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Pascal GASTINEAU, Emmanuelle TAUGOURDEAU

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Abstract

This paper examines a situation where a decision-maker determines the appropriate compensation that should be implemented for a given ecological damage. The compensation can be either or both in monetary and environmental units to meet three goals: i) no aggregate welfare loss, ii) minimization of the cost associated with the compensation, iii) minimal environmental compensation requirement. The findings suggest that - in some cases - providing both monetary and environmental compensation can be the best option. We also emphasize the impact of implementing a minimal environmental compensation constraint especially in terms of equity and cost efficiency.

JEL codes: H43, Q51, Q57

Keywords: Environmental Damage, Compensation, Welfare, Inequity

Résumé

Cet article détermine la compensation optimale qu'un décideur public doit imposer de mettre en place à un pollueur responsable d'un dommage environnemental. La compensation peut être soit monétaire, soit environnementale, soit une combinaison des deux. Elle doit permettre d'atteindre trois objectifs : i) pas de perte de bien-être agrégée, ii) une minimisation du coût associé à la compensation, iii) une compensation écologique minimale. Les résultats montrent que - dans certains cas - une compensation à la fois monétaire et environnementale peut être la meilleure option. Nous insistons également sur les impacts de la mise en oeuvre d'une contrainte de compensation écologique minimale notamment en termes d'équité et d'efficacité.

Codes de Classification JEL : H43, Q51, Q57

Mots clefs : Dommage environnemental, Compensation, Bien-être, Inéquité

1 Introduction

This paper aims to analyze the choice of a policy-maker in charge of determining the scaling of compensation for accidental environmental damage. As a form of compensation, the policy-maker may choose between prescribing a uniform amount of money to each individual and/or restoring a natural resource similar to the damaged one. Given the properties of the injured population (number of agents and heterogeneity in wealth or preferences), the policy-maker pursues a trade-off between two conflicting objectives: equity and efficiency. Here, equity refers to the idea that each agent does not suffer similarly from the damage and does not benefit similarly from the compensation. As a result, the pattern of compensation may either reestablish equity (no change in individual and aggregate welfare) or maintain a certain level of inequity resulting from the damage, since agents support any welfare losses whereas others benefit from welfare gain even if the aggregate welfare remains unchanged. We oppose this equity purpose to an efficiency one, here defined in terms of costs: an efficient compensation will be the one which ensures no aggregate welfare change together with a minimum level of costs.

Decision-makers are aware of the need to prevent and to remedy for environmental damage. This growing environmental awareness was notably embodied in various statutes such as the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Oil Pollution Act of 1990 (OPA) in the U.S. and the Directive 2004/35/EC on Environmental Liability with regard to the prevention and remedying of environmental damage in the European Union. These texts highlight the role that authorities have to play in order to establish a common framework that any polluter may comply with.

In addition, there is a sharp debate on the best way to offset the damages on natural resources and services. Generally, two types of compensation are distinguished: environmental compensation and monetary compensation. The first one consists in providing an environmental restoration or implementing other actions that provide benefit to the restoration. The second one consists in an amount of money paid to the prejudiced people. Within the last couple of years, ecological compensation for the loss of environmental assets (whether the ecological damage is planned or accidental) gained popularity. Moreover, the resource-to-resource (R-R) or service-to-service (S-S) equivalence approaches are considered as a first option by the European Directive. Furthermore, this Directive precludes the use of direct monetary payments to victims.

Non-monetary methods such as equivalency analyses (EA) aim to implement actions that provide natural resources and/or services of the same type, quality and quantity as those of damaged ones (i.e. 'in-kind' compensation) (Dunford et al., 2004; Zafonte

and Hampton, 2007).¹ These techniques determine the necessary compensation to offset past, current and future damages without directly valuing them in economic terms, by equalizing the amount of loss and gain of resources and services over time. To do so, they use a selection of *proxies* (metrics) representing the most important ecosystem services (English et al., 2009).² The presupposed advantages of S-S and R-R methods (i.e. "no net loss" principle) stand in contrast with drawbacks associated with well-known monetary valuation techniques. However, none of the methods are perfect and the reliability of the equivalency methods to measure the environmental damage and/or scale and to determine the appropriate compensation is under discussion. On the ecological side, while stressing the usefulness of the equivalency methods, Dunford et al. (2004) also emphasize their weaknesses: a high degree of uncertainty concerning estimates of compensatory restoration and their difficulty to consider complex impacts and phenomenon. Many attempts are made to improve ecological equivalency methods by focusing on specific issues: uncertainty (Moilanen et al., 2009), temporal dynamics (Bendor, 2009) or spatial analysis (Bruggeman et al., 2005; Bruggeman et al., 2008).³ On the economic side, Zafonte and Hampton (2007) suggest that, under certain conditions, resource equivalency analysis (REA, i.e. R-R) provides an acceptable approximation of compensating wealth. By contrast, many authors argue that ecological equivalence specified in biophysical equivalents could fail to provide a satisfactory compensation in a welfare perspective (Flores and Thacher, 2002). Flores and Thacher (2002) also stress the potential economic inefficiencies that could occur when the money component is excluded from the analysis and thus recommend a case by case determination of the adequate compensation that would better consider distributional issues associated with compensatory projects.

In this paper, we go further in the analysis of compensation by showing that environmental and monetary compensations are not antinomic and may be implemented simultaneously. Due to heterogeneous individual preferences (or income), compensation can result in some losers and winners relative to their initial (pre-injury or pre-project) utility. Therefore, careful attention must be paid to the characteristics and the size of the population affected by an environmental damage when determining the compensation to implement. Thus, we study how the decision-maker can combine both of them in order to determine the adequate compensation at minimal cost. Of course, this analysis is only relevant when an ecological compensation with a similar natural resource or service is

¹This option is preferred to 'out-of-kind' compensation in which the adverse impacts to one resource (or habitat) are mitigated through the creation, restoration, or enhancement of another resource (or habitat).

²When equivalency approaches can not be used, valuation scaling approaches (value-to-cost and value-to-value) are recommended.

³See Quétier and Lavorel (2011) for a synthesis.

feasible.

In line with Cole (2012), this paper allows us to investigate equity and cost efficiency issues associated with an enforced ecological compensation. We depart from Cole by considering equity issues for the prejudiced population instead of considering the society on its whole. Moreover, contrary to Cole (2012) who compares both compensation schemes, we allow for a mixed compensation in which both of the compensatory methods may be implemented at the same time.

To reach our goal, we propose a simple model of an economy with two goods, a composite good and a natural resource. In this model, we determine which type of compensation the decision-maker may enforce the polluter to implement given the magnitude of the damage, the number and the characteristics of the prejudiced agents, and the cost associated with each compensation scheme. Since we do not introduce any incentives in our model (prevention, mitigation), we focus on accidental or unanticipated damages. Moreover, our model refers to marginal damages in the sense that they do not alter the agents' preferences. For instance, these damages could be either an accidental release of hazardous-substance into the environment (soil or river) or unanticipated temporary damages to verges and footpaths due to road building processes. In these cases, ecological compensation could consist in replanting plants or restoring fish streams. To determine the optimal compensation scheme, the decision-maker pursues three goals:

- no welfare loss for the whole population impacted by the environmental damage;
- minimization of the cost of the compensation scheme, in line with recommendation of "reasonable cost" of the European directive 2004/35/EC;
- environmental compensation cannot be less than a given quantity defined by an EA criterion.

In doing so, the objective of the present paper is in line with the objective of the European Directive 2004/35/EC, namely "to establish a common framework for the [...] remedying of environmental damage at a reasonable cost to society". We consider an heterogeneous population and examine the appropriate compensation for the case of a log linear utility function. We show that the eligible compensation mechanism (which meets the three conditions) varies with the magnitude of the environmental impact, the design of heterogeneity and the number of agents that need compensation. We also show that enforcing a minimal non-monetary compensation not only implies ecological effects but also impacts the equity and cost efficiency issues associated with the compensation. More precisely, when the constraint is binding, an ecological constraint can reduce inequity at the expense of a rise in cost inefficiency.

The article is organized as follows. Section 2 presents the model. Optimal compensation schemes are derived in Section 3 according to two types of population heterogeneity:

heterogeneity in preferences for goods and heterogeneity in wealth. The last section concludes and suggests future directions for additional work.

2 The Model

We consider a two-period economy composed by n heterogeneous agents in which the agent i 's lifetime utility is given by:

$$U_i = \delta^t u_{it}(X_{it}, q_t) \quad \text{with } i = 1, \dots, n \text{ and } t = 1, 2$$

where u_{it} is the agent i 's utility in period t , δ is the time-preference rate, X_{it} measures the agent i 's private consumption and q_t the level of the environmental good or service measured in physical units at time t .

The "lifetime" indirect utility of agent i is given by:

$$V_i = v_i(W_i, q_1, q_2) \quad (1)$$

where W_i stands for the agent i 's intertemporal income which is exogenously given.

We assume that the natural resource is accidentally damaged in the first period and compensated in the second one according to a compensating rule decided by a policy-maker. The compensation is twofold: a monetary compensation identical for each agent whatever his type, and an environmental compensation.

Leaving the utility of an individual unchanged following an environmental damage implies:

$$dV_i = \frac{\partial v_i}{\partial W_i} dW_i + \frac{\partial v_i}{\partial q_1} dq_1 + \frac{\partial v_i}{\partial q_2} dq_2 = 0 \quad (2)$$

where $dq_1 < 0$ stands for the accidental damage and $dq_2 > 0$, the environmental compensation while dW_i is the monetary compensation.

The individual willingness to accept a monetary compensation for the environmental damage is defined as:⁴

$$WTA_i^W = \left(\frac{\partial v_i}{\partial q_1} / \frac{\partial v_i}{\partial W_i} \right) (-dq_1) \quad (3)$$

It expresses how much money the individual i is willing to accept in exchange for the loss (dq_1) .

Using the same reasoning it is possible to express a WTA in terms of environmental unit:

$$WTA_i^q = \left(\frac{\partial v_i}{\partial q_1} / \frac{\partial v_i}{\partial q_2} \right) (-dq_1).$$

⁴ WTA_i^W is the value of dW_i obtained by equation (2) stating that $dq_2 = 0$. WTA_i^W is identified with the compensating variation. The absence of environmental damage is the reference state for most people. WTA is the better measure to use (Knetsch, 2007).

We denote by $\mathcal{W} = \sum_{i=1}^n V_i$ the aggregate welfare of the n victims.

When determining the compensation pattern, the decision-maker aims to account for three criteria: minimize the costs involved by the implementation of the whole compensation, leave the aggregate welfare unchanged and comply with a minimal environmental compensation requirement.

The program of the decision-maker writes:

$$\min_{MC, dq_2} C(dq_2, MC) \quad (4)$$

subject to

$$d\mathcal{W} = 0 \quad (5)$$

$$dq_2(1 + \sigma)^{-1} \geq -dq_1 \quad (6)$$

$$MC \geq 0 \quad (7)$$

where $MC = dW_i \forall i$ is the monetary compensation, dq_2 the environmental compensation, and C is the cost function associated to the compensation. \mathcal{W} stands for the aggregate welfare and constraint (5) characterizes the fact that the compensating policy must leave the aggregate welfare unchanged. Constraint (6) specifies that the environmental compensation must at least be equal to a given value larger than the initial damage. This value corresponds to the one that would be determined when using Equivalence Approaches (EA) in their simplest formulation, i.e. the "discounted" environmental gain equalizes the "discounted" environmental loss. In this expression, σ is the discount rate associated to the EA constraint.⁵ Note that no ex-post redistribution of monetary compensation between losers and gainers is feasible.

The Lagrangian associated to this program is given by

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

where λ_1 is the Lagrangian multiplier associated to constraint (5), λ_2 to (6) and λ_3 to (7).

The conditions arising from solving the Lagrangian are:

$$\frac{\partial \mathcal{L}}{\partial MC} = -\frac{\partial C}{\partial MC} + \lambda_1 \frac{\partial d\mathcal{W}}{\partial MC} + \lambda_3 = 0 \quad (8)$$

$$\frac{\partial \mathcal{L}}{\partial dq_2} = -\frac{\partial C}{\partial dq_2} + \lambda_1 \frac{\partial d\mathcal{W}}{\partial dq_2} + \lambda_2 = 0 \quad (9)$$

⁵The determination of the appropriate discount rate is still controversial in the literature. In practice, a 3 percent rate is recommended for equivalency analysis in the US (NOAA, 1999).

$$\frac{\partial \mathcal{L}}{\partial \lambda_1} = d\mathcal{W} = \sum_{i=1}^n dv_i = 0 \quad (10)$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_2} = dq_2(1 + \sigma)^{-1} + dq_1 \geq 0 \quad (11)$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_3} = MC \geq 0 \quad (12)$$

Four regimes can be distinguished from this program, that determine the pattern of the compensation:

- regime 1: (monetary compensation $[\mathcal{R}_1]$) : $\lambda_2 > 0; \lambda_3 = 0 \Rightarrow dq_2 = -dq_1(1 + \sigma); MC > 0$. In this case both compensations are implemented but the level of the environmental compensation being the minimal one defined by the EA constraint, we call this case "monetary compensation". Without the EA constraint, the environmental compensation would be between 0 and $-dq_1(1 + \sigma)$. This case leads to the relation

$$\left[\frac{\partial d\mathcal{W}}{\partial MC} / \frac{\partial d\mathcal{W}}{\partial dq_2} \right] > \left[\frac{\partial C}{\partial MC} / \frac{\partial C}{\partial dq_2} \right] \quad (13)$$

One unit spent on monetary compensation generates more welfare than one unit spent on environmental compensation. Then the decision-maker should favor monetary compensation in order to compensate at minimal cost.

- regime 2: (mixed compensation $[\mathcal{R}_2]$): $\lambda_2 = \lambda_3 = 0 \Rightarrow dq_2 > -dq_1(1 + \sigma); MC > 0$. There exists a couple of compensation tools (MC^*, dq_2^*) such that:

$$\left[\frac{\partial d\mathcal{W}}{\partial MC} / \frac{\partial d\mathcal{W}}{\partial dq_2} \right] = \left[\frac{\partial C}{\partial MC} / \frac{\partial C}{\partial dq_2} \right] \quad (14)$$

The ratio of the marginal differences in utility equals the ratio of the marginal costs. In other words, there exists a couple (MC^*, dq_2^*) such that the welfare that we get from an additional unit of MC or dq_2 per fund spent is the same.

- regime 3: (environmental compensation $[\mathcal{R}_3]$): $\lambda_2 = 0; \lambda_3 > 0 \Rightarrow dq_2 > -dq_1(1 + \sigma); MC = 0$, which implies

$$\left[\frac{\partial d\mathcal{W}}{\partial MC} / \frac{\partial d\mathcal{W}}{\partial dq_2} \right] < \left[\frac{\partial C}{\partial MC} / \frac{\partial C}{\partial dq_2} \right] \quad (15)$$

This is the opposite case to regime 1. The decision-maker should promote environmental compensation.

- regime 4: (minimal compensation $[\mathcal{R}_4]$) $\lambda_2 > 0; \lambda_3 > 0 \Rightarrow dq_2 = -dq_1(1 + \sigma); MC = 0$ For $\lambda_2 > 1$ and $\lambda_3 > 0$ there is no optimal solution. There is a 'second best' solution such that there is no monetary compensation and minimal environmental compensation. For \mathcal{R}_4 , $dW > 0$. This regime does not fulfill constraint (5).

3 Application

We now specify both the cost and the utility functions. We assume a log linear utility function of the form

$$U_{it} = \alpha_i \ln X_{it} + (1 - \alpha_i) \ln q_t$$

where α_i is the agent i 's weight for the consumption bundle in utility.

The agent i 's lifetime utility function rewrites:

$$U_i = \alpha_i \ln X_{1i} + (1 - \alpha_i) \ln q_1 + \delta \alpha_i \ln X_{2i} + \delta(1 - \alpha_i) \ln q_2$$

Assuming that agents can lend in a perfect capital market, the intertemporal budget constraint writes $W_i = X_{i1}(1 + r) + X_{i2}$ where r is the interest rate. The arbitrage in private consumption between period 1 and 2 gives the relation between both private consumptions $\frac{X_{2i}}{X_{1i}} = \delta_i(1 + r)$ that combined with the intertemporal budget constraint gives the demand for private goods so that the indirect utility writes

$$V_i = \alpha_i \ln \left(\frac{W_i}{(1 + \delta)(1 + r)} \right) + (1 - \alpha_i) \ln q_1 + \delta \alpha_i \ln \left(\frac{\delta}{(1 + \delta)} W_i \right) + \delta(1 - \alpha_i) \ln q_2 \quad (16)$$

Finally, we assume that the cost function for compensation is given by:

$$C(dq_2, MC) = nMC + a(dq_2)^b$$

The cost of compensation is decomposed in two parts: a lump sum part (nMC) which characterizes the monetary compensation granted uniformly to all agents, and a second part which is proportional to the restoration and depends on the type of the nature that should be restored ($b > 0$ can be either ≥ 1 or < 1). Note that with the cost function we use, it is straightforward that the program is quasiconvex in MC , whereas it is quasiconvex in dq_2 for $b \geq 1$.

3.1 Heterogeneity in preference for goods

3.1.1 Optimal compensation scheme

We assume that agents are only differentiated by their preference for goods, α_i . The aggregate welfare function writes:

$$\mathcal{W} = \mathcal{W}[v_1(W, q_1, q_2), \dots, v_n(W, q_1, q_2)]$$

It can be rewritten as

$$\begin{aligned} \mathcal{W} &= \sum_{i=1}^n v_i(W, q_1, q_2) \\ &= n\bar{\alpha} \ln \left(\frac{W}{(1+\delta)(1+r)} \right) + n(1-\bar{\alpha}) \ln q_1 + n\delta\bar{\alpha} \ln \left(\frac{\delta}{(1+\delta)} W \right) + n\delta(1-\bar{\alpha}) \ln q_2 \end{aligned}$$

where $\bar{\alpha} = \frac{1}{n} \sum \alpha_i$ is the mean preference for the private good.

Condition (5) becomes

$$d\mathcal{W} = (1+\delta) \frac{n\bar{\alpha}}{W} MC + \frac{n(1-\bar{\alpha})}{q_1} dq_1 + n\delta \frac{(1-\bar{\alpha})}{q_2} dq_2 = 0 \quad (17)$$

so that

$$MC = W \frac{(1-\bar{\alpha})}{\bar{\alpha}(1+\delta)} \left(\frac{-dq_1}{q_1} - \frac{\delta}{q_2} dq_2 \right) \quad (18)$$

or

$$dq_2 = \left(\frac{-dq_1}{q_1} - MC \frac{\bar{\alpha}(1+\delta)}{(1-\bar{\alpha})W} \right) \frac{q_2}{\delta} \quad (19)$$

Given this relation between both compensations, we are able to distinguish two different cases according to the value of b : $b \geq 1$ or $b < 1$.

Proposition 1 *For $b \geq 1$ four solutions can emerge from the program of the decision-maker*

1. $dq_2 = -dq_1(1+\sigma)$ and $MC = -dq_1 W \frac{(1-\bar{\alpha})}{\bar{\alpha}(1+\delta)} \left(\frac{1}{q_1} - \frac{\delta}{q_2}(1+\sigma) \right)$ iff $n < \underline{n}$ and $(1+\sigma) < \frac{q_2}{q_1} \frac{1}{\delta}$ (regime 1)

with

$$\underline{n} = ab \frac{(1+\delta)\bar{\alpha}}{(1-\bar{\alpha})W} \frac{q_2 (- (1+\sigma) dq_1)^{b-1}}{\delta}$$

2. $dq_2 = \left(\frac{(1-\bar{\alpha})nW\delta}{\bar{\alpha}(1+\delta)q_2ab} \right)^{\frac{1}{b-1}}$ and $MC = \frac{(1-\bar{\alpha})W \left(\frac{-dq_1}{q_1} \right)}{(1+\delta)\bar{\alpha}} - \left(\frac{\delta(1-\bar{\alpha})W}{q_2(1+\delta)\bar{\alpha}} \right)^{\frac{b}{b-1}} \left(\frac{n}{ab} \right)^{\frac{1}{b-1}}$ iff $\bar{n} > n > \underline{n}$ (regime 2)

with

$$\bar{n} = ab \frac{(1+\delta)\bar{\alpha}}{(1-\bar{\alpha})W} \left(\frac{q_2}{\delta} \right)^b \left(-\frac{dq_1}{q_1} \right)^{b-1}$$

3. $MC = 0$ and $dq_2 = -\frac{q_2}{q_1} \frac{1}{\delta} dq_1$ iff $n > \bar{n}$ and $(1 + \sigma) < \frac{q_2}{q_1} \frac{1}{\delta}$ (regime 3)

4. $MC = 0$ and $dq_2 = -dq_1(1 + \sigma)$ iff $(1 + \sigma) > \frac{q_2}{q_1} \frac{1}{\delta}$ (regime 4)

Proof. See Appendix A.

Proposition 1 highlights the four different regimes of compensation scheme for $b \geq 1$.

Regime 4 is the one which corresponds to the seminal EA compensation. Without EA constraint, condition (6) does not hold and regime 4 does not exist anymore. In this regime, the marginal rate of substitution between the environmental good in period 1 and 2 $\left(\frac{\partial v_i}{\partial q_1} / \frac{\partial v_i}{\partial q_2} = \frac{q_2}{q_1} \frac{1}{\delta}\right)$ is low so that a very low level of dq_2 is required to compensate the loss of one unit of q_1 . In this regime, the minimum compensation $MC = 0$ and $dq_2 = -dq_1(1 + \sigma)$ is then higher than the required one. Due to the constraint, this scheme of compensation does not fulfill the welfare condition since it implies a higher level of aggregate welfare than required i.e. $d\sum V_i > 0$. The occurrence of this regime crucially depends on the discount rate in the EA constraint. Especially, if we consider that the discount rate σ equals the time preference rate ($\delta = \frac{1}{1+\sigma}$) then this regime applies as soon as $q_2 < q_1$ which seems to be consistent in case of a damage in period 1.

The three other regimes check the welfare condition. They occur when the discount rate is relatively high compared to the marginal rate of substitution between the environmental good in period 1 and 2 $\left(\frac{q_2}{q_1} \frac{1}{\delta} > (1 + \sigma)\right)$. The compensation schemes (regime 1, 2 or 3) depend on the number of victims. The explanation lies in the cost function and the nature of the goods which characterizes the properties of both types of compensation: the monetary compensation is granted uniformly to all victims so that the cost of such compensation is linearly increasing with the number of agents. Conversely, the amount of environmental compensation is fixed whatever the number of agents it benefits, so that its cost is stable with n . Intuitively, it is more relevant to implement a monetary compensation for a low level of n and an environmental compensation for a high level of n .

As Figure 1 shows, for a low n ($n < \underline{n}$) [regime 1], the best compensation scheme is that which implements the minimum level required of environmental compensation together with the value of the monetary compensation that leaves the aggregate welfare unchanged.⁶ The level of MC is fixed whatever the level of $n \in [0, \underline{n}]$. This is due to the EA constraint that implies a higher environmental compensation than the level that would be optimal without any constraint. For $n \geq \underline{n}$, the EA constraint plays no role as $dq_2 \geq -dq_1(1 + \sigma)$. The value of \underline{n} increases with $\bar{\alpha}$ and $(-dq_1)$ and decreases with W

⁶The following parameter set was used for numerical simulation: ($W = 372000$, $\bar{\alpha} = 0.8$, $\delta = 0.67$, $q_1 = 10000$, $q_2 = 10000$, $dq_1 = -200$, $a = 300$, $b = 1.75$, $\sigma = 0.34$). Natural resource recovery is achieved in one period, i.e. $q_1 = q_2$, each period lasting 10 years. dq_1 depicts a temporary loss.

and δ . An agent who values more the future expects a higher level of compensation so that the switch from regime 1 to regime 2 occurs for a lower n . Conversely a lower weight for the environmental good in the utility (high $\bar{\alpha}$) implies a lower need for compensation and the limit between both regimes is shifted for a higher n . Finally, a higher damage directly increases the EA constraint and consequently shifts the limit for a higher n .

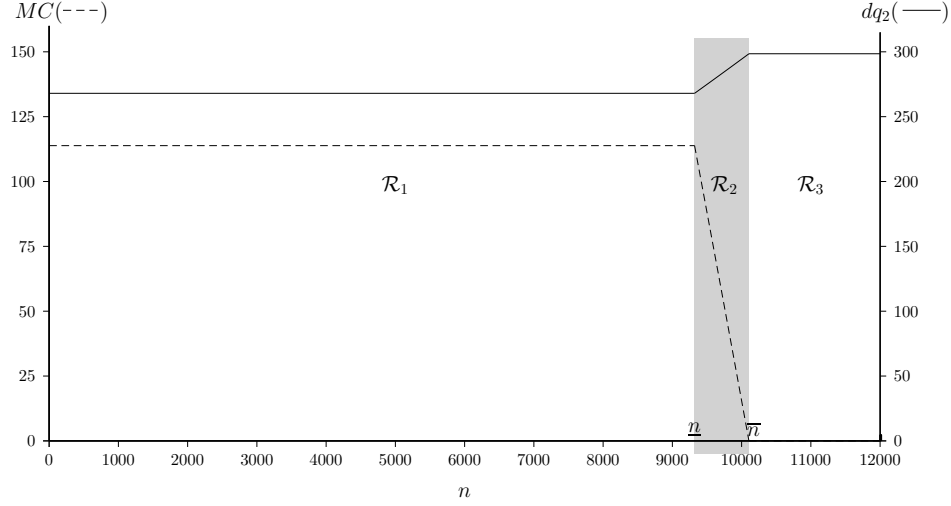


Figure 1: Optimal Compensation Scheme as a function of the population size

When $n \in [\underline{n}, \bar{n}]$ [regime 2], the EA constraint is still not bound and the level of dq_2 increases with n . This implies a corresponding decrease of the monetary compensation since MC weighs more and more relatively to dq_2 in the cost function. This trend lasts until it is no longer useful to use any monetary compensation that has become too heavy in the cost function. In the last regime ($n > \bar{n}$) [regime 3], the environmental compensation is the only compensating tool that is used to leave the society's welfare unchanged. For the same reasons as the value of \underline{n} , \bar{n} increases with $\bar{\alpha}$ and $(-dq_1)$, and decreases with W and δ .

For regime 2 which implies the use of both types of compensation ($n \in [\underline{n}, \bar{n}]$), the comparative static analysis gives the following relations:⁷

$$\frac{\partial(dq_2)}{\partial \bar{\alpha}} < 0; \frac{\partial(dq_2)}{\partial W} > 0; \frac{\partial(dq_2)}{\partial \delta} > 0; \frac{\partial(dq_2)}{\partial(-dq_1)} = 0$$

and

$$\left. \begin{aligned} \frac{\partial MC}{\partial(-dq_1)} > 0; \frac{\partial MC}{\partial \delta} < 0; \frac{\partial MC}{\partial \bar{\alpha}} > 0 \\ \frac{\partial MC}{\partial W} < 0 \end{aligned} \right\} \iff n > \bar{n} \left(\frac{b-1}{b} \right)^{b-1}$$

⁷See Appendix B.

The compensation scheme is obtained by equating the ratio of the marginal variations of utilities $\left(\frac{\partial W}{\partial MC} / \frac{\partial W}{\partial dq_2} = \frac{(1+\delta)\bar{\alpha}q_2}{W\delta(1-\bar{\alpha})}\right)$ to the ratio of the marginal costs $\left(\frac{\partial C}{\partial MC} / \frac{\partial C}{\partial dq_2} = \frac{n}{ab(dq_2)^{b-1}}\right)$. Note that none of the ratios are affected by a change in MC while an increase of dq_2 decreases the ratio of the marginal costs.

The impact of the environmental damage $(-dq_1)$ on the monetary compensation is obviously positive. A higher damage implies a higher compensation. Nevertheless, it is surprisingly null on the environmental compensation. Indeed, the intuitive positive effect of $(-dq_1)$ on dq_2 is offset by the trade-off effect between MC and dq_2 . Why does this trade-off effect not impact MC ? The explanation comes from the cost function. The marginal cost of compensation with respect to MC is constant and equal to n whatever the level of MC while the marginal cost of compensation with respect to dq_2 is increasing with dq_2 . Following a rise in $(-dq_1)$ the higher level of dq_2 due to the environmental willingness to accept increases the weight of dq_2 in the cost function and implies a trade-off in favor of MC which diminishes the required level of dq_2 . As a result, following an increase of $(-dq_1)$, the monetary compensation increases and the environmental compensation remains unchanged.⁸ Note that in regime 3, when MC is reduced to zero, since there is no trade-off between both types of compensation, the level of dq_2 is positively linked to the environmental damage.

The impact of wealth on compensation is twofold. On the one hand, the intertemporal wealth impacts negatively the ratio of the marginal variation of utilities while it does not affect the ratio of the marginal costs. Maintaining both ratios equal implies that a higher level of wealth induces a higher environmental compensation. On the other hand, the level of wealth impacts the monetary compensation through two channels. The direct effect can be deduced from the willingness to accept derived from Equation (17) with $dq_2 = 0$. A richer agent is inclined to require a higher amount of MC to compensate the environmental damage than a poor agent.⁹ The indirect effect comes from the trade-off between both compensations. A rise in dq_2 tends to diminish the level of MC and this decrease is stronger with a higher W . Since the intertemporal wealth has a positive effect on dq_2 , this indirect effect is negative on MC . The whole effect on MC depends on which effect dominates. The negative direct effect wins for a sufficiently high number of agents. As we have shown, a rise in n modifies the compensation scheme in favor of dq_2 with respect to MC while it does not modify the willingness to accept. A higher weight of dq_2 leads to a direct effect on MC dominated by the indirect effect through dq_2 . The whole impact of wealth on MC is then negative.

The impact of the time preference is less ambiguous. The equalization of the ratios

⁸The offset of both effects on dq_2 comes from the specification of both the utility function and the cost function.

⁹The impact of $-dq_1$ on MC is given by the relation $\frac{dMC}{(-dq_1)} = \frac{(1-\bar{\alpha})W}{(1+\delta)\bar{\alpha}q_1}$

links positively δ with dq_2 : the more the second period is valued in the utility, the higher is the level of required environmental compensation. The effect of δ on MC is also unambiguously negative. The direct effect through the willingness to accept is negative: the valuation of the damage in period one is lower with a higher δ so that the required monetary compensation is lower. In addition, the positive effect of δ on dq_2 impacts negatively the monetary compensation.

The mean preference for the private good ($\bar{\alpha}$) is negatively linked to dq_2 in the equality of the marginal utilities ratio to the marginal costs ratio. The lower the weight of the environmental good in the utility (high $\bar{\alpha}$), the lower the effect of environmental damage on the utility and the lower the required environmental compensation. Similarly to the impact of wealth, there are two effects of opposite sign of the monetary compensation. The direct effect is negative while the effect through dq_2 is positive. Again, the whole effect depends on the value of n . A high level of n implies a high weight of dq_2 and the positive effect through dq_2 dominates the direct negative effect.

Let us now look at the optimal compensation without any EA constraint. In this case, regimes 1 and 4 disappear and only regimes 2 and 3 remain. Under regime 2, the compensation scheme leads to an increasing level of dq_2 and a decreasing level of MC as stressed by Figure 2.

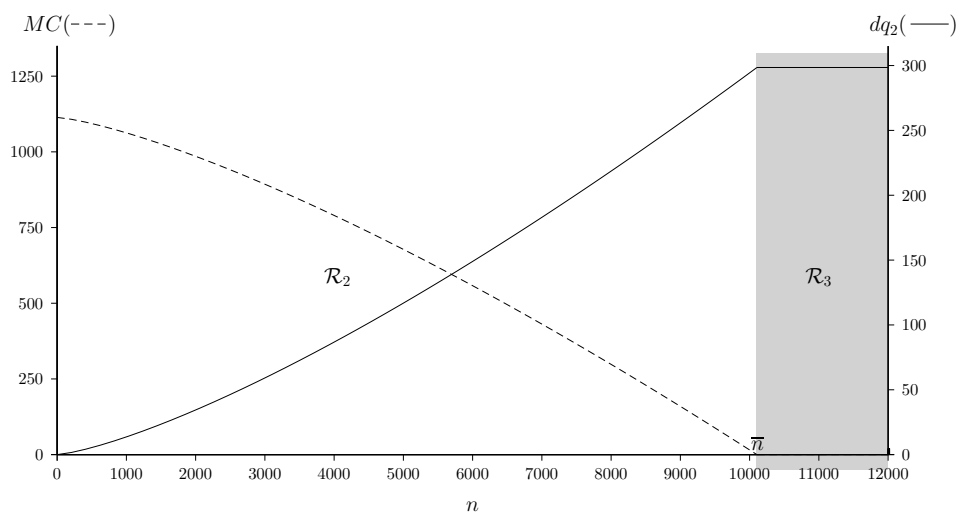


Figure 2: Compensation scheme without EA constraint (CS_0)

Under both regimes $dq_2 > 0$ whatever the value of n . Nevertheless the level of environmental compensation is very low ($dq_2 \approx 0$) for small n .

As mentioned in the proof of the previous proposition, when $b < 1$, the cost function is concave which implies that the compensation which is implemented is a corner solution of the problem of cost minimization.

Proposition 2 *For $b < 1$, three solutions can emerge from the program of the decision-maker*

1. $dq_2 = -dq_1(1 + \sigma)$ and $MC = -dq_1 W \frac{(1-\bar{\alpha})}{\bar{\alpha}(1+\delta)} \left(\frac{1}{q_1} - \frac{\delta}{q_2}(1 + \sigma) \right)$ iff $(1 + \sigma) < \frac{q_2}{q_1} \frac{1}{\delta}$ and $n < \hat{n}$ (regime 1)

$$\text{with } \hat{n} = \frac{a(-dq_1)^{b-1} \left(\left(\frac{q_2}{q_1} \frac{1}{\delta} \right)^b - (1 + \sigma)^b \right)}{W \frac{(1-\bar{\alpha})}{\bar{\alpha}(1+\delta)} \frac{\delta}{q_2} \left(\frac{q_2}{q_1} \frac{1}{\delta} - (1 + \sigma) \right)}$$

2. $MC = 0$ and $dq_2 = -\frac{q_2}{q_1} \frac{1}{\delta} dq_1$ iff $(1 + \sigma) < \frac{q_2}{q_1} \frac{1}{\delta}$ and $n > \hat{n}$ (regime 3)

3. $MC = 0$ and $dq_2 = -dq_1(1 + \sigma)$ iff $(1 + \sigma) > \frac{q_2}{q_1} \frac{1}{\delta}$ (regime 4)

Proof. See Appendix C.

With $b < 1$ the limit between regime 1 and 3 is given by \hat{n} . As previously explained, a higher (resp. lower) level of n goes in favor of the use of environmental (resp. monetary) compensation. Contrary to the case with $b > 1$, there is no more optimal mixed compensation and regime 1 switches directly to regime 3 with the increase in n since only corner solutions enable to minimize the cost.

3.1.2 Cost and welfare analyses

In this section, we investigate the cost associated with alternative compensation schemes and their welfare implications. We concentrate on cases where $b > 1$. First recall that for a slightly high discount rate, the compensation scheme reduces to regime 4 (no monetary compensation and a minimal environmental compensation driven by the EA constraint whatever the level of n). The change of the aggregate welfare is positive as well as every individual welfare variation.¹⁰ The agent that values the environmental good the most (lowest α_i) wins the most. We denote this compensation scheme by CS_{EA} and the optimal Compensation Scheme given by Proposition 1 by CS^* . We also denote by CS_0 the scheme that combines monetary and environmental compensation without EA constraint. As already seen, the compensation scheme (CS_0) is composed of two regimes characterized by:

- $dq_2 = \left(\frac{(1-\bar{\alpha})nW\delta}{\bar{\alpha}(1+\delta)q_2ab} \right)^{\frac{1}{b-1}}$ and $MC = \frac{(1-\bar{\alpha})W \left(\frac{-dq_1}{q_1} \right)}{(1+\delta)\bar{\alpha}} - \left(\frac{\delta(1-\bar{\alpha})W}{q_2(1+\delta)\bar{\alpha}} \right)^{\frac{b}{b-1}} \left(\frac{n}{ab} \right)^{\frac{1}{b-1}}$ iff $\bar{n} > n$ (regime 2)

¹⁰ $dV_i = (1 - \alpha_i)dq_1 \left[-\frac{1}{q_1} + \frac{\delta}{q_2}(1 + \sigma) \right] > 0 \quad \forall i \quad \text{under regime 4.}$

- $MC = 0$ and $dq_2 = -\frac{q_2}{q_1} \frac{1}{\delta} dq_1$ iff $n > \bar{n}$ (regime 3)

Finally, we introduce two other compensation schemes that could be referred as benchmark cases: Full environmental compensation (CS_{Fenv}) and Full monetary compensation (CS_{Fmon}). They are defined as follows:

- (CS_{Fenv}): $dq_2 = -\frac{q_2}{q_1} \frac{1}{\delta} dq_1$ and $MC = 0$
- (CS_{Fmon}): $MC = W \frac{(1-\alpha)}{\alpha(1+\delta)} \left(\frac{-dq_1}{q_1} \right)$ and $dq_2 = 0$

Note that CS_{Fenv} and CS_{Fmon} are fixed and do not vary with n .

Figure 3 shows the costs associated with these compensation schemes (CS_0 , CS_{Fenv} , CS_{Fmon}) and with CS^* (composed of regimes 1, 2 and 3).¹¹ From a cost minimization perspective, we observe that for $n < \underline{n}$ the compensation scheme described by regime 1 (thick line) is not the least costly possible option. The EA constraint imposes an additional cost. Without this constraint, there would exist two better options: Full monetary compensation (dashed line) for $n < (\underline{n}/b)$ and monetary compensation associated with environmental compensation at a level lower than $(-dq_1)(1+\sigma)$ (dotted line) for $n < \underline{n}$.¹² For $n \geq \underline{n}$, CS^* is the less costly option (jointly with CS_0 for $\underline{n} \leq n \leq \bar{n}$ and with CS_0 and CS_{Fenv} for $n \geq \bar{n}$).

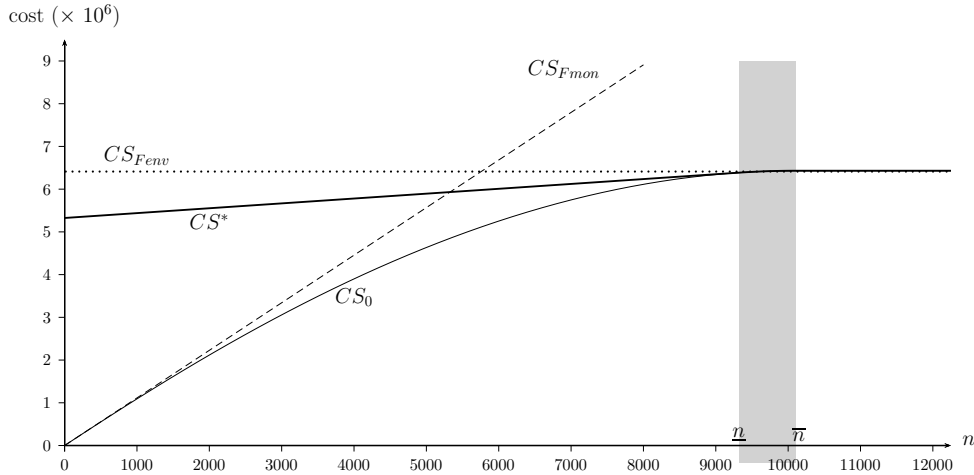


Figure 3: Costs associated with the four compensation schemes when $1 + \sigma < \frac{q_2}{q_1} \frac{1}{\delta}$

If either regimes 1, 2 and 3 leave the aggregate welfare unchanged, it is not true for individual ones. As shown in Figures 4.a and 4.b, compensation may result in losers and

¹¹Due to Proposition 1, this comment applies only for discount rates that ensure $(1 + \sigma) < \frac{q_2}{q_1} \frac{1}{\delta}$

¹²The threshold \underline{n}/b results from the equalization of costs associated with the CS_{Fmon} scheme and the CS^* scheme.

winners. This inequity is reduced as the share of the environmental compensation grows (regime 2).

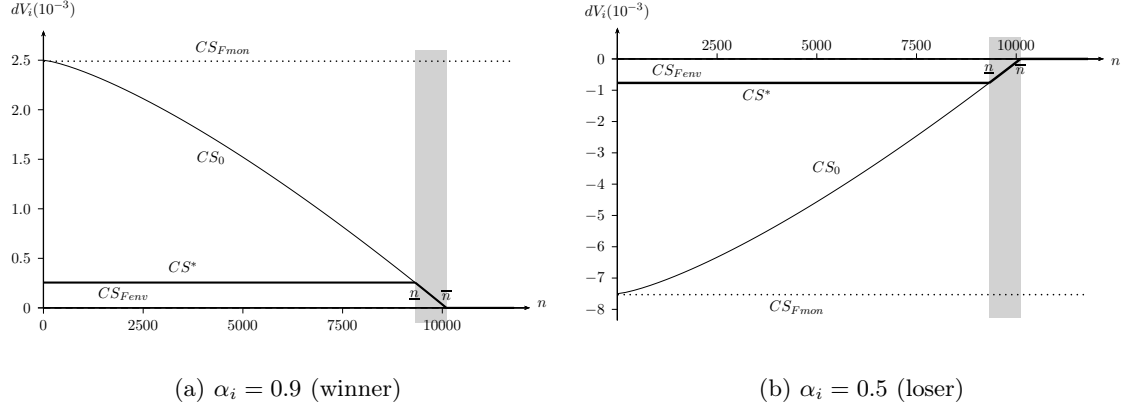


Figure 4: Individual welfare gain/loss for two different levels of α_i when $1 + \sigma < \frac{q_2}{q_1} \frac{1}{\delta}$

When expressed - totally or partially - in monetary terms, necessary compensation has to be large for people who value money the less (low α_i) (Brekke, 1997). Under regimes 1 and 2, individuals with $\alpha_i = \bar{\alpha}$ do not support any individual welfare variations whereas individuals with $\alpha_i < \bar{\alpha}$ incur a loss of welfare decreasing with α_i and n and individuals with a $\alpha_i > \bar{\alpha}$ benefit from a gain of welfare (see appendix D). This gain increases with α_i and decreases with n (Figure 4.a).

Both cost and welfare analyses highlight that regime 1 is worth in terms of cost compared to a compensation scheme without EA constraint (CS_0) but better in terms of equity. As suggested by figures 4.a and 4.b, when the EA constraint applies, it limits the gains for the winners but also the losses for the losers. In the trade-off between efficiency and equity, the EA constraint diminishes the cost efficiency of the compensation but also lowers inequity between agents. In that context, while the primary justification of the EA constraint is based on environmental criteria, it may also be supported for equity purposes. Figures 4.a and 4.b also show that the monetary compensation (CS_{Fmon}) is the worst in terms of equity compared to the other compensation schemes.

Finally, under regime 3 where the only compensation is the environmental one, every individual welfare loss from the damage is offset by the environmental compensation. For this regime, the compensation granted to all individuals corresponds to a pure intertemporal compensation with a good similar to the damaged one. WTA_i^q does not vary with n and is similar for all individuals, i.e. $WTA_i^q = \frac{-dq_1}{q_1} \frac{q_2}{\delta} = dq_2 \forall i$. From a welfare perspective, a Full environmental compensation is the most appropriate solution since there are no welfare losses at aggregate and individual levels. Nevertheless, Figure 3 shows that for a low n the cost of the Full environmental compensation is definitely higher than the cost associated with other compensation schemes.

When agents highly weigh the gains associated to the future environmental good respectively to the gains associated to the present environmental good (high σ), regime 4 applies. The implemented environmental compensation (resulting from the EA constraint) is higher than the one which would leave the aggregate welfare unchanged. As a result, cost associated to this regime is constant and higher than cost associated to the other schemes except for the pure monetary compensation with a high number of victims (Figure 5).¹³

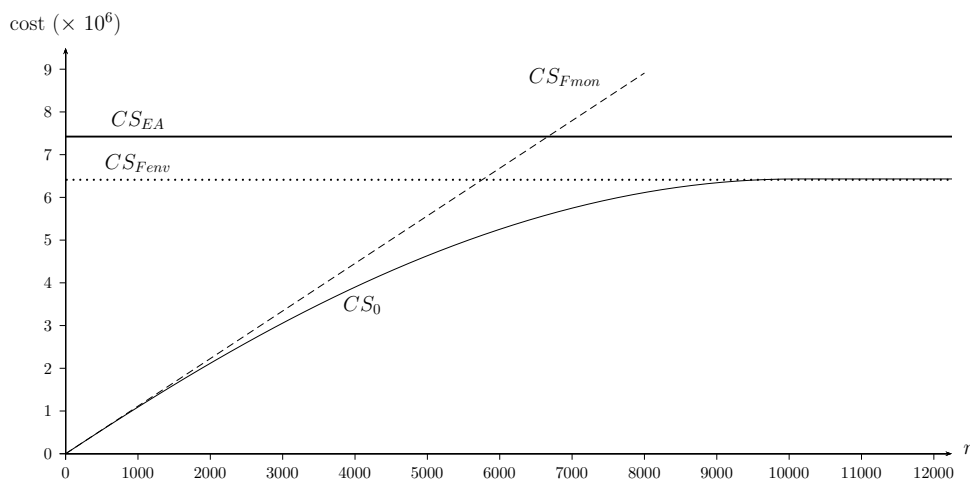


Figure 5: Costs associated with the four compensation schemes when $1 + \sigma > \frac{q_2}{q_1} \frac{1}{\delta}$

Under regime 4, whatever the level of α_i , agents win from compensation (except for $\alpha_i = 1$). In addition, the agents who value more the environmental goods win more, as shown in Figure 6.¹⁴

To sum up, a EA constraint avoids any loser that would exist under all the other regimes, but at the expense of high costs.

¹³For the numerical simulation the new value of σ is 0.62.

¹⁴See Appendix D.

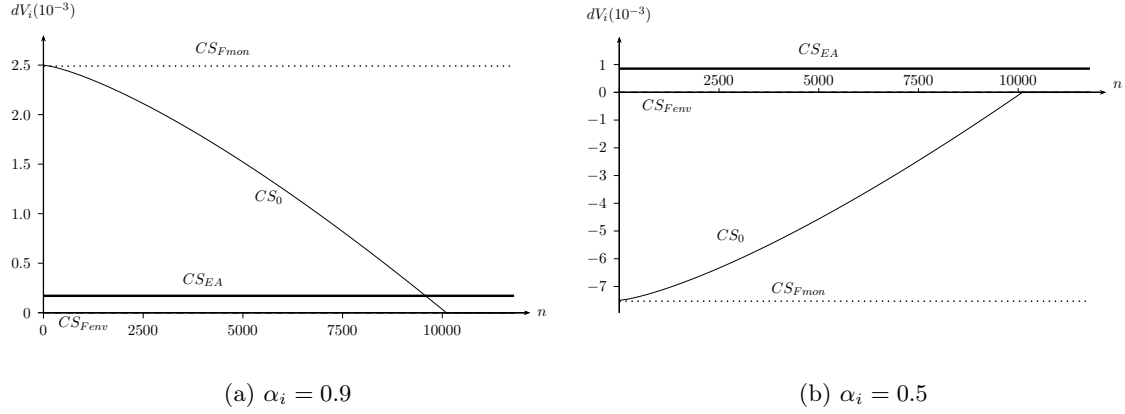


Figure 6: Individual welfare gain/loss for two different levels of α_i when $1 + \sigma > \frac{q_2}{q_1} \frac{1}{\delta}$

3.2 Heterogeneity in wealth

In this section, we assume that agents are differentiated according to their wealth, W_i . The aggregate welfare function writes:

$$\mathcal{W} = \mathcal{W}[v(W_1, q_1, q_2), \dots, v(W_n, q_1, q_2)]$$

and can be rewritten as:

$$\begin{aligned} \mathcal{W} &= \sum_{i=1}^n v(W_i, q_1, q_2) \\ &= \alpha \sum_{i=1}^n \ln \left(\frac{W_i}{(1+\delta)(1+r)} \right) + n(1-\alpha) \ln q_1 + \delta \alpha \sum_{i=1}^n \ln \left(\delta \frac{W_i}{(1+\delta)} \right) + n\delta(1-\alpha) \ln q_2 \end{aligned}$$

Condition (5) becomes:

$$d\mathcal{W} = d \sum_{i=1}^n V_i = \frac{\alpha(1+\delta)}{\bar{W}} MC \sum_{i=1}^n \frac{\bar{W}}{W_i} + \frac{n(1-\alpha)}{q_1} dq_1 + n\delta \frac{(1-\alpha)}{q_2} dq_2 = 0 \quad (20)$$

where $\bar{W} = \frac{\sum_{i=1}^n W_i}{n}$, so that

$$dq_2 = \left(\frac{-dq_1}{q_1} - MC \frac{\alpha(1+\delta)}{(1-\alpha)\bar{W}} \frac{1}{n} \sum_{i=1}^n \frac{\bar{W}}{W_i} \right) \frac{q_2}{\delta}$$

and

$$MC = \frac{1}{\frac{1}{n} \sum_{i=1}^n \frac{\bar{W}}{W_i}} \frac{(1-\alpha)}{\alpha(1+\delta)} \left(\frac{-dq_1}{q_1} - \frac{\delta}{q_2} dq_2 \right) \bar{W}$$

where $\frac{1}{n} \sum_{i=1}^n \frac{\bar{W}}{W_i} = I_W \geq 1$ is a measure of the average wealth inequality in the society.

An increase in I_W implies a greater wealth inequality in the society ($I_W = 1$ means no inequality).¹⁵

¹⁵When considering the special case where $dq_2 = 0$, in analogy with Medin et al. (2001), MC corresponds to the per person 'benefit' when equal marginal utility of the environmental good is assumed.

Similarly to the heterogeneous preferences case, we distinguish two different cases according to the value of b with respect to 1.

Proposition 3 *For $b \geq 1$, four solutions can emerge from the program of the decision-maker*

1. $dq_2 = -dq_1(1 + \sigma)$ and $MC = (-dq_1) \frac{(1-\alpha)}{\alpha(1+\delta)} \frac{\bar{W}}{I_W} \left(\frac{1}{q_1} - \frac{\delta}{q_2}(1 + \sigma) \right)$ iff $n < \underline{n}$ and $(1 + \sigma) < \frac{q_2}{q_1} \frac{1}{\delta}$ (regime 1)
with

$$\underline{n} = \frac{\alpha}{(1-\alpha)} \frac{(1+\delta)}{\delta} q_2 ab \frac{I_W}{\bar{W}} ((1+\sigma)(-dq_1))^{b-1}$$

2. $dq_2 = \left[\frac{n(1-\alpha)\delta}{ab\alpha(1+\delta)q_2} \frac{\bar{W}}{I_W} \right]^{\frac{1}{b-1}}$ and $MC = \frac{(1-\alpha)}{\alpha(1+\delta)} \frac{\bar{W}}{I_W} \frac{-dq_1}{q_1} - \left(\frac{(1-\alpha)}{\alpha(1+\delta)} \frac{\bar{W}}{I_W} \frac{\delta}{q_2} \right)^{\frac{b}{b-1}} \left[\frac{n}{ab} \right]^{\frac{1}{b-1}}$ iff $\bar{n} > n > \underline{n}$ (regime 2)
with

$$\bar{n} = ab \left(\frac{(1+\delta)\alpha}{(1-\alpha)} \frac{I_W}{\bar{W}} \right) \left(\frac{q_2}{\delta} \right)^b \left(\frac{-dq_1}{q_1} \right)^{b-1}$$

3. $MC = 0$ and $dq_2 = -\frac{q_2}{q_1} \frac{1}{\delta} dq_1$ iff $n > \bar{n}$ and $(1 + \sigma) < \frac{q_2}{q_1} \frac{1}{\delta}$ (regime 3)

4. $MC = 0$ and $dq_2 = -dq_1(1 + \sigma)$ iff $(1 + \sigma) > \frac{q_2}{q_1} \frac{1}{\delta}$ (regime 4)

Proof. Similar to Proof of Proposition 1 where conditions (6) and (7) imply:

$$dq_2 > -dq_1(1 + \sigma) \iff n > \frac{\alpha}{(1-\alpha)} \frac{(1+\delta)}{\delta} q_2 ab \frac{I_W}{\bar{W}} ((1+\sigma)(-dq_1))^{b-1} = \underline{n}$$

$$MC > 0 \iff n < ab \left(\frac{(1+\delta)\alpha}{(1-\alpha)} \frac{I_W}{\bar{W}} \right) \left(\frac{q_2}{\delta} \right)^b \left(\frac{-dq_1}{q_1} \right)^{b-1} = \bar{n}$$

both conditions can be fulfilled iff

$$\bar{n} > \underline{n} \iff \frac{q_1}{q_2} < \frac{1}{\delta(1+\sigma)}$$

■

The comments about each regime are quite similar to those for heterogeneous preferences. Here we concentrate on the distinctions between both cases. The values of MC and dq_2 show that the heterogeneity in wealth introduces the expression \bar{W}/I_W instead of n . It is defined by $MC = \frac{n}{\sum_{i=1}^n \left(\frac{\partial v}{\partial W_i} / \frac{\partial v}{\partial q_1} \right)} (-dq_1)$. If equal marginal utility of income is assumed (i.e $I_W = 1$ in our case), then we have $MC = \frac{1}{n} \sum_{i=1}^n \left(\frac{\partial v}{\partial q_1} / \frac{\partial v}{\partial W_i} \right) (-dq_1) = \frac{1}{n} \sum_{i=1}^n WTA_i^W$.

of W with no heterogeneity. This expression highlights two different elements in the wealth heterogeneity: the value of the average wealth (how rich the society is), and the distribution effect (how unequal the society is).

The comparative static analysis for regime 2 gives the following relations:¹⁶

$$\frac{\partial(dq_2)}{\partial(-dq_1)} = 0; \frac{\partial(dq_2)}{\partial\alpha} < 0; \frac{\partial(dq_2)}{\partial\bar{W}} > 0; \frac{\partial(dq_2)}{\partial\delta} > 0; \frac{\partial(dq_2)}{\partial I_W} < 0$$

and

$$\left. \begin{array}{l} \frac{\partial MC}{\partial(-dq_1)} > 0; \frac{\partial MC}{\partial\delta} < 0; \\ \frac{\partial MC}{\partial\alpha} > 0 \\ \frac{\partial MC}{\partial\bar{W}} < 0 \\ \frac{\partial MC}{\partial I_W} > 0 \end{array} \right\} \iff n > \bar{n} \left(\frac{b-1}{b} \right)^{b-1}$$

The impacts of $(-dq_1)$ and δ are similar to the case with heterogeneity in preferences, even for α , instead of $\bar{\alpha}$. Here the impact of \bar{W} can be compared to the impact of W in the previous case. A richer society is inclined to require a higher amount of MC to compensate the environmental damage than a poor society, but the trade-off between both compensations implies that for a sufficiently high level of n , the indirect effect from dq_2 on MC dominates and the whole impact of the average wealth on \underline{n} is positive. The impact of I_W is of opposite sign. An increase in I_W implies a higher income inequality in the population.¹⁷ On one hand, since poorer agents value more a monetary compensation (V_i is concave in W_i), a lower monetary compensation is required for any $I_W > 1$ than when there is no inequality in wealth ($I_W = 1$). On the other hand, the environmental compensation is identically valued whatever the level of wealth of the agents (income inequality plays no role). As a result, the frontiers which separate regime 1 and 2 and regime 2 and 3 are shifted for higher levels of n and the scales for which regime 1 and 2 apply become larger. Conversely, since \bar{n} increases with I_W , the scale of regime 3 is reduced since environmental compensation is not increasingly valued by poor people.

As already stressed in the previous subsection, monetary compensation will be in favor of individuals that value money the most. As shown in Figure 7.a the poorest individuals ($W_i < \bar{W}/I_W$) are the winners.¹⁸ Under regime 4, every individual wins from the minimal environmental compensation. In addition, the gain from the environmental compensation is the same for each individual whatever his wealth. Indeed, heterogeneity only impacts the welfare through the monetary compensation which is here null.

¹⁶See Appendix E.

¹⁷A rise in I_W is here defined as a mean preserving spread in the sense that the ratio I_W rises but the mean wealth remains unchanged, so that wealth inequality clearly increases in the population.

¹⁸The following parameter set was used for numerical simulation: ($\bar{W} = 400000$, $I_W = 1.5$, $\bar{\alpha} = 0.8$, $\delta = 0.67$, $q_1 = 10000$, $q_2 = 10000$, $dq_1 = -200$, $a = 300$, $b = 1.75$, $\sigma = 0.34$).

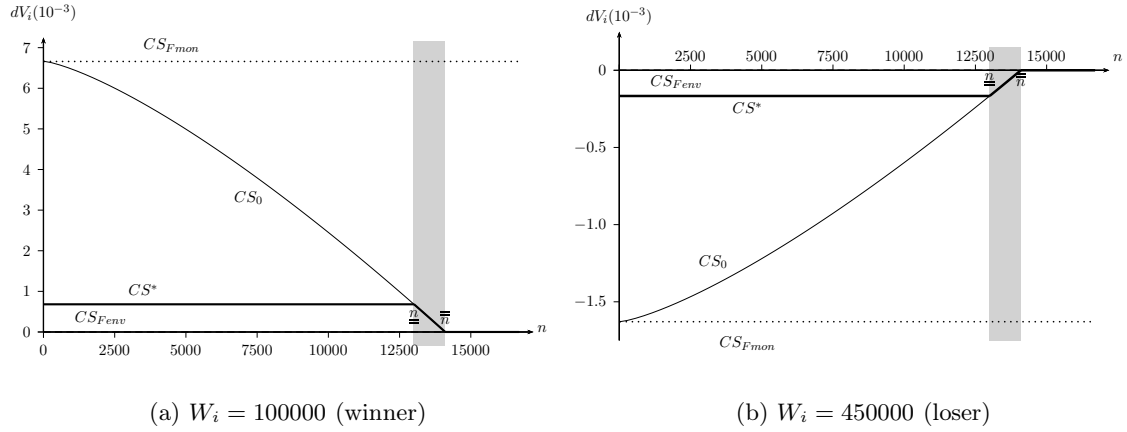


Figure 7: Individual welfare gain/loss for two different levels of W_i

Proposition 4 *For $b < 1$, three solutions can emerge from the program of the decision-maker*

1. $dq_2 = -dq_1(1 + \sigma)$ and $MC = (-dq_1) \frac{(1-\alpha)}{\alpha(1+\delta)} \frac{\bar{W}}{I_W} \left(\frac{1}{q_1} - \frac{\delta}{q_2}(1 + \sigma) \right)$ iff $(1 + \sigma) < \frac{q_2}{q_1} \frac{1}{\delta}$ and $n < \tilde{n}$ (regime 1)
2. $MC = 0$ and $dq_2 = -\frac{q_2}{q_1} \frac{1}{\delta} dq_1$ iff $(1 + \sigma) < \frac{q_2}{q_1} \frac{1}{\delta}$ and $n > \tilde{n}$ (regime 3)
3. $MC = 0$ and $dq_2 = -dq_1(1 + \sigma)$ iff $(1 + \sigma) > \frac{q_2}{q_1} \frac{1}{\delta}$ (regime 4)

$$\text{with } \tilde{n} = \frac{a(-dq_1)^{b-1} \left(\left(\frac{q_2}{q_1} \frac{1}{\delta} \right)^b - (1 + \sigma) \right)}{I_W \bar{W} \frac{(1-\alpha)}{\alpha(1+\delta)} \frac{\delta}{q_2} \left(\frac{q_2}{q_1} \frac{1}{\delta} - (1 + \sigma) \right)}$$

Proof. Similar to Proposition 1 with the comparison of cases 2 and 3 that yields:

$$\tilde{C}_3 < \tilde{C}_1 \iff n > \frac{\bar{W}}{I_W} \frac{a(-dq_1)^{b-1} \left(\left(\frac{q_2}{q_1} \frac{1}{\delta} \right)^b - (1 + \sigma) \right)}{\frac{(1-\alpha)}{\alpha(1+\delta)} \frac{\delta}{q_2} \left(\frac{q_2}{q_1} \frac{1}{\delta} - (1 + \sigma) \right)} = \tilde{n}$$

■

For $b < 1$, the level of n separating both regimes 1 and 3, i.e. \tilde{n} , decreases with I_W . Then heterogeneity in wealth goes in favor of an environmental compensation since the borders of this regime are extended.

4 Concluding remarks

While the European Directive 2004/35/EC precludes the use of monetary compensation in response to an environmental damage, this article reintroduces the monetary compensation as a potential compensating tool complementing an environmental compensation.

We explore which satisfactory compensation can be provided at a minimal cost under an ecological constraint (here EA constraint). The results feature that the best way to provide compensation for ecological damage at a minimal cost may be sensitive to several parameters: nature of heterogeneity, number of victims, relative costs of monetary and environmental compensations.

More precisely, we show that when the population affected by the environmental damage is small, the equivalency constraint implies the use of a minimal natural resource quantity that would not be provided without this constraint for cost reason. But this constraint enables to diminish the inequity generated by the environmental damage on the heterogeneous population. Although the main purpose of enforcing an ecological constraint is an environmental one (i.e. "*no net loss*" principle) it also has welfare and cost implications. In that sense, a key result of our paper is to find the optimal balance between equity and cost efficiency considerations.

However, to go further, some results of our paper may be linked to prevention issues. For instance, we show that a poor population (low mean income) values more the monetary compensation than a rich and as a consequence, accepts a lower level of money to compensate the damage it supports. This mechanism extends the use of monetary compensation. Moreover, if this poor affected population is relatively small, the polluter can consider that the cost of compensation it should support in case of damage is sufficiently low to not undertake any prevention measure that could avoid any environmental damage. Facing this kind of possible behaviors, the use of a minimal ecological constraint is strongly justified to avoid them.

Moreover, as shown in this paper, the use or not of an ecological constraint crucially modifies the optimal compensation scheme. Without such a constraint, a mixed compensation is desirable for a relatively small population of victims. Finally, as often mentioned in the literature devoted to the Equivalency Analysis, the choice of the value attributed to the discount rate is determinant for the determination of the optimal compensation. According to this value, the compensation can be either the one resulting from the Equivalent Analysis method or a more complex one depending on the number of victims.

Work still remains to be done to get a better understanding of all the implications of providing compensation for an environmental damage. In particular, a better consideration of natural resource dynamics as well as a deeper study of redistributive effects of the trade-off between money and nature should be considered in a next step. Heterogeneous discount rates would be another interesting question.

Appendix

A. Proof of Proposition 1

Rewriting the cost function in dq_2 according to (18) gives

$$C(dq_2, MC) = nW \frac{(1 - \bar{\alpha})}{\bar{\alpha}(1 + \delta)} \left(\frac{-dq_1}{q_1} - \frac{\delta}{q_2} dq_2 \right) + a(dq_2)^b$$

which is clearly quasi-convex in dq_2 if and only if $b \geq 1$. Minimizing this cost function gives

$$dq_2 = \left(\frac{(1 - \bar{\alpha})nW\delta}{\bar{\alpha}(1 + \delta)q_2ab} \right)^{\frac{1}{b-1}}$$

and condition (7) gives the value for MC

$$MC = \frac{(1 - \bar{\alpha})W \left(\frac{-dq_1}{q_1} \right)}{(1 + \delta)\bar{\alpha}} - \left(\frac{\delta(1 - \bar{\alpha})W}{q_2(1 + \delta)\bar{\alpha}} \right)^{\frac{b}{b-1}} \left(\frac{n}{ab} \right)^{\frac{1}{b-1}}$$

Conditions (6) and (7) imply

$$dq_2 > -(1 + \sigma)dq_1 \iff n > ab \frac{(1 + \delta)\bar{\alpha}}{(1 - \bar{\alpha})W} \frac{q_2(- (1 + \sigma)dq_1)^{b-1}}{\delta} = \underline{n}$$

$$MC > 0 \iff n < ab \left(\frac{(1 + \delta)\bar{\alpha}}{(1 - \bar{\alpha})W} \right) \left(\frac{q_2}{\delta} \right)^b \left(\frac{-dq_1}{q_1} \right)^{b-1} = \bar{n}$$

both conditions will be fulfilled iff

$$\bar{n} > \underline{n} \iff (1 + \sigma) < \left(\frac{q_2}{q_1} \frac{1}{\delta} \right) \text{ for } b \geq 1$$

- If $n > \bar{n} > \underline{n}$ then $MC = 0$ and dq_2 is derived from (19). It corresponds to condition (13).
- If $n < \underline{n} < \bar{n}$ then dq_2 is implemented at its minimal level i.e. $dq_2 = -(1 + \sigma)dq_1$ and MC is derived from (18). It corresponds to condition (15).
- If $(1 + \sigma) > \left(\frac{q_2}{q_1} \frac{1}{\delta} \right)$, which implies $\underline{n} > \bar{n}$, none of condition (6) and (7) are fulfilled so that both compensations are implemented at their minimal level whatever the level of n , i.e. $MC = 0$ and $dq_2 = -dq_1(1 + \sigma)$.

B. Comparative statics for heterogeneity in preferences

$$\begin{aligned}\frac{\partial MC}{\partial \bar{\alpha}} &= \left(-\frac{1}{\alpha^2}\right) \left(\frac{(-dq_1)W}{(1+\delta)q_1} - \frac{b}{b-1} \left(\frac{\delta W}{q_2(1+\delta)}\right)^{\frac{b}{b-1}} \left(\frac{(1-\bar{\alpha})}{\bar{\alpha}}\right)^{\frac{1}{b-1}} \left(\frac{n}{ab}\right)^{\frac{1}{b-1}}\right) \\ \frac{\partial MC}{\partial \bar{\alpha}} &> 0 \iff \frac{\bar{\alpha}(1+\delta)}{W(1-\bar{\alpha})} \left(\frac{(-dq_1)}{q_1}\right)^{b-1} \left(\frac{q_2}{\delta}\right)^b \left(\frac{(b-1)}{b}\right)^{b-1} ab < n \\ &\iff \bar{n} \left(\frac{b-1}{b}\right)^{b-1} < n\end{aligned}$$

$$\begin{aligned}\frac{\partial MC}{\partial W} &= \frac{\frac{(1-\bar{\alpha})}{q_1}(-dq_1)}{(1+\delta)\bar{\alpha}} - \frac{b}{b-1} \left(W \frac{\delta^{\frac{(1-\bar{\alpha})}{q_2}}}{(1+\delta)\bar{\alpha}}\right)^{\frac{b}{b-1}} \frac{1}{W} \left(\frac{n}{ab}\right)^{\frac{1}{b-1}} \\ \frac{\partial MC}{\partial W} &> 0 \iff \frac{(1+\delta)\bar{\alpha}}{W(1-\bar{\alpha})} \left(\frac{(-dq_1)}{q_1}\right)^{b-1} \left(\frac{q_2}{\delta}\right)^b \left(\frac{(b-1)}{b}\right)^{b-1} ab > n \\ &\iff \bar{n} \left(\frac{b-1}{b}\right)^{b-1} > n\end{aligned}$$

$$\frac{\partial MC}{\partial \delta} = -\frac{\frac{(1-\bar{\alpha})}{q_1}(-dq_1)}{(1+\delta)^2 \frac{\bar{\alpha}}{W}} - \frac{b}{b-1} \left(\frac{n}{ab} \frac{\delta^{\frac{(1-\bar{\alpha})}{q_2}}}{(1+\delta)\frac{\bar{\alpha}}{W}}\right)^{\frac{1}{b-1}} \frac{\frac{(1-\bar{\alpha})}{q_2}}{\frac{\bar{\alpha}}{W}} \frac{\delta}{(1+\delta)^2} < 0$$

C. Proof of Proposition 2

Rewriting the cost function in MC according to (18) gives

$$C(dq_2, MC) = nMC + a \left(\left(\frac{-dq_1}{q_1} - MC \frac{\bar{\alpha}(1+\delta)}{(1-\bar{\alpha})W} \right) \frac{q_2}{\delta} \right)^b$$

which is clearly quasi-convex in dq_2 if and only if $b \geq 1$. For $b < 1$, minimizing the cost leads to set $MC = 0$ (condition (7)). The value of dq_2 is then derived from (19) which corresponds to regime 3 if the parameters are such that $dq_2 > -dq_1(1+\sigma)$ for $dq_2 = \frac{-dq_1}{q_1} \frac{q_2}{\delta}$ and to regime 4 otherwise.

Rewriting the cost function in dq_2 according to (18) gives

$$C(dq_2, MC(dq_2)) = nW \frac{(1-\bar{\alpha})}{\bar{\alpha}(1+\delta)} \left(\frac{-dq_1}{q_1} - \frac{\delta}{q_2} dq_2 \right) + a(dq_2)^b$$

which is clearly quasi-convex in dq_2 if and only if $b \geq 1$. For $b < 1$, the cost function is convex in dq_2 so that the only solution which minimizes the cost is a corner solution. According to condition (6) minimizing the cost requires $dq_2 = -dq_1(1+\sigma)$. The value of MC is derived from (18), which corresponds to regime 1 if the parameters are such that $MC > 0$ for $MC = -dq_1 W \frac{(1-\bar{\alpha})}{\bar{\alpha}(1+\delta)} \left(\frac{1}{q_1} - \frac{\delta}{q_2}(1+\sigma) \right)$ and to regime 4 otherwise.

We now compare regime 1 and regime 3.

Under regime 3, the cost reduces to

$$C_3(dq_2, MC) = a \left(\frac{-dq_1}{q_1} \frac{q_2}{\delta} \right)^b$$

whereas under regime 1, the cost reduces to

$$C_1(dq_2, MC) = n(-dq_1) W \frac{(1 - \bar{\alpha})}{\bar{\alpha}(1 + \delta)} \left(\frac{1}{q_1} - \frac{\delta}{q_2}(1 + \sigma) \right) + a(-(1 + \sigma)dq_1)^b$$

$$C_3 < C_1 \iff n > \frac{q_2 \bar{\alpha}(1 + \delta) a (-dq_1)^{b-1} \left(\left(\frac{q_2}{q_1} \frac{1}{\delta} \right)^b - (1 + \sigma)^b \right)}{W(1 - \bar{\alpha})\delta \left(\frac{q_2}{q_1} \frac{1}{\delta} - (1 + \sigma) \right)} = \hat{n}$$

D. Individual welfare losses/gains with respect to α_i .

For agent i

$$dV_i = (1 + \delta) \frac{\alpha_i}{W} MC + \frac{(1 - \alpha_i)}{q_1} dq_1 + \delta \frac{(1 - \alpha_i)}{q_2} dq_2$$

and the variation of welfare with respect to α_i is given by:

$$\frac{\partial dV_i}{\partial \alpha_i} = (1 + \delta) \frac{MC}{W} - \frac{dq_1}{q_1} - \delta \frac{dq_2}{q_2} > 0$$

- Under regime 2, replacing MC by its expression (19) gives

$$\frac{\partial dV_i}{\partial \alpha_i} = \left(\frac{1}{\bar{\alpha}} \right) \left(-\frac{dq_1}{q_1} - \delta \frac{dq_2}{q_2} \right) > 0 \text{ from (20) since } MC > 0$$

Since $dV_i = 0$ for $\alpha_i = \bar{\alpha}$, then $dV_i > 0$ (resp. < 0) for any $\alpha_i < \bar{\alpha}$ (resp. $\alpha_i > \bar{\alpha}$)

- Under Regime 3, $MC = 0$ and $dq_2 = -\frac{q_2}{q_1} \frac{1}{\delta} dq_1$ such that

$$\frac{\partial dV_i}{\partial \alpha_i} = -\frac{dq_1}{q_1} + \frac{dq_1}{q_1} = 0$$

- Under Regime 4, $MC = 0$ and $dq_2 = -dq_1(1 + \sigma)$ so that

$$\frac{\partial dV_i}{\partial \alpha_i} = dq_1 \left(-\frac{1}{q_1} + \frac{1}{q_2} \frac{(1 + \sigma)}{\delta} \right) < 0 \text{ since } (1 + \sigma) > \frac{q_2}{q_1} \frac{1}{\delta}$$

E. Comparative statics for heterogeneity in wealth

$$\frac{\partial dq_2}{\partial \alpha} = -\frac{1}{\alpha^2} \frac{1}{b-1} \left(\frac{1-\alpha}{\alpha} \right)^{\frac{2-b}{b-1}} \left[\frac{n\delta I_W}{ab(1+\delta)q_2} \right]^{\frac{1}{b-1}} < 0$$

$$\frac{\partial dq_2}{\partial \delta} = \frac{1}{(1+\delta)^2} \frac{1}{b-1} \left(\frac{\delta}{1+\delta} \right)^{\frac{2-b}{b-1}} \left[\frac{n(1-\alpha)I_W}{ab\alpha q_2} \right]^{\frac{1}{b-1}} > 0$$

$$\frac{\partial dq_2}{\partial n} = 2 \frac{1}{b-1} \frac{1}{n} \left[\frac{n(1-\alpha)I_W}{ab\alpha(1+\delta)q_2} \right]^{\frac{1}{b-1}} > 0$$

$$\frac{\partial MC}{\partial n} = \frac{(1-\alpha)}{\alpha(1+\delta)} I_W \overline{W} \left(-\frac{\delta}{q_2} \frac{1}{b-1} \frac{1}{n} \left[\frac{n(1-\alpha)\delta}{ab\alpha(1+\delta)q_2} \frac{\overline{W}}{I_W} \right]^{\frac{1}{b-1}} \right) < 0$$

$$\frac{\partial MC}{\partial \alpha} = \left(-\frac{1}{\alpha^2} \right) \left[\frac{(-dq_1)}{q_1} - \frac{b}{b-1} \left(\frac{1-\alpha}{\alpha} \right)^{\frac{1}{b-1}} \frac{\delta}{q_2} \left(\frac{n\delta}{ab(1+\delta)q_2} \frac{\overline{W}}{I_W} \right)^{\frac{1}{b-1}} \right]$$

$$\begin{aligned} \frac{\partial MC}{\partial \alpha} &> 0 \Leftrightarrow \frac{(-dq_1)}{q_1} < \frac{b}{b-1} \left(\frac{1-\alpha}{\alpha} \right)^{\frac{1}{b-1}} \frac{\delta}{q_2} \left(\frac{n\delta}{ab(1+\delta)q_2} \frac{\overline{W}}{I_W} \right)^{\frac{1}{b-1}} \\ &\Leftrightarrow n > \left(\frac{b-1}{b} \right)^{\frac{b-1}{2}} \overline{n} \end{aligned}$$

$$\begin{aligned} \frac{\partial MC}{\partial I_W} &= -\frac{(1-\alpha)}{\alpha(1+\delta)} \frac{\overline{W}}{I_W^2} \left(\frac{1}{q_1} (-dq_1) - \frac{\delta}{q_2} \left[\frac{n(1-\alpha)\delta}{ab\alpha(1+\delta)q_2} \frac{\overline{W}}{I_W} \right]^{\frac{1}{b-1}} \left(\frac{b}{b-1} \right) \right) > 0 \\ &\Leftrightarrow n > \left(\frac{b-1}{b} \right)^{\frac{b-1}{2}} \overline{n} \end{aligned}$$

$$\begin{aligned} \frac{\partial MC}{\partial \overline{W}} &= \frac{(1-\alpha)}{\alpha(1+\delta)} I_W \left(\frac{1}{q_1} (-dq_1) - \frac{\delta}{q_2} \left[\frac{n(1-\alpha)\delta}{ab\alpha(1+\delta)q_2} I_W \overline{W} \right]^{\frac{1}{b-1}} \left(\frac{b}{b-1} \right) \right) > 0 \\ &\Leftrightarrow n < \left(\frac{b-1}{b} \right)^{\frac{b-1}{2}} \overline{n} \end{aligned}$$

$$\frac{\partial MC}{\partial \delta} = -\frac{(1-\alpha)}{\alpha(1+\delta)^2} \frac{\overline{W}}{I_W} \frac{-dq_1}{q_1} - \frac{1}{\delta(1+\delta)} \left(\frac{(1-\alpha)}{\alpha(1+\delta)} \frac{\overline{W}}{I_W} \frac{\delta}{q_2} \right)^{\frac{1}{b-1}} \left[\frac{n}{ab} \right]^{\frac{1}{b-1}} < 0$$

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