraint takes into account the maximum distance between the damage and impact sites. It could reflect local ordinances imposing the compensation to be implemented within a distance $d$ from the damage.

The compensation cost minimization program faced by the policy-maker writes as follows:

$$\min_{y,dq_2} C(dq_2, y) = C_1\left(dq_2\right) + C_2\left(dq_2, y\right) \tag{9}$$

subject to

$$dq_2 \geq -\sigma dq_1 \tag{10}$$

$$d\mathcal{W} \geq 0 \tag{11}$$

$$\left(y - 1/2\right)^2 \leq d^2 \tag{12}$$

where conditions (10), (11) and (12) are respectively the NNL, NWO, and location constraints.

When solving program (9), the NWO condition places an important restriction on the choice of the ecological compensation $dq_2$. This explains why the planner may have to choose a compensation $dq_2$ above the minimal level $-\sigma dq_1$ in order to prevent any aggregate welfare loss $d\mathcal{W} \geq 0$. From Section 2.1, we know that the agents' WTA depends on the location $y$ where the compensation $dq_2$ is implemented. For this reason, the cost of the compensation policy will generally depend on that location $y$ even in the absence of land cost. It is up to the planner to choose the location site $y$ that minimizes the total cost $C(dq_2, y)$. The planner's problem can also be understood as a 2-stage program: in stage 1, the planner decides the location of the compensation $y$ given the cost of the compensation policy determined in stage 2; in stage 2, the planner decides the required level of the compensation $dq_2$ in each location $y$ while meeting the constraints of the problem.

The Lagrangian function associated to the planner's program is given by

$$\mathcal{L} = C\left(dq_2, y\right) - \lambda_1 d\mathcal{W} - \lambda_2(dq_2 + \sigma dq_1) - \lambda_3\left[d^2 - \left(y - 1/2\right)^2\right]$$

where $\lambda_1$, $\lambda_2$, $\lambda_3$ are the Lagrangian multipliers associated to constraints (11), (10) and (12).

The first-order conditions write:

$$\frac{\partial \mathcal{L}}{\partial y} = \frac{\partial C_2}{\partial y} - \lambda_1 \frac{\partial d\mathcal{W}}{\partial y} + \lambda_3 (2y - 1) = 0 \tag{13}$$

$$\frac{\partial \mathcal{L}}{\partial dq_2} = \frac{\partial C_1}{\partial dq_2} + \frac{\partial C_2}{\partial dq_2} - \lambda_1 \frac{\partial d\mathcal{W}}{\partial dq_2} - \lambda_2 = 0 \tag{14}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_1} = -d\mathcal{W} \leq 0; \qquad \frac{\partial \mathcal{L}}{\partial \lambda_2} = -(dq_2 + \sigma dq_1) \leq 0; \qquad \frac{\partial \mathcal{L}}{\partial \lambda_3} = (y - 1/2)^2 - d^2 \leq 0$$

Five regimes determining the patterns of the optimal compensation can be distinguished:

- Regime $A_0$ corresponding to a situation where $d\mathcal{W} > 0$.

and 4 other regimes where $d\mathcal{W} = 0$

- Regime $A_1$: $dq_2 > -\sigma dq_1$ and $(y - 1/2)^2 < d^2$.
- Regime $A_2$: $dq_2 > -\sigma dq_1$ and $y = 1/2 \pm d$.
- Regime $A_3$: $dq_2 = -\sigma dq_1$ and $(y - 1/2)^2 < d^2$.
- Regime $A_4$: $dq_2 = -\sigma dq_1$ and $y = 1/2 \pm d$.

The solution to these regimes are derived in detail in Appendix 1.

In order to interprete the regimes, we first represent the impact that the implementation of the minimal ecological compensation $dq_2 = -\sigma dq_1$ in location $y$ would have on welfare $d\mathcal{W}$. This impact can be obtained from relation (15) (in Appendix) which can be represented by a parabola in the plane $(\sigma, y)$ when $dq_2 = -\sigma dq_1$. Figure 2 says that implementing the minimal ecological compensation $-\sigma dq_1$ in a location $y$ inside (*resp.* outside) the parabola will be welfare improving $d\mathcal{W} > 0$ (*resp.* welfare decreasing $d\mathcal{W} < 0$). Along the parabola itself, welfare remains unchanged $d\mathcal{W} = 0$.

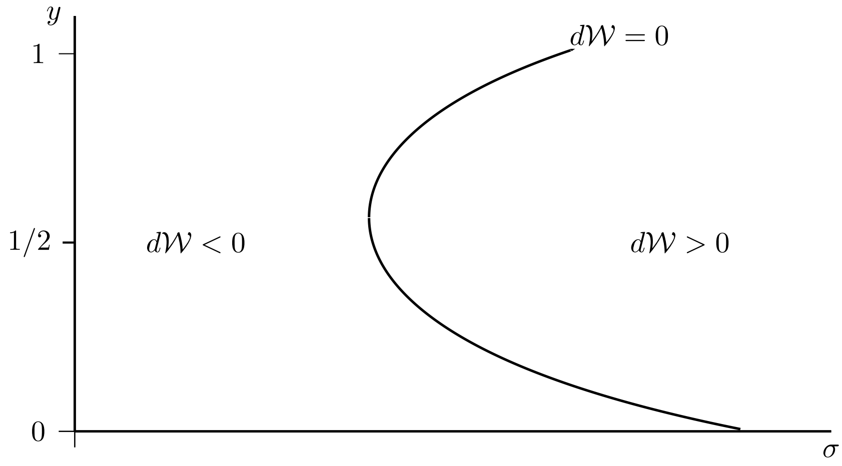

Figure 2: Impact of the minimal ecological compensation ($dq_2 = -\sigma dq_1$) on welfare in the plane ($\sigma$,$y$)

For illustration purposes, we assume a soft location constraint (i.e. $d$ is large) and represent regimes $A_0$, $A_1$, $A_2$, $A_4$ in the plane $(\sigma, y)$, see Figure 3.

When the ecological constraint is strong (i.e. high mitigation ratio $\sigma$), implementing the minimal ecological compensation $dq_2 = -\sigma dq_1$ improves welfare $d\mathcal{W} > 0$, so that regime $A_0$ applies. Because $\sigma$ is high, the minimal compensation can actually be implemented in any location $y$ along the segment and still deliver $d\mathcal{W} > 0$. This is because the ecological constraint is so demanding that the implementation of the minimal compensation improves welfare regardless of its location.

When the ecological constraint is weak (i.e. low $\sigma$), we already know from Figure 2 that implementing the minimal ecological compensation would decrease the aggregate welfare. For this reason, a larger compensation $dq_2 > -\sigma dq_1$ is needed. In that case, regime $A_1$ applies. Because the impact of the compensation on welfare depends on where the compensation $dq_2$ is actually implemented, not all locations are equivalent in terms of cost. Regime $A_1$

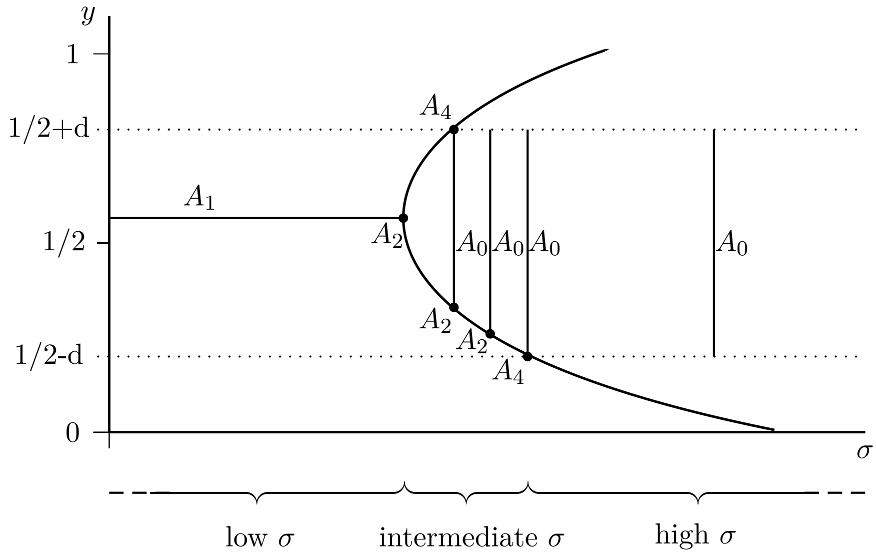

Figure 3: Representation of regimes $A_0$, $A_1$, $A_2$, and $A_4$ in the plane $(\sigma, y)$ (in the case of a soft location constraint) for the economy represented in Figure 2 with the environment distribution given by $q(z = 0.4) = q(z = 0.5) = q(z = 0.6) = 1000$ in both periods

determines the location leading to the minimum cost $dq_2$ while maintaining welfare constant $d\mathcal{W} = 0$. Note that in the case of a tight location constraint (i.e. small $d$), regime $A_2$ would apply instead of regime $A_1$ as the location constraint (12) would become binding.

For intermediate values of $\sigma$, not all locations $y$ along the segment can meet both the NNL and NWO conditions. The sub-segment of locations where the minimal ecological compensation can be implemented is actually constrained by the parabola. Regimes $A_2$ and $A_4$ correspond to end-points of such sub-segments lying along the parabola.

# 3 Applications

In order to characterize the location of ecological compensation, determine its impact on ecological cost, and study the role of land costs, we solve the program (9) in two different scenarios. The first one abstracts from land costs so as to focus on the interaction between the NNL and NWO principles. The second one focuses on the role of land costs and the location constraint.

## 3.1 Ecological cost of the NWO principle and compensation location

In this Section we explain how the location of the compensation matters when minimizing the ecological cost. This will help us to understand the ecological cost associated with the NWO principle.

For this purpose we use the economy of the Example of Section 2.1 consisting of 3 agents with logarithmic preferences and the environment distributed over 3 locations around the middle of the segment, see Figure 1.

Here there is no land cost $C_2(dq_2, y) = 0$ so that the total cost of compensation reduces to the ecological cost $C_1$ that is assumed to be linear: $C_1(dq_2) = \nu \cdot dq_2$, with $\nu > 0$ being the cost of a unit of compensation.

The objective of the policy-maker reduces to the minimization of the compensation quantity:

$$\min_{dq_2} \quad C(dq_2) = \nu \cdot dq_2$$

subject to the NNL, NWO, and location constraints (10), (11), and (12).

The optimal restoration site $(y^*)$ is the location where to implement the minimum compensation $dq_2^*$.

The solution to the planner's problem is determined by solving for the possible regimes $A_0$, $A_1$, $A_2$, $A_3$, $A_4$ identified in Section 2.2. These regimes are represented in the plane $(d, \sigma)$, see Figure 12 in Appendix 2.

These regimes can be interpreted in terms of the level of compensation $dq_2$ and its location $y$, see Figure 4.

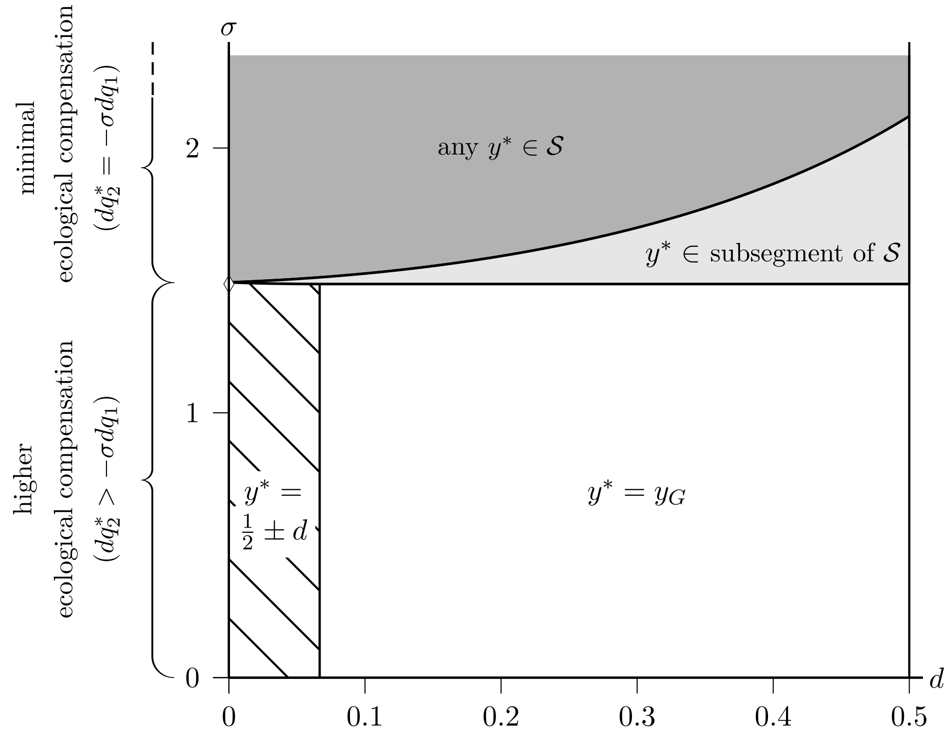

Figure 4: Optimal environmental policy $(dq_2^*, y^*)$ in the plane $(d,\sigma)$ for the economy of Figure 2 with the environment distribution given by $q(z = 0.4) = q(z = 0.5) = q(z = 0.6) = 1000$ in both periods

In the grey and light grey areas, $dq_2^*$ is given by the minimal ecological compensation $-\sigma dq_1$, and $y^* \in \mathcal{S}$ or a subsegment of $\mathcal{S}$ respectively. In the hatched and white areas, $dq_2^*$ is higher than the minimal ecological compensation, and $y^*$ is a corner solution (i.e. $y^* = 1/2 \pm d$) or the gravity center $y_G$ of marginal utilities of the environmental good.

In the grey and light grey areas, the minimal ecological compensation $-\sigma dq_1$ is sufficient to meet the NWO condition. In the grey area, where the mitigation ratio $\sigma$ is large, compensation can be implemented in any location along the segment $\mathcal{S}$ and still strictly improve the aggregate welfare $d\mathcal{W} > 0$. In the light grey area, not all feasible locations along the segment $\mathcal{S}$ will meet the NWO condition as the mitigation ratio $\sigma$ is only intermediate. However, there is always a sub-segment of locations in $\mathcal{S}$ where implementing the minimal compensation meets the NWO condition. As was already shown in Figure 3, the set of such locations shrinks as the mitigation ratio $\sigma$ decreases.

In the hatched and white areas, the minimal ecological compensation $-\sigma dq_1$ never meets the NWO condition and implementing it would actually decrease the aggregate welfare. When the mitigation ratio $\sigma$ is low, the minimal compensation $-\sigma dq_1$ is correspondingly low making it impossible for the aggregate welfare not to decrease. As a consequence, the planner has to implement a higher compensation ($dq_2 > -\sigma dq_1$) so as to prevent welfare from decreasing. From Section 2.1, we know that the individual and the society WTA depend on where the compensation is implemented. This means that the cost of compensation depends crucially on its location. Consider the white area. Figure 5 illustrates various options available to the planner, each of them implying a different ecological cost. The first option is on-site compensation (in $y = 1/2$) which treats all agents equally in terms of welfare, see Proposition 1 (iii). A possible alternative is to provide the best population access to the restoration in $y = y_P$. We see that this alternative provides a lower cost than on-site compensation. In our framework, it is up to the planner to choose the best location in terms of cost. The optimal location is given by Eq. (17) which leads to the gravity center $y_G$ of marginal utilities of the environmental good.[2] This characterization is obtained due to the absence of land cost. Importantly, we see that the optimal restoration site is not determined by the gravity center of population because for welfare purposes it is the marginal valuation of the environmental good that matters, not just access to population.

In the light grey area, the gravity center $y_G$ of marginal utilities is not feasible as smaller values of $d$ make the location constraint binding. In

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[2] From Eq. (17), we get $y_G = \sum_i \left( \frac{\partial v_i / \partial Q}{\sum_j \partial v_j / \partial Q} \right) s_i$ as $C_2(dq_2, y) = 0$.

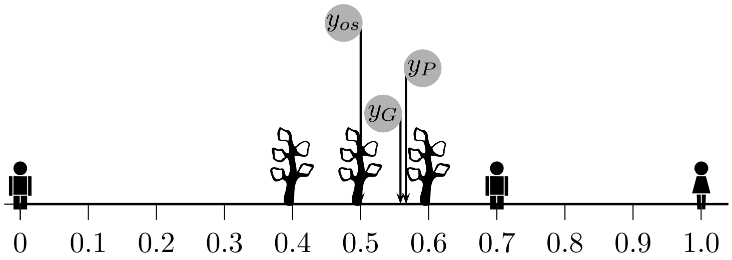

Figure 5: Compensation cost depending on the location of compensation

On-site restoration in $y = 1/2$ is the most costly. While the compensation in $y_P$ favoring population access is a cheaper option, the location that minimizes the compensation cost corresponds to the gravity center $y_G$ of marginal utilities of the environmental good.
The cost parameter is: $\nu = 1500$.
The compensation parameters are as follows:

| | $y$ | $dq_2$ | $C(dq_2)$ |
|---|---|---|---|
| $y_{os}$ | 0.5 | 298.507 | 447,760.5 |
| $y_G$ | 0.558432 | 297.55 | 446,325 |
| $y_P$ | 0.5666666 | 297.569 | 446,353.5 |

that case, the location $y^*$ consists of a corner of the feasible segment (e.g. $y^* = 1/2 \pm d$).

The larger the mitigation ratio $\sigma$, the more likely the minimal ecological compensation becomes compatible with the NWO condition and the larger the set of compensation sites where this minimal compensation can be implemented. If not so, a higher compensation has to be implemented by the planner in order to meet the NWO condition. The corresponding additional compensation cost depends crucially on location. When feasible (i.e. $d$ is large enough), the gravity center $y_G$ of marginal utilities minimizes the cost of that compensation.

In our example, choosing where to locate the ecological compensation is not driven by spatial determinants such as land cost, which is assumed to be zero here, but rather by welfare and ecological cost considerations.

### 3.2 Land cost and Inequality

In this Section we show the impact of land costs on the compensation location and the role of the location constraint on inequality.

For this purpose we consider a planner program (9) with land costs as opposed to that of Section 3.1.

The city consists of a density of agents $\mu(s)$ that decreases from left to right and an homogeneous environmental distribution $q(s)$

$$\begin{aligned}\mu(s) &= \mathcal{P}(1-s), \text{ for } 0 \le s \le 1 \text{ with } \mathcal{P} > 0 \\ q(s) &= q > 0, \text{ for } 1/4 \le s \le 3/4\end{aligned}$$

where $\mathcal{P}$ the size of population, see Figure 6.

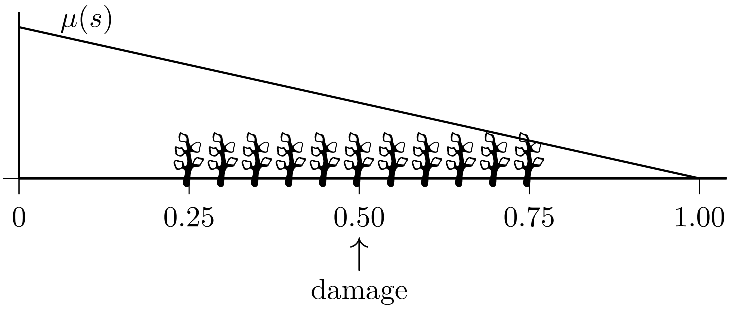

Figure 6: An economy consisting of a continuum of agents $[\mu(s) = \mathcal{P}(1-s)]$ and a constant environment distribution $[q(s) = q > 0$, for $1/4 \le s \le 3/4]$

The land cost $C_2$ is given by[3]

$$C_2(dq_2, y) = dq_2(a\mu(y) + p), \text{ with } a, p > 0$$

where $a$ and $p$ are the variable and fixed cost parameters.

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[3] Here the total cost can be decomposed in $C_1 = \nu dq_2$ and $C_2 = dq_2(a\mu(y) + p)$. So $C(dq_2, y) = ((\nu + p) + a\mu(y))dq_2$.

With a continuum of individuals distributed on $\mathcal{S}$, the change in welfare $d\mathcal{W}$ is now given by

$$\begin{aligned} d\mathcal{W} = &\left(\int_{\mathcal{S}} \partial v/\partial Q_1 \left[1-\tau\left(s-1/2\right)^2\right]\mu(s)\mathrm{d}s\right) dq_1 \\ &+ \left(\int_{\mathcal{S}} \partial v/\partial Q_2 [1-\tau\left(s-y\right)^2]\mu(s)\mathrm{d}s\right) dq_2 \end{aligned}$$

Figure 7 determines the role of land costs on the location of the compensation. It represents the optimal location $y^*$ in terms of the variable and fixed land costs $a$ and $p$. Here we assume that the location constraint in program (9) is not binding so that regime $A_1$ of Section 2.2 applies.[4] In the absence of variable land costs ($a = 0$), just like in regime $A_1$ of Section 3, the location $y^*$ is given by the gravity center $y_G$ of marginal utilities of the environmental good. This is where the ecological cost satisfying the NWO condition is the lowest: compensation in another location than $y_G$ is possible but necessarily more costly.[5] The presence of land costs introduces a trade-off between the ecological and land costs $C_1$ and $C_2$. When the ratio $a/p$ increases, the compensation relocates towards a less populated area where land is cheaper, that is $y^*$ increases with the ratio of the variable and fixed land costs.

As we are getting away from the gravity center $y_G$, the relocation implies a higher ecological cost, see Figure 8. Of course, the relocation towards cheaper zones leads to total compensation cost $C$ to decrease. So, the effect of the variable land cost $a$ is to relocate the compensation away from the gravity center $y_G$ towards less populated areas even if this makes the corresponding ecological cost higher. The effect of the fixed land cost $p$ is to keep the compensation around the gravity center $y_G$ where the ecological cost is lower but the population density higher.

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[4] This situation corresponds to the case of either no location constraint at all or of a large parameter $d$.

[5] From expression (17) in regime $A_1$, we have $y_G = \sum_i \left(\frac{\partial v_i/\partial Q}{\sum_j \partial v_j/\partial Q}\right) s_i = 0.318$.

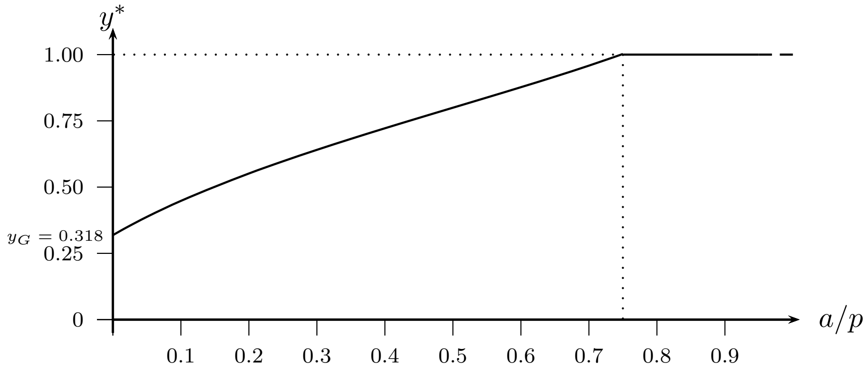

Figure 7: Role of the variable $a$ and fixed $p$ land costs on the optimal location $y^*$ of compensation

Note that the effect of population size $\mathcal{P}$ is to relocate the compensation to less populated areas as a higher $\mathcal{P}$ increases the variable land cost.

Figure 9 represents the impact of the location constraint (12) on the compensation cost $C(dq_2, y)$. When the location constraint is soft (i.e. $d$ large), the location constraint is not binding and regime $A_1$ applies. The lowest ecological compensation meeting the NWO condition is to be implemented in location $y^*$ interior to the segment $S$. Compensating in another location than $y^*$ is possible but necessarily more costly. When the location constraint becomes harder (i.e. $d$ decreases), the location constraint becomes binding, regime $A_1$ ceases to apply and gives rise to regime $A_3$. In that case, the level of ecological compensation increases as the optimal location $y^*$ of regime $A_1$, where the compensation would be lower, is not feasible anymore. So, ordinances restricting the compensation location increase the compensation cost by excluding locations where the corresponding compensation would be lower.

On top of affecting the compensation cost, the location of the compensation affects the inequality across agents. As shown in Section 2.1, agents are

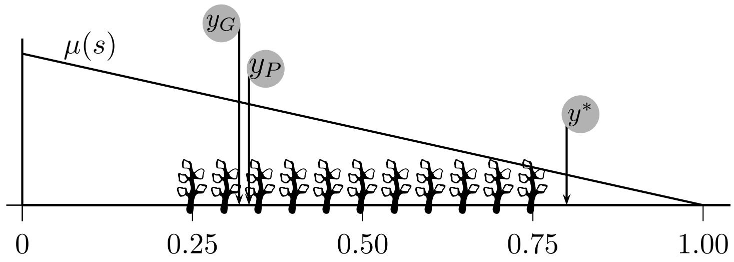

Figure 8: Compensation cost depending on the location of compensation

The compensation in $y = y_P$ favoring population access provides a lower ecological cost than on-site compensation. From Section 3.1, implementing the compensation in the center of gravity $y_G$, of marginal utilities of the environmental good provides the lowest ecological cost. Here, because of land costs, the location $y^*$ that minimizes the total cost is in a cheaper land zone.

The parameter values are as follows: $\mathcal{P} = 10$; $\nu = 1500$; $a = 250$; $p = 500$.

The compensation parameters are:

| | $y$ | $dq_2$ | $C(dq_2, y)$ | $C_1(dq_2)$ | $C_2(dq_2, y)$ |
|---|---|---|---|---|---|
| $y_G$ | 0.3186 | 290.284 | 1,074,921.652 | 435,426 | 639,495.652 |
| $y_P$ | 0.3333 | 290.334 | 1,064,799.945 | 435,501 | 629,298.945 |
| $y^*$ | 0.799577 | 360.053 | 900,513.256 | 540,079.5 | 360,433.756 |

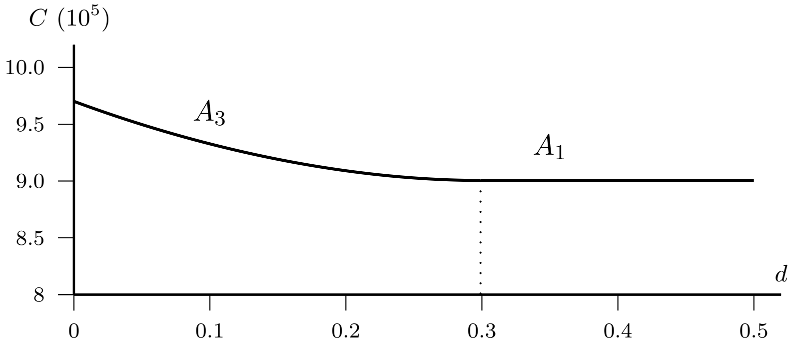

Figure 9: Role of the location constraint on the compensation cost

impacted differently by both the damage and the restoration. This is because both ecological costs and benefits decay with spatial distance. Under the NWO constraint, agents' benefit from the compensation outweights the cost of the damage. However, the NWO condition holds at the aggregate level only, and not at the individual one. As explained in Section 2.2, some agents will gain from the environmental policy while others will lose. Also, it was shown that implementing a policy maintaining the aggregate welfare constant (e.g. like in regime $A_1$) separates spatially winners from losers, see Proposition 1 (iii).

Figure 10 depicts how the inequality across individuals is affected by the tightness of the location constraint. It shows that on-site restoration (i.e. $d = 0$) is neutral in terms of welfare as the utility of each agent remains unchanged, see Proposition 1 (i). When the location constraint becomes softer (i.e. $d$ increases) but still binding, more sites become available so that the corresponding compensation decreases as was shown above. This reduction in ecological cost is accompanied by an increase in the inequality of treatment of individuals. When the location constraint becomes even softer (i.e. $d$ increases further), regime $A_1$ is reached, after which inequality no more increases given that the location $y^*$ remains constant in regime $A_1$. Note that Proposition 1 (iii) is not telling us directly where winners and losers are located, but only that there exists a location $s^*$ that separates them. Here it turns out that $s^* < y_G$.[6] So, in the case of a high variable fixed cost ratio $a/p$, agents located in $s < s^*$ lose while those located in $s > s^*$ win so that in the areas of the damage and the compensation agents win from the policy. However, in the case of a low $a/p$ ratio, it is the converse: agents in the areas of the damage and the compensation lose from the policy.

Figure 11 illustrates the trade-off faced by the policy-maker between the

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[6] Here, $s^* = 0.3143$.

compensation cost and inequality. The Figure results from the combination of Figures 9 and 10. A hard location constraint (i.e. small *d*) has the advantage of making the solution more equal because the ecological compensation is implemented closer to the damage. A soft location constraint (i.e. large *d*) enlarges the set of possible restoration sites allowing for a lower compensation cost at the expense of a higher inequality among the impacted population.

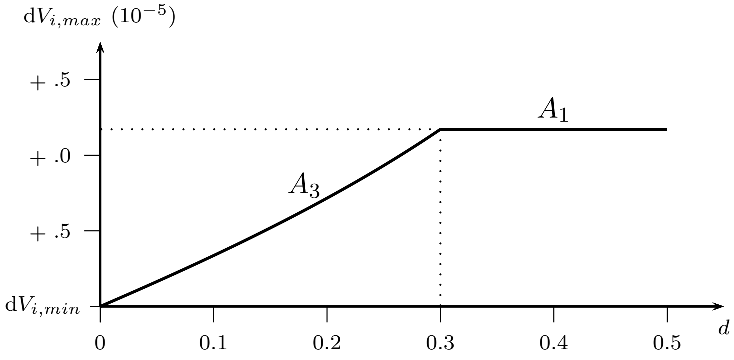

Figure 10: Role of the location constraint on inequality

The inequality across agents (y-axis) is measured by the difference between the largest individual welfare gain ($\mathrm{d}V_{i,max}$) and the largest individual welfare loss ($\mathrm{d}V_{i,min}$).

## 4 Conclusion

In this paper we developed a framework that tackles ecological compensation under both NNL and NWO objectives. Our model shows that in the absence of land cost, locating the compensation in the gravity center of marginal utilities of environmental consumption minimizes the ecological cost. On the other hand, land costs relocate the compensation in less populated areas in order to benefit from cheaper land.

We also show that the constraint on the maximum distance between

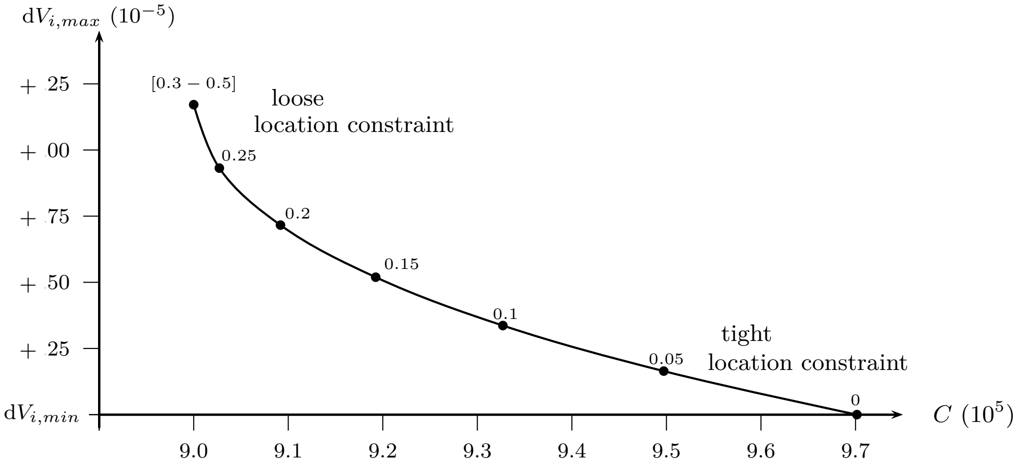

Figure 11: Trade-off between the compensation cost $C$ and inequality

The inequality across agents (y-axis) is measured by the difference between the largest individual welfare gain ($\mathrm{d}V_{i,max}$) and the largest individual welfare loss ($\mathrm{d}V_{i,min}$).

the impact and restoration sites plays an important role on welfare. A soft location constraint on offsets allows a reduction in the ecological cost but increases the inequality across agents. This result shows how the role of the location constraint on the trade-off between ecological cost and inequality. This means that the NWO alone is not enough to limit inequality induced by the policy. A hard location constraint can limit the inequality across agents, which could be key for the acceptance of the development project.

Moreover, there are several potential directions for further research. First, the possibility of restoration in multiple sites could be a natural extension of our work. Even though single location offsets are generally favored, multiple location offsets are also accepted. The possibility of spreading the compensation (sometimes referred to as a "composite offset" (BBOP, 2009))[7]

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[7] According to BBOP (2009) a composite offset is "an offset comprised of activities in more than one location, each of which contributes some but not all of the essential

on the territory could allow the implementation of more suitable solutions.[8] However, in the presence of economies of scale in the restoration activity, it will also be more costly. Second, habitat banking mitigation and pooling could also be studied. Generally preferred to Permittee Responsible Mitigation (PRM) for economic (economies of scale) and efficiency reasons (in ecological term and monitoring), this method gains in popularity. Third, heterogeneity would deserve further study. It may arise from heterogeneous preferences (e.g. in terms of the valuation of the environmental good) or heterogeneous socioeconomic group characteristics (BenDor et al., 2008). Heterogeneity leads to important social implications. In the Chicago region, wetlands are relocated to areas of higher median household income, lower percentage of minorities and higher levels of education. The reverse is observed in North Carolina. The effect on land market should be also explored. Finally, having a better understanding of welfare cumulative impacts resulting from minor land developments taking place over time (Richert et al., 2015) would also be interesting.

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components required to ensure no net loss of biodiversity."

[8] We here neglect the ecological issue associated with such practice.

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# A Appendix 1

- Regime $A_0$ corresponds to situations where $d\mathcal{W} > 0$.

  As $dq_2 = -\sigma dq_1$, the compensation $y$ satisfies

  $$\frac{\sum_i \frac{\partial v_i}{\partial Q_1}\left[1-\tau\left(s_i-1/2\right)^2\right]}{\sum_i \frac{\partial v_i}{\partial Q_2}[1-\tau\left(s_i-y\right)^2]} < \sigma \ ; \ (y-1/2)^2 \leq d^2 \ ; \ \frac{\partial C_2}{\partial y} = 0$$

  In regime $A_0$, all restoration schemes increase the aggregate welfare of individuals compared to the initial one.

The other regimes correspond to situations where the restoration scheme maintains the aggregate welfare at its initial level, that is

$$d\mathcal{W} = \sum_i \frac{\partial v_i}{\partial Q_1}\left[1-\tau\left(s_i-1/2\right)^2\right]dq_1 + \sum_i \frac{\partial v_i}{\partial Q_2}[1-\tau\left(s_i-y\right)^2]dq_2 = 0 \tag{15}$$

- Regime $A_1$: $dq_2 > -\sigma dq_1$ and $(y-1/2)^2 < d^2$.

  As $\lambda_2 = \lambda_3 = 0$, by eliminating the Lagrange multiplier $\lambda_1$ from (13) and (14), we get

  $$\frac{\partial d\mathcal{W}/\partial dq_2}{\partial d\mathcal{W}/\partial y} = \frac{\partial C_1/\partial dq_2 + \partial C_2/\partial dq_2}{\partial C_2/\partial y} \tag{16}$$

  The ratio of the marginal differences in utility equals the ratio of the marginal costs or say differently, since we have:

  $$\frac{\partial d\mathcal{W}/\partial dq_2}{\partial d\mathcal{W}/\partial y} = \frac{-dq_2}{dy}$$

  when $d\mathcal{W}$ =0, this condition also equates the marginal value of distance (i.e. the marginal rate of substitution between distance and quantity of restoration) to the ratio of the marginal cost. This condition rewrites:

  $$\left(\frac{\partial C_1}{\partial dq_2} + \frac{\partial C_2}{\partial dq_2}\right)\frac{\sum_i \frac{\partial v_i}{\partial Q_2}2\tau\left(s_i-y\right)}{\sum_i \frac{\partial v_i}{\partial Q_2}[1-\tau\left(s_i-y\right)^2]} = \frac{\partial C_2}{\partial y} \tag{17}$$

Remaining the aggregated welfare unchanged implies:

$$dq_2 = \frac{\sum_i \frac{\partial v_i}{\partial Q_1}\left[1 - \tau\left(s_i - \frac{1}{2}\right)^2\right]}{\sum_i \frac{\partial v_i}{\partial Q_2}\left[1 - \tau\left(s_i - y\right)^2\right]}(-dq_1)$$

Combining both conditions gives the optimal compensation scheme $(dq_2^\star, y^\star)$ as interior solution the program of the policy-maker.

For the two following regimes, the less costly couple $(dq_2, y)$ compensation scheme ensuring no loss of welfare is located outside the boundaries defined by the rule $(\sigma, d)$. Respecting the rules implies higher cost. In Regime $A_2$ the binding constraint concerns the amount of compensation while in regime $A_3$ the binding constraint relies on the distance constraint.

- Regime $A_2$: $dq_2 > -\sigma dq_1$ and $y = 1/2 \pm d$

In the area defined by the rule $\sigma$, the location of the compensation minimizing the cost does not respect the distance constraint (12). This implies

$$\left|\frac{\partial d\mathcal{W}/\partial dq_2}{\partial d\mathcal{W}/\partial y} - \frac{\partial(C_1 + C_2)/\partial dq_2}{\partial C_2/\partial y}\right| = \lambda_3 \|d\| \tag{18}$$

with $\lambda_3 > 0$. The distance $\|y - \frac{1}{2}\|$ is set at his maximal level $d$ and the amount $dq_2$ of compensation is determined by letting the aggregate welfare unchanged that is:

$$dq_2^{*,-/+} = \frac{\sum_i \frac{\partial v_i}{\partial Q_1}\left[1 - \tau\left(s_i - 1/2\right)^2\right]}{\sum_i \frac{\partial v_i}{\partial Q_2}\left[1 - \tau\left(s_i - 1/2 \pm d\right)^2\right]}(-dq_1)$$

To determine at which side of the damage the compensation will be implemented we have to compare the total cost $C$ obtained for both couples $(dq_2^{*,-}, \frac{1}{2} - d)$ and $(dq_2^{*,+}, \frac{1}{2} + d)$.

- Regime $A_3$: $dq_2 = -\sigma dq_1$ and $(y - 1/2)^2 < d^2$.

  In the area defined by the rule $d$, the amount of compensation minimizing the cost does not respect the ecological constraint (10).

  This case leads to the relation:

$$\frac{\partial d\mathcal{W}/\partial dq_2}{\partial d\mathcal{W}/\partial y} < \frac{\partial (C_1 + C_2)/\partial dq_2}{\partial C_2/\partial y} \tag{19}$$

  The amount $dq_2$ is set at his minimal level $-dq_1\sigma$ and the location $y$ is determined by letting the aggregate welfare unchanged that is:

$$\sum\nolimits_i \frac{\partial v_i}{\partial Q_1}\left[1 - \tau\left(s_i - 1/2\right)^2\right] = \sum\nolimits_i \frac{\partial v_i}{\partial Q_2}[1 - \tau\left(s_i - y\right)^2]\sigma \tag{20}$$

$$\sum\nolimits_i \frac{\partial v_i}{\partial Q_2}\left(s_i - y\right)^2 = \frac{\sum_i \frac{\partial v_i}{\partial Q_2}}{\tau} - \frac{\sum_i \frac{\partial v_i}{\partial Q_1}\left[1 - \tau\left(s_i - 1/2\right)^2\right]}{\sigma\tau} \tag{21}$$

- Regime $A_4$: $dq_2 = -\sigma dq_1$ and $y = 1/2 \pm d$. In this case, neither the location nor the amount of compensation that minimize the cost respect the constraints defined by the rule $(\sigma, d)$ so that both are binded. This regime is a very particular situation where the compensation design $(dq_2, y) = (-\sigma dq_1, 1/2 \pm d)$ enables the policy-maker to maintain the aggregate welfare unchanged.

  Contrary to regime $A_2$ to determine at which side of the damage the compensation will be implemented we only have to compare the cost $C_2$ obtained for both couples $(-\sigma dq_1, \frac{1}{2} - d)$ and $(-\sigma dq_1, \frac{1}{2} + d)$.

# B Appendix 2

The curves (dotted, bold dashed and plain) represent the solutions of the policy-maker program i.e the couple $(dq_2^*, y^*)$ that ensures $d\mathcal{W} = 0$ when the

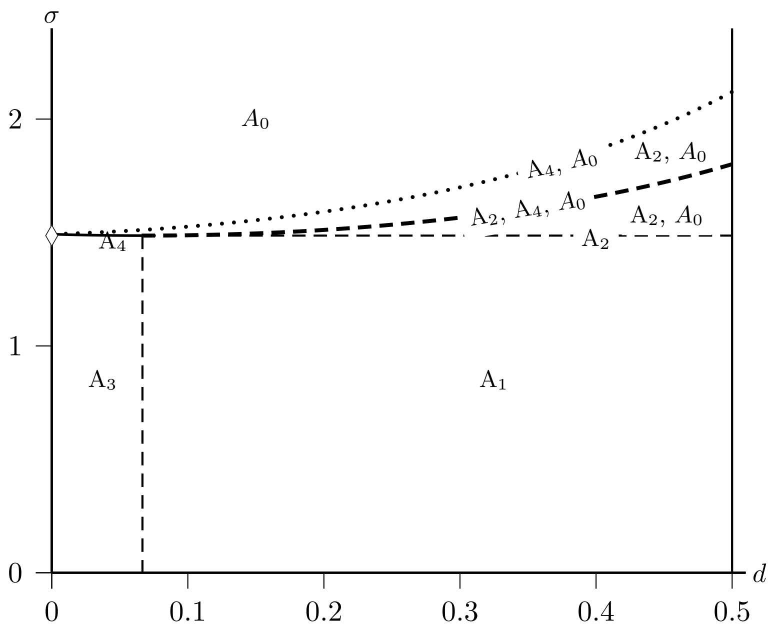

Figure 12: Intervention areas

NNL constraints are binding. The upper curve corresponds to the compensation solutions located on the left side of the damage (between 0 and 0.5) while the lower curve corresponds to the ones located on the right side of the damage. The particular point defined by $d = 0$ characterizes the "on-site compensation". These curves together with the vertical line separate the regimes described in Section 4 resulting from the NNL constraints enforced by the National authority. The vertical line is drawn from the point that generates the lower cost with no welfare loss (intersection of the plain and dashed curves).