Compensating for environmental damages

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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) minimization of the cost associated with the compensation, ii) no aggregate welfare loss, iii) minimal environmental compensation requirement. The findings suggest that - in some cases - providing both monetary and environmental compensation can be the cost-minimizing option. Minimal compensation constraints can increase total compensation costs but reduce individual gains and losses relative to the initial situation that arise from heterogeneous tradeoffs between income and environmental quality.

Keywords: Environmental Damage, Compensation, Welfare, Inequity

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,

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equity refers to the idea that each agent suffers differently from the damage and benefits differently 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 suffer from welfare losses whereas others benefit from welfare gains 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 consist in ensuring no change in aggregate welfare while maintaining 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 compensations are distinguished: environmental compensation and monetary compensation. The first one consists in providing an environmental restoration or implementing other actions that provide benefits to the restoration. The second one consists in an amount of money paid to the prejudiced people. Within the last couple of years, the issue of environmental compensations for the loss of environmental assets (whether the ecological damage is planned or accidental) have been gaining 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 compensations to offset past,

[1] This option is preferred to "out-of-kind" compensation in which the adverse impacts to one resource (or

current and future damages without directly valuing them in economic terms, by equalizing the amount of losses and gains 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 phenomena. 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 wealth compensation. 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

habitat) are mitigated through the creation, restoration, or enhancement of another resource (or habitat).

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

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

an environmental damage when determining the compensation to be implemented. 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 environmental compensation with a similar natural resource or service is available.

In line with Cole (2013), this paper allows us to investigate equity and cost efficiency issues associated with an enforced environmental compensation. We depart from Cole by considering equity issues for a prejudiced population instead of taking the society as a whole. Moreover, contrary to Cole (2013) who compares the compensation schemes separately, we allow for a mixed compensation in which both of the compensatory methods may be implemented simultaneously.

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, environmental 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". The aim of the introduction of an EA criterion, in accordance with the "*no net loss*" principle, is to ensure that the destruction or degradation of an environmental good is sufficiently offset. Considering an heterogeneous population, 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 require compensations. 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 ecological constraint is binding, it 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 directions for further research.

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:

$$U_i = u_{i1}(X_{i1}, q_1) + \delta u_{i2}(X_{i2}, q_2)$$

where u_{it} is the agent i 's utility in period t, δ characterizes 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. 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. Then the lifetime indirect utility of agent i can be written:

$$V_i = v_i(W_i, q_1, q_2) \tag{1}$$

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:

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

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

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

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

It expresses how much money the individual i is willing to accept in exchange for the loss dq_1. Assuming that the environmental good q_1 is normal, the income elasticity of the willingness to pay is positive.[5] As a result, in line with Brekke (1997), a rich agent is inclined to require a higher amount of monetary compensation to compensate the environmental damage than a poor agent.

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

$$WTA_i^q = \left(\frac{\partial v_i}{\partial q_1} / \frac{\partial v_i}{\partial q_2} \right) (-dq_1). \tag{4}$$

Note that both expressions of willingness to accept depend positively on the magnitude of the environmental impact.

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

[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).

[5] See Ebert (2003) for an exhaustive analysis on the effect of the distribution of income on the marginal willingness to accept.

The program of the decision-maker writes:

$$\min_{MC,dq_2} \; C(dq_2, MC) \tag{5}$$

subject to

$$d\mathcal{W} = 0 \tag{6}$$

$$dq_2 \geq -dq_1\sigma \tag{7}$$

$$MC \geq 0 \tag{8}$$

where $MC = dW_i \; \forall i$ is the monetary compensation, dq_2 is the environmental compensation, and C is the cost function associated to the compensation. $\mathcal{W} = \sum_{i=1}^{n} V_i$ stands for the aggregate welfare of the n victims and constraint (6) characterizes the fact that the compensating policy must leave the aggregate welfare unchanged. Combined with (2), this constraint implies a clear trade-off mechanism between both compensations for a given environmental damage. Constraint (7) with $\sigma > 1$ 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 equals the "discounted" environmental loss. In this expression, σ is the discount parameter associated to the EA constraint.[6] Note that no ex-post redistribution of monetary compensation between losers and gainers is feasible.

2.1 Compensation scheme

The Lagrangian associated to this program is given by

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

where λ_1 is the Lagrangian multiplier associated to constraint (6), λ_2 to (7) and λ_3 to (8).

The conditions arising from solving the Lagrangian are:

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

[6] The 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).

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

$$\frac{\partial \mathcal{L}}{\partial \lambda_1} = d\mathcal{W} = 0; \qquad \frac{\partial \mathcal{L}}{\partial \lambda_2} = dq_2 + dq_1\sigma \geq 0; \qquad \frac{\partial \mathcal{L}}{\partial \lambda_3} = MC \geq 0$$

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

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

$$\left[\frac{\partial d\mathcal{W}}{\partial MC} / \frac{\partial d\mathcal{W}}{\partial dq_2}\right] > \left[\frac{\partial C}{\partial MC} / \frac{\partial C}{\partial dq_2}\right] \tag{9}$$

  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 the minimal cost.

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

$$\left[\frac{\partial d\mathcal{W}}{\partial MC} / \frac{\partial d\mathcal{W}}{\partial dq_2}\right] = \left[\frac{\partial C}{\partial MC} / \frac{\partial C}{\partial dq_2}\right] \tag{10}$$

  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 gain from an additional unit of MC or dq_2 per fund spent is the same due to the trade-off mechanism resulting from constraints (2) and (6).

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

$$\left[\frac{\partial d\mathcal{W}}{\partial MC} / \frac{\partial d\mathcal{W}}{\partial dq_2}\right] < \left[\frac{\partial C}{\partial MC} / \frac{\partial C}{\partial dq_2}\right] \tag{11}$$

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

- Regime 4: (minimal compensation $[\mathcal{R}_4]$) $\lambda_2 > 0; \lambda_3 > 0 => dq_2 = -dq_1\sigma; MC = 0$. This regime does not fulfill constraint (6). The EA constraint applies and overcompensates the loss of the social welfare.

Three remarks can be made here concerning the choice between regimes 1, 2 and 3. First, assuming that the marginal cost of the monetary compensation is equal to the number of victims $\left(\frac{\partial C}{\partial MC} = n\right)$ and that the marginal cost of environmental compensation does not depend on n, the frontiers between the three regimes depend on the number of victims (n). It is particularly clear when agents are perfectly homogeneous which imply identical willingnesses to accept ($WTA_i^W = WTA^W \quad \forall i$ and $WTA_i^q = WTA^q \quad \forall i$). Then $\frac{\partial d\mathcal{W}/\partial MC}{\partial d\mathcal{W}/\partial dq_2} = \frac{WTA^q}{WTA^W}$ and $\frac{\partial C/\partial MC}{\partial C/\partial dq_2} = \frac{n}{\partial C/\partial dq_2}$. Obviously, Regime 1 applies to a small number of victims whereas Regime 3 applies to a large one. A higher damage directly increases the EA constraint and consequently shifts the limits of the regimes to a higher n. The introduction of a degree of heterogeneity does not change the qualitative results.[7]

Second, the choice between regime 1, 2 or 3 crucially depends on the magnitude of the environmental impact $(-dq_1)$ since it affects the EA constraint together with the willingnesses to accept (WTA_i^W and WTA_i^q).

Third, when the EA constraint no longer exists, regimes 1 and 4 disappear and only regimes 2 and 3 remain.

2.2 Cost and welfare analysis

Even if the compensation mechanism leaves the aggregate welfare unchanged when agents are heterogeneous, it does not necessarily imply that individual welfare remains unchanged as well. Under each regime, we can determine which agent is inclined to lose or win according to their willingness to accept together with equations (2) and (6).

Compensation implies a loss (no change, gain) for the agent whose willingness to accept satisfies the following conditions:

- For Regime 1: $WTA_i^W > (=, <) \frac{MC}{1-\frac{\sigma}{WTA_i^q}}$

[7] For instance, when heterogeneity between agents such that $WTA_i^q = WTA^q \; \forall i$ and $\frac{\partial v_i}{\partial q_2} = \frac{\partial v_j}{\partial q_2} \; \forall i, j$ is introduced, we have $\frac{\partial d\mathcal{W}/\partial MC}{\partial d\mathcal{W}/\partial dq_2} = \frac{1}{n}\sum \frac{WTA^q}{WTA_i^W}$. The choice between regimes is still determined by threshold levels of n.

- For Regime 2: $WTA_i^W > (=,<) \frac{MC}{1+\frac{1}{WTA_i^q}(-dq_2)}$
- For Regime 3: $WTA_i^q > (=,<)\, dq_2$

Let us consider the case where agents have identical WTA_i^q. In Regime 3, the compensation is fully granted in environmental units and leaves each individual welfare unchanged. When the compensation includes a uniform monetary component ($\mathcal{R}_1$ and $\mathcal{R}_2$), compensation results in losers and winners. If individuals are only differentiated by their income, then a rich agent loses and a poor agent wins. If they are only differentiated by their preferences for the environmental good, we can intuitively assume that WTA_i^W increases with the preference for the environmental good. An agent who values more (less) the environmental good loses (wins) from compensation. When WTA_i^q differs between agents, Regime 3 implies a gain (loss) in individual welfare for agents with a high (low) WTA_i^q. In regimes 1 and 2, agents characterized by a high (low) willingness to accept incur a loss (gain) in welfare.

Let us now compare the costs associated to the different regimes. We denote by $CS^*_{\mathcal{R}_i}$ with $i = 1, 2, 3$ the cost associated with the compensation scheme under $\mathcal{R}_1$, $\mathcal{R}_2$ and $\mathcal{R}_3$. We also denote by CS_0 the scheme that combines monetary and environmental compensation without the EA constraint. 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 characterized as follows:

$CS_{Fenv} : dq_2 > 0 \quad \text{and} \quad MC = 0 \quad \forall n$

$CS_{Fmon} : MC > 0 \quad \text{and} \quad dq_2 = 0 \quad \forall n$

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

Due to the characteristics of the cost function and the characterization of each compensation scheme, we can clearly deduce the following relationships:

- $CS_{Fenv} > CS^*_{\mathcal{R}_i} \geq CS_0$ for $i = 1, 2$ and the values of n corresponding to regimes 1 and 2
- $CS_{Fenv} = CS^*_{\mathcal{R}_3} = CS_0 < CS_{Fmon}$ for the values of n corresponding to Regime 3.
- $CS_{Fmon} < CS^*_{\mathcal{R}_1}$ for sufficiently low values of n in Regime 1.

- $$\left.\begin{array}{l} CS_{Fmon} > CS^*_{\mathcal{R}_2} \\ CS_{Fenv} > CS^*_{\mathcal{R}_2} \end{array}\right\}$$ for the values of n corresponding to Regime 2.

From a cost minimization perspective, we deduce that for low values of n the compensation scheme described by Regime 1 is not the least costly possible option since the EA constraint imposes an additional cost. Without this constraint, there would exist two better options: Full monetary compensation and mixed compensations without the EA constraint. $CS^*_{\mathcal{R}_2}$ is the least costly option jointly with CS_0 for the values of n corresponding to Regime 2 and with CS_0 and CS_{Fenv} for the values of n corresponding to Regime 3.

When regime 4 applies (no monetary compensation and a minimal environmental compensation driven by the EA constraint), the change in the aggregate welfare is positive. In this particular case, the compensation cost is higher than the one which would leave the aggregate welfare unchanged. As a result, the cost associated with this regime (CS_{EA}) is constant and higher than the cost associated with the other schemes except for the pure monetary compensation associated with a large number of victims.

3 Application

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

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

where α_i is the agent i's preference for the private good.[8]

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. The indirect utility writes

$$V_i = \alpha_i \ln\left(\frac{W_i}{(1+\delta)\,(1+r)}\right) + (1-\alpha_i)\ln q_1 + \delta\alpha_i \ln\left(\frac{\delta}{(1+\delta)}W_i\right) + \delta(1-\alpha_i)\ln q_2 \quad (12)$$

and the willingnesses to accept given by (3) and (4) are:

$$WTA_i^W = \frac{(1-\alpha_i)W_i}{q_1\alpha_i(1+\delta)} \quad (13)$$

[8]Following Leroux (1987), this specification allows the environmental good to be a normal good and the properties of the willingness to accept with respect to the income apply.

$$WTA_i^q = \frac{1}{\delta}\frac{q_2}{q_1} = WTA^q \quad \forall i \tag{14}$$

The willingness to accept a monetary compensation is decreasing with the income and the preference for the public good while the willingness to accept an environmental compensation is identical for each agent whatever the nature of heterogeneity.

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

$$C\left(dq_2, MC\right) = nMC + \mathbb{1}_{\{MC>0\}}CF_{MC} + a\left(dq_2\right)^b \tag{15}$$

The cost function is decomposed into three parts: a lump sum part (nMC) which characterizes the monetary compensation granted uniformly to all agents, a fixed cost (CF_{MC}) associated to the implementation of a monetary compensation and a cost proportional to the ecological restoration which depends on the type of the good that should be restored ($b > 0$ can be either ≥ 1 or < 1).[9] The greater a and b, the higher the weight of environmental compensation in the whole cost. The fixed cost component (CF_{MC}) may characterize the cost of conducting a study which uses the monetary valuation methodology. This cost can significantly vary according to how the survey was conducted (mail, telephone or in-person surveys). When the monetary compensation is not chosen, the fixed cost associated to the monetary compensation disappears and only the cost associated to the ecological compensation remains in the cost function. Since the cost function is not continuous at $MC = 0$, the comparison of costs under each scenario determines the best compensation scheme. It is straightforward that the program is quasiconvex in MC whereas it is quasiconvex in dq_2 for $b \geqslant 1$. Due to the form of the cost function and the objective to limit the cost of compensation while maintaining the level of the social welfare, it is intuitive that a monetary compensation should be implemented when faced with a small number of victims and an environmental compensation should be implemented when the number of victims is large. Indeed, while the marginal cost of monetary compensation is equal to n, the marginal cost

[9] On the one hand, the marginal cost of providing environmental goods is decreasing for a levee that could be moved back to create a tidal marsh ($b < 1$). It may have significant environmental benefits without substantially raising the cost of compensation. On the other hand, when lands are being purchased and managed for conservation, the marginal cost of environmental compensation is likely to be increasing ($b > 1$).

of environmental compensation is increasing with dq_2 and does not depend on the number of victims.

3.1 Heterogeneity in the preference for goods

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

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

Solving the program described by Equations (5) to (8) gives the following values for MC and dq_2 in the different regimes (see Appendix A.):

- Regime 1: $dq_2 = -dq_1\sigma$ and $MC = -dq_1 W \frac{(1-\overline{\alpha})}{\overline{\alpha}(1+\delta)}\left(\frac{1}{q_1} - \frac{\delta}{q_2}\sigma\right)$
- Regime 2: $dq_2 = \left(\frac{(1-\overline{\alpha})nW\delta}{\overline{\alpha}(1+\delta)q_2 ab}\right)^{\frac{1}{b-1}}$ and $MC = \frac{(1-\overline{\alpha})W\left(\frac{-dq_1}{q_1}\right)}{(1+\delta)\overline{\alpha}} - \left(\frac{\delta(1-\overline{\alpha})W}{q_2(1+\delta)\overline{\alpha}}\right)^{\frac{b}{b-1}}\left(\frac{n}{ab}\right)^{\frac{1}{b-1}}$
- Regime 3: $dq_2 = -\frac{q_2}{q_1}\frac{1}{\delta}dq_1$ and $MC = 0$
- Regime 4: $dq_2 = -dq_1\sigma$ and $MC = 0$

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

Given the cost function and the 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 $b \geq 1$ the optimal compensation scheme is of the following form:*

1. *When $\sigma < \frac{q_2}{q_1}\frac{1}{\delta}$*
   - (a) *if $CF_{MC} \geq \widehat{CF}$, Regime 1 applies for $n \leq \underline{\widehat{n}}$ and Regime 3 applies for $n \geq \underline{\widehat{n}}$*
   - (b) *if $CF_{MC} < \widehat{CF}$, Regime 1 applies for $n \leq \underline{n}$, Regime 2 applies for $\underline{n} < n < \hat{\hat{n}}$ and Regime 3 applies for $n \geq \hat{\hat{n}}$*
2. *When $\sigma \geq \frac{q_2}{q_1}\frac{1}{\delta}$, Regime 4 applies $\forall\ n$*

with

$$\widehat{CF} = a\left(-dq_1\right)^b \left(\left(\frac{q_2}{q_1}\frac{1}{\delta} \right)^b + (b-1)\,\sigma^b - \frac{q_2}{q_1}\frac{1}{\delta} b\sigma^{b-1} \right)$$

$$\widehat{\underline{n}} = \frac{a(-dq_1)^b\left(\left(\frac{q_2}{q_1}\frac{1}{\delta}\right)^b - \sigma^b\right) - CF_{MC}}{\left(-dq_1\frac{(1-\overline{\alpha})W}{\overline{\alpha}(1+\delta)}\right)\left(\frac{1}{q_1} - \frac{\delta}{q_2}\sigma\right)}; \qquad \underline{n} = ab\frac{(1+\delta)\overline{\alpha}}{(1-\overline{\alpha})W}\frac{q_2(-\sigma dq_1)^{b-1}}{\delta}$$

and $\widehat{\overline{n}}$ *is the solution of the equation* $F(n) = 0$ *with*

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

Proof. See Appendix B. ■

Regime 4 crucially depends on the discount parameter (σ) in the EA constraint. Especially, if we consider that $\delta = \frac{1}{\sigma}$ then this regime applies as soon as $q_2 < q_1$ which seems to be consistent in case of a damage in period 1.[10]

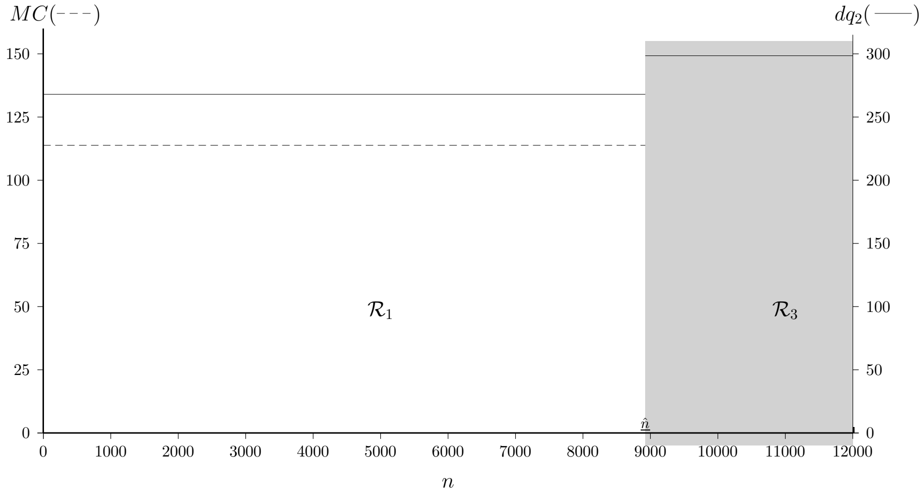
The three other regimes occur when the discount parameter is relatively high compared to the marginal rate of substitution between the environmental good in period 1 and 2 $\left(\frac{q_2}{q_1}\frac{1}{\delta} > \sigma\right)$.

Proposition 1 highlights the role of the fixed cost in the choice of the regime and gives the threshold values of n which determine the switch between one regime to another one. Figure 1 illustrates Case 1 of Proposition 1.[11] Under Case 1.b., the value of $\underline{n}$ increases with $\overline{\alpha}$, $(-dq_1)$, a and b, and decreases with W and δ. An agent who values more the future expects a lower 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 $\overline{\alpha}$) implies a lower need for compensation and the limit between both regimes is shifted to a higher level of n. The interval $(\underline{n}, \widehat{\overline{n}})$ on which Regime 2 applies is the largest for $CF_{MC} = 0$ and decreases with CF_{MC}. The discontinuity of the levels of dq_2 and MC between regimes 2 and 3 is due to the fixed costs in the cost function. Under Case 1.a., the fixed costs are too high ($CF_{MC} > \widehat{CF}$) and Regime 2 never applies since it is always too costly compared to Regime 3. $\widehat{CF}$ is increasing with a and b whereas it is not affected either by $\bar{\alpha}$ or W.

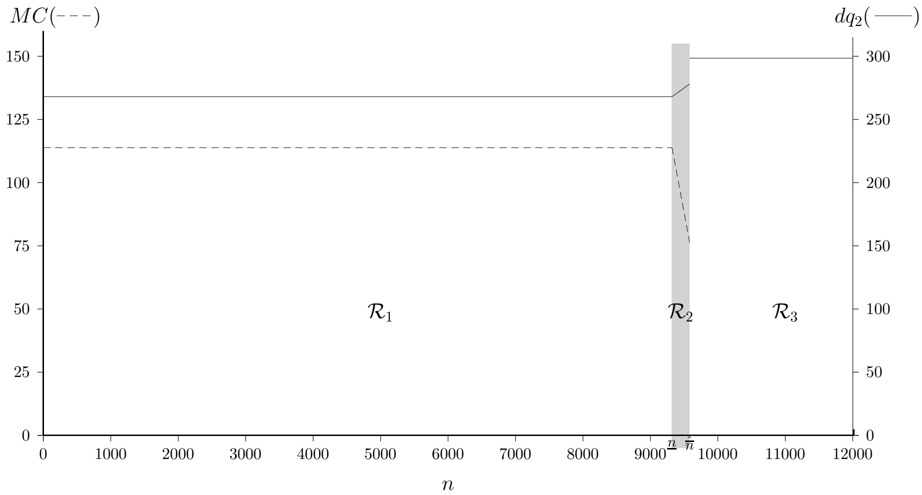
[10]This situation corresponds to the case where the discount rate (here $(\sigma - 1)$) equals the time preference rate ($(1-\delta)/\delta$).

[11]The following parameter set was used for numerical simulations: ($W = 372000$, $\overline{\alpha} = 0.8$, $\delta = 0.67$, $q_1 = 10000$, $q_2 = 10000$, $dq_1 = -200$, $a = 300$, $b = 1.75$, $\sigma = 1.34$)

In addition, Regime 1 is reduced ($\widehat{n} < \underline{n}$) because it is very costly to implement a monetary compensation.



(a) $CF_{MC} > \widehat{CF}$



(b) $CF_{MC} < \widehat{CF}$

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

For Regime 2, the impact of the environmental damage $(-dq_1)$ on the monetary compensation is obviously positive while the positive effect of $(-dq_1)$ on dq_2 is offset by the trade-off effect between MC and dq_2 due to the quasi linearity of the cost function.

The impact of wealth on compensation can be clearly explained by equation (10) which can be rewritten here as $\frac{\overline{WTA}^q}{\overline{WTA}^W} = \frac{n}{ab(dq_2)^{b-1}}$ where $\overline{WTA}$ represents the average willingness to accept. A rise in W diminishes the ratio of the average willingness to accept so that the environmental compensation becomes more cost efficient. It tends to increase the environmental compensation whereas the impact on monetary compensation depends on the willingness to accept effect ($\overline{WTA}^W$) relatively to the trade-off effect between both compensations. The willingness to accept effect diminishes with n so that the monetary compensation decreases with an increase of the wealth for a relatively large number of victims.[12] The impact of the mean preference for the private good ($\overline{\alpha}$) operates through the same channels. A raise in $\overline{\alpha}$ increases the environmental compensation and decreases the monetary compensation for a relatively large number of victims.[13]

The effect of the time preference is clear: the more the second period is valued in the utility, the higher is the level of required environmental compensation. The impact of δ on MC is also unambiguously negative through both the willingness to accept effect and the trade-off effect.

Figure 2 stresses the case without any EA constraint. As stipulated in the general 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. Under both regimes, $dq_2 > 0$ whatever the value of n. Nevertheless, the level of environmental compensation is low for small values of n.

When $b < 1$, the cost function is concave with respect to dq_2 which implies that the result is a corner solution of the problem of cost minimization.

Proposition 2 *For $b < 1$, the optimal compensation scheme is the following*

1. *If $\sigma < \frac{q_2}{q_1}\frac{1}{\delta}$ Regime 1 applies for $n \leq \widehat{n}$ and Regime 3 applies for $n \geq \widehat{n}$*

2. *If $\sigma \geq \frac{q_2}{q_1}\frac{1}{\delta}$ Regime 4 applies $\forall\ n$*

---

[12] $\frac{\partial MC}{\partial W} < 0 \Longleftrightarrow n > \overline{n}\left(\frac{b-1}{b}\right)^{b-1}$ where the value of $\overline{n}$ is given in Appendix B.

[13] The threshold level is again $\overline{n}\left(\frac{b-1}{b}\right)^{b-1}$

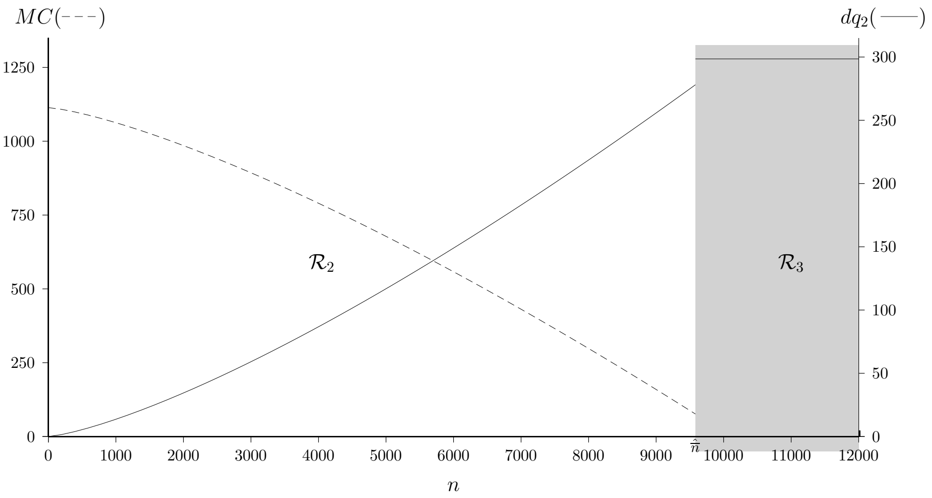


Figure 2: Compensation scheme without EA constraint (CS_0)

$$\textit{with } \widehat{n} = \frac{a(-dq_1)^{b-1}\left(\left(\frac{q_2}{q_1}\frac{1}{\delta}\right)^b - \sigma^b\right) - CF_{MC}}{W\frac{(1-\overline{\alpha})}{\overline{\alpha}(1+\delta)}\frac{\delta}{q_2}\left(\frac{q_2}{q_1}\frac{1}{\delta} - \sigma\right)}$$

Proof. See Appendix C. ■

With $b < 1$ the limit between regimes 1 and 3 is given by $\widehat{n}$. 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 longer an optimal level of mixed compensation and regime 1 switches directly to Regime 3 with the increase in n since only corner solutions enable to minimize the cost. Since condition (6) is not fulfilled, the trade-off mechanism does not work anymore and Regime 2 disappears.

Turning to the cost and welfare analysis, first recall that for a slightly high discount parameter, 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.[14] The agent that values the environmental good the most (lowest α_i) gains the most.

Figure 3 depicts the costs associated with the different compensation schemes (CS_0, CS_{Fenv}, CS_{Fmon} and with $CS^*_{\mathcal{R}_i}$ with $i = 1, 2$ and 3) for the case $b > 1$ and $\sigma < \frac{q_2}{q_1}\frac{1}{\delta}$.[15]

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

[15] CS_0 is decomposed in two parts:

- $dq_2 = \left(\frac{(1-\overline{\alpha})nW\delta}{\overline{\alpha}(1+\delta)q_2ab}\right)^{\frac{1}{b-1}}$ and $MC = \frac{(1-\overline{\alpha})W\left(\frac{-dq_1}{q_1}\right)}{(1+\delta)\overline{\alpha}} - \left(\frac{\delta(1-\overline{\alpha})W}{q_2(1+\delta)\overline{\alpha}}\right)^{\frac{b}{b-1}}\left(\frac{n}{ab}\right)^{\frac{1}{b-1}}$ $n < \widehat{n}$ *(Regime 2)*

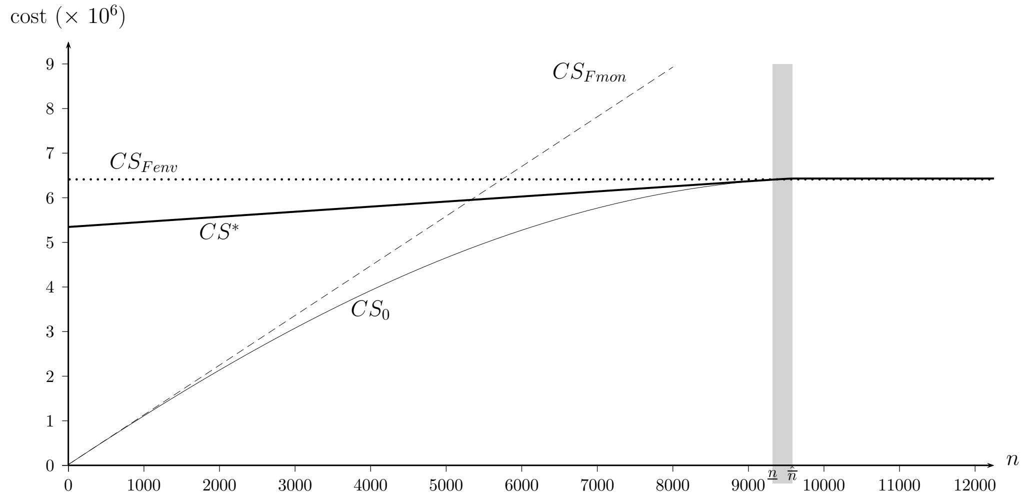


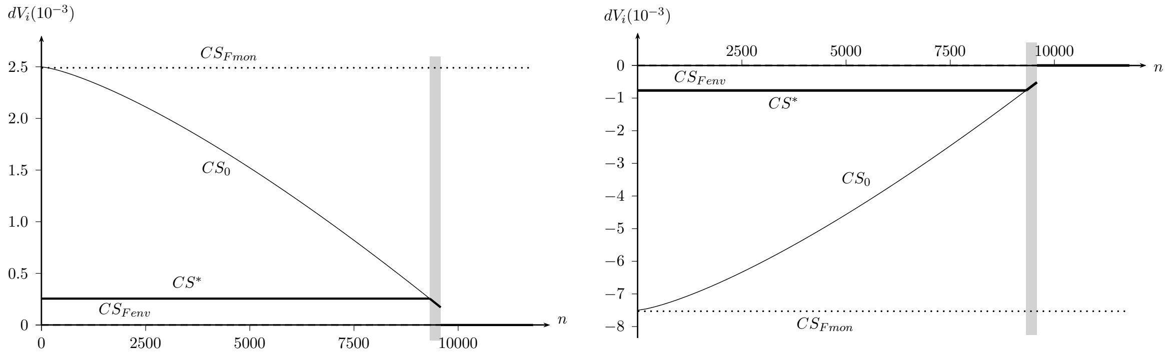
Figure 3: Costs associated with the four compensation schemes when $\sigma < \frac{q_2}{q_1}\frac{1}{\delta}$

We can clearly observe the ranking of costs described in the general case. This cost analysis must be put in perspective with the welfare analysis derived from the minimization program. Clearly it results in losers and winners in regimes 1 and 2. Since WTA_i^q is identical for each gain, the individual welfare change is determined by WTA_i^W which decreases with α_i. Individuals with $\alpha_i = \overline{\alpha}$ do not incur any individual welfare variations whereas individuals with $\alpha_i < \overline{\alpha}$ incur a welfare loss decreasing with α_i and n (Figure 4.a) and individuals with a $\alpha_i > \overline{\alpha}$ benefit from a welfare gain. This gain increases with α_i and decreases with n (Figure 4.b). Moreover inequities between losers and gainers are reduced as the share of the environmental compensation grows. Under Regime 3, each individual welfare remains unchanged. The compensation granted to all individuals corresponds to a pure intertemporal compensation with a good similar to the damaged one.

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

- $MC = 0$ and $dq_2 = -\frac{q_2}{q_1}\frac{1}{\delta}dq_1$ iff $n > \widehat{\overline{n}}$ *(Regime 3)*

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



(a) $\alpha_i = 0.9$ (winner)

(b) $\alpha_i = 0.5$ (loser)

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

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 worse in terms of equity compared to the other compensation schemes.

Finally, under Regime 3, every individual welfare loss from the damage is offset by the environmental compensation ($WTA_i^q = WTA^q \quad \forall i$). From a welfare perspective, a Full environmental compensation is the most appropriate solution since there is no welfare loss at both 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 weight the gains associated to the future environmental good respectively to the gains associated to the present environmental good (high σ), Regime 4 applies. This case is depicted in Figure 5.[16]

Under Regime 4, whatever the level of α_i, agents gain from compensation (except for $\alpha_i = 1$). In addition, the agents who value more the environmental goods gain more, as shown in Figure 6.[17]

[16]For the numerical simulation the new value of σ is 1.62.

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

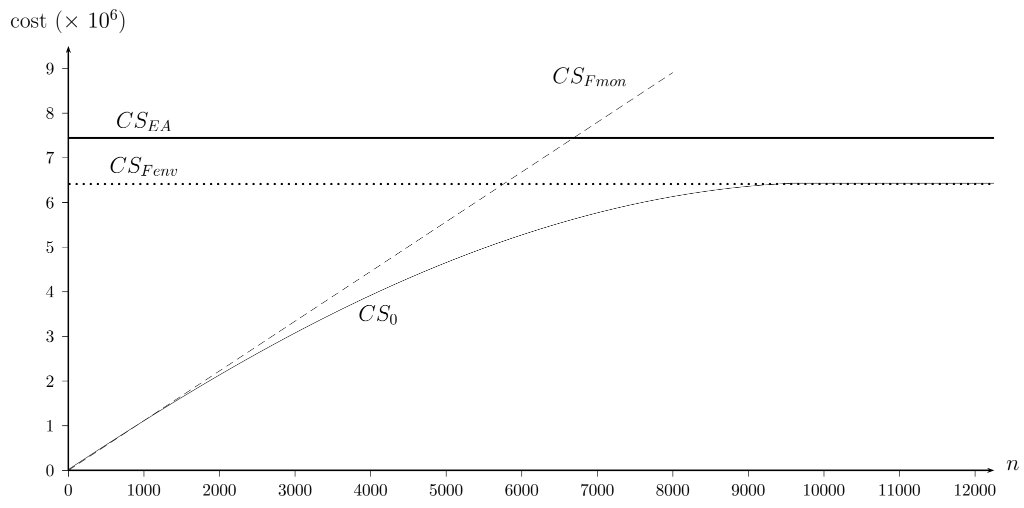
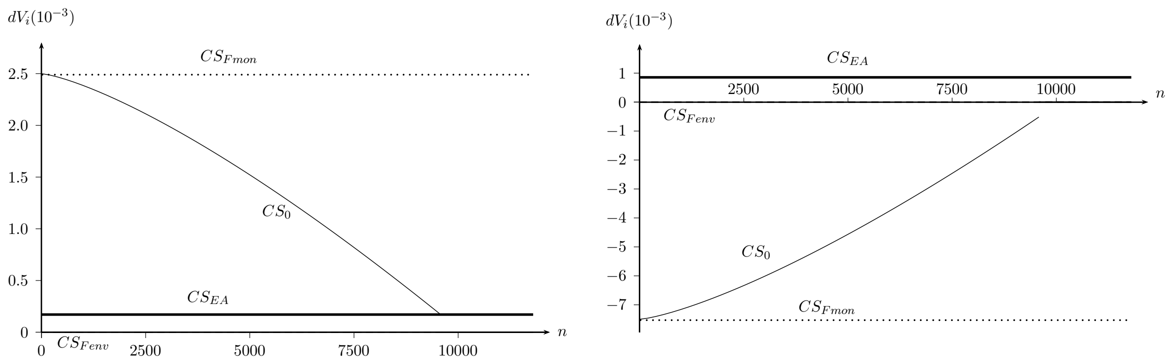


Figure 5: Costs associated with the alternative compensation schemes when $\sigma > \frac{q_2}{q_1}\frac{1}{\delta}$



(a) $\alpha_i = 0.9$

(b) $\alpha_i = 0.5$

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

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:

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

Solving the program described by Equations (5) to (8) leaves regimes 3 and 4 unchanged while the values for MC and dq_2 in regimes 1 and 2 are:

- Regime 1: $dq_2 = -dq_1\sigma$ and $MC = (-dq_1)\frac{(1-\alpha)}{\alpha(1+\delta)}\frac{\overline{W}}{I_W}\left(\frac{1}{q_1} - \frac{\delta}{q_2}\sigma\right)$

- Regime 2: $dq_2 = \left[\frac{n(1-\alpha)\delta}{ab\alpha(1+\delta)q_2}\frac{\overline{W}}{I_W}\right]^{\frac{1}{b-1}}$ and $MC = \frac{(1-\alpha)}{\alpha(1+\delta)}\frac{\overline{W}}{I_W}\frac{-dq_1}{q_1} - \left(\frac{(1-\alpha)}{\alpha(1+\delta)}\frac{\overline{W}}{I_W}\frac{\delta}{q_2}\right)^{\frac{b}{b-1}}\left[\frac{n}{ab}\right]^{\frac{1}{b-1}}$

where $\frac{1}{n}\sum_{i=1}^{n}\frac{\overline{W}}{W_i} = I_W \geq 1$ 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).[18]

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

Proposition 3 *For $b \geq 1$ the optimal compensation scheme is of the following form:*

1. *When $\sigma < \frac{q_2}{q_1}\frac{1}{\delta}$*

   (a) *if $CF_{MC} \geq \widehat{CF}$, Regime 1 applies for $n \leq \underline{\underline{\widehat{n}}}$ and Regime 3 applies for $n \geq \underline{\underline{\widehat{n}}}$*

   (b) *if $CF_{MC} < \widehat{CF}$, Regime 1 applies for $n \leq \underline{\underline{n}}$, Regime 2 applies for $\underline{\underline{n}} < n < \widehat{\overline{\overline{n}}}$ and Regime 3 applies for $n \geq \widehat{\overline{\overline{n}}}$*

2. *When $\sigma \geq \frac{q_2}{q_1}\frac{1}{\delta}$, Regime 4 applies $\forall\ n$*

with

$$\underline{\underline{\widehat{n}}} = \frac{a(-dq_1)^b\left(\left(\frac{q_2}{q_1}\frac{1}{\delta}\right)^b - \sigma^b\right) - CF_{MC}}{\left(-dq_1\frac{(1-\alpha)}{\alpha(1+\delta)}\frac{\overline{W}}{I_W}\right)\left(\frac{1}{q_1} - \frac{\delta}{q_2}\sigma\right)};\ \underline{\underline{n}} = ab\frac{(1+\delta)\alpha}{(1-\alpha)}\frac{I_W}{\overline{W}}\frac{q_2(-\sigma dq_1)^{b-1}}{\delta}$$

and $\widehat{\overline{\overline{n}}}$ is the solution of the equation $G(n) = 0$ with

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

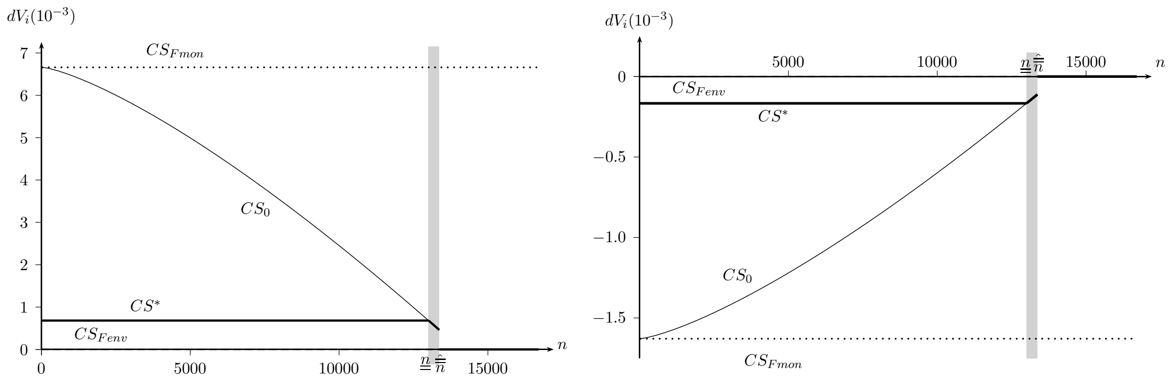
Proof. See Appendix D. ■

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 $\overline{W}/I_W$ instead of W with no heterogeneity. This expression highlights two different elements in the wealth heterogeneity:

[18] When considering the special case where $dq_2 = 0$, in analogy with Medin et al. (2001), MC corresponds to the per person 'benefit' when marginal utility of the environmental good is assumed to be identical. It is defined by $MC = \frac{n}{\sum_{n=1}^{n}\left(\frac{\partial v}{\partial W_i}/\frac{\partial v}{\partial q_1}\right)}(-dq_1)$. If marginal utility of income is assumed to be identical (i.e $I_W = 1$ in our case), then we have $MC = \frac{1}{n}\sum_{n=1}^{n}\left(\frac{\partial v}{\partial q_1}/\frac{\partial v}{\partial W_i}\right)(-dq_1) = \frac{1}{n}\sum_{n=1}^{n} WTA_i^W$.

the value of the average wealth (how rich the society is), and the distribution effect (how unequal the society is).

In Regime 2, the impact of $\overline{W}$ can be compared to the impact of W in the previous case. The impact of I_W is of opposite sign. Due to the concavity of the indirect utility function in wealth, a more inequal society implies a lower average monetary willingness to accept. Then all the mechanisms that operate with $\overline{W}$ still remain but go in the opposite side.



(a) $W_i = 100000$ (winner)

(b) $W_i = 450000$ (loser)

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

As already mentioned, monetary compensation will be in favor of individuals that value money the most. As shown in Figure 7.a the poorest individuals ($W_i < \overline{W}/I_W$) are the winners.[19] 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.

Proposition 4 *For $b < 1$, the optimal compensation scheme is the following*

1. *If $\sigma < \frac{q_2}{q_1}\frac{1}{\delta}$ Regime 1 applies for $n \leq \widetilde{n}$ and Regime 3 applies for $n \geq \widetilde{n}$*
2. *If $\sigma \geq \frac{q_2}{q_1}\frac{1}{\delta}$ Regime 4 applies $\forall\ n$*

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

[19] The following parameter set was used for numerical simulation: ($\overline{W} = 400000$, $I_W = 1.5$, $\overline{\alpha} = 0.8$, $\delta = 0.67$, $q_1 = 10000$, $q_2 = 10000$, $dq_1 = -200$, $a = 300$, $b = 1.75$, $\sigma = 1.34$).

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

$$\widetilde{C}_3 < \widetilde{C}_1 \Longleftrightarrow n > \frac{\frac{\overline{W}}{I_W} a \left(-dq_1\right)^{b-1} \left(\left(\frac{q_2}{q_1} \frac{1}{\delta} \right)^b - \sigma \right) - CF_{MC}}{\frac{(1-\alpha)}{\alpha(1+\delta)} \frac{\delta}{q_2} \left(\frac{q_2}{q_1} \frac{1}{\delta} - \sigma \right)} = \widetilde{n} \quad \blacksquare$$

For $b < 1$, the level of n which seperates 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, without the equivalency constraint the environmental compensation will not be provided since the cost of repair is to high. Although this constraint increases cost inefficiency, it 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.

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 population and as a consequence, accepts a lower level of money to compensate the damage it incurs. This mechanism extends the use of monetary compensation. Moreover, if this poor population is relatively small, the polluter will be induced not to undertake any prevention measures to avoid potential environmental damage since the cost incurred for compensation in case of damage will be small.

Moreover, as shown in this paper, whether the ecological constraint is included or not 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 crucial 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 compensations 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 the next step. Both time preference issues and discount rate issues would be relevant topics for further research in a dynamic perspective.

Acknowledgements

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Appendix

A. Values of dq_2 and MC for each regime

The aggregate welfare function can be rewritten as

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

Condition (6) becomes

$$d\mathcal{W} = (1+\delta)\frac{n\overline{\alpha}}{W}MC + \frac{n(1-\overline{\alpha})}{q_1}dq_1 + n\delta\frac{(1-\overline{\alpha})}{q_2}dq_2 = 0 \tag{16}$$

so that

$$MC = W\frac{(1-\overline{\alpha})}{\overline{\alpha}(1+\delta)}\left(\frac{-dq_1}{q_1} - \frac{\delta}{q_2}dq_2\right) \tag{17}$$

or

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

Rewriting the cost function in dq_2 according to (17) for $MC > 0$ gives

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

which is clearly quasi-convex in dq_2 if and only if $b \geq 1$.

Minimizing this cost function gives

$$dq_2 = \left(\frac{(1-\overline{\alpha})nW\delta}{\overline{\alpha}(1+\delta)q_2ab}\right)^{\frac{1}{b-1}} \tag{19}$$

and condition (8) gives the value for MC

$$MC = \frac{(1-\overline{\alpha})W\left(\frac{-dq_1}{q_1}\right)}{(1+\delta)\overline{\alpha}} - \left(\frac{\delta(1-\overline{\alpha})W}{q_2(1+\delta)\overline{\alpha}}\right)^{\frac{b}{b-1}}\left(\frac{n}{ab}\right)^{\frac{1}{b-1}} \tag{20}$$

we can deduce

regime 1: $dq_2 = -\sigma dq_1$ and MC is derived from (17)

regime 2: dq_2 and MC are given by (19) and (20)

regime 3: $MC = 0$ and dq_2 is derived from (18)

regime 4: $MC = 0$ and $dq_2 = -dq_1\sigma$

B. Proof of Proposition 1

Under Regime 2, conditions (7) and (8) imply

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

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

The interval on which Regime 2 may apply is reduced to $n \in \left]\underline{n}, \overline{n}\right[$.

Both conditions will be fulfilled iff

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

- If $\sigma > \left(\frac{q_2}{q_1}\frac{1}{\delta}\right)$, which implies $\underline{n} > \overline{n}$, none of the conditions (7) and (8) are fulfilled so that both compensations are implemented at their minimal level whatever the level of n, i.e. $MC = 0$ and $dq_2 = -dq_1\sigma$ (Regime 4).
- If $\sigma < \left(\frac{q_2}{q_1}\frac{1}{\delta}\right)$ we have $\overline{n} > \underline{n}$

  To check which regime (1, 2 or 3) is optimal to implement, we have to compare the costs associated with the different regimes. The optimal regime is the one which implies the lowest cost.

  Under regime 1 the cost reduces to

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

  under Regime 2 the cost becomes

$$C_2 = n\frac{(1-\overline{\alpha})\left(-\frac{dq_1}{q_1}\right)W}{(1+\delta)\,\overline{\alpha}} + a\,(1-b)\left(\frac{(1-\overline{\alpha})nW\delta}{\overline{\alpha}(1+\delta)q_2ab}\right)^{\frac{b}{b-1}} + CF_{MC}$$

  and under Regime 3

$$C_3 = a\left(\frac{q_2}{q_1}\frac{1}{\delta}\,(-dq_1)\right)^b$$

  Let us compare C_1 to C_3

$$C_1 < C_3 \Longleftrightarrow n < \frac{a\,(-dq_1)^b\left(\left(\frac{q_2}{q_1}\frac{1}{\delta}\right)^b - \sigma^b\right) - CF_{MC}}{\left(-dq_1\frac{(1-\overline{\alpha})W}{\overline{\alpha}(1+\delta)}\right)\left(\frac{1}{q_1} - \frac{\delta}{q_2}\sigma\right)} = \widehat{\underline{n}}$$

with

$$\underline{\widehat{n}} > \underline{n} \Longleftrightarrow CF_{MC} < a\left(-dq_1\right)^b \left(\left(\frac{q_2}{q_1}\frac{1}{\delta}\right)^b - (1-b)\,\sigma^b - \frac{q_2}{q_1}\frac{1}{\delta}b\sigma^{b-1}\right) = \widehat{CF}$$

Now, let us compare C_2 to C_3

$$C_2 < C_3 \Longleftrightarrow n\frac{(1-\overline{\alpha})\left(-\frac{dq_1}{q_1}\right)W}{(1+\delta)\,\overline{\alpha}} + n^{\frac{b}{b-1}}a\,(1-b)\left(\frac{(1-\overline{\alpha})W\delta}{\overline{\alpha}(1+\delta)q_2ab}\right)^{\frac{b}{b-1}} + CF_{MC} < a\left(\frac{q_2}{q_1}\frac{1}{\delta}\left(-dq_1\right)\right)^b$$

we define

$$\begin{aligned} F\left(n\right) &= n\frac{(1-\overline{\alpha})\left(-\frac{dq_1}{q_1}\right)W}{(1+\delta)\,\overline{\alpha}} - n^{\frac{b}{b-1}}a\,(b-1)\left(\frac{(1-\overline{\alpha})W\delta}{\overline{\alpha}(1+\delta)q_2ab}\right)^{\frac{b}{b-1}} + CF_{MC} - a\left(\frac{q_2}{q_1}\frac{1}{\delta}\left(-dq_1\right)\right)^b \\ F'\left(n\right) &= \frac{(1-\overline{\alpha})\left(-\frac{dq_1}{q_1}\right)W}{(1+\delta)\,\overline{\alpha}} - n^{\frac{1}{b-1}}ab\left(\frac{(1-\overline{\alpha})W\delta}{\overline{\alpha}(1+\delta)q_2ab}\right)^{\frac{b}{b-1}} < 0 \end{aligned}$$

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

Then $F\left(n\right)$ increases on $[0, \overline{n}]$

$$\begin{aligned} F\left(\overline{n}\right) &= CF_{MC} > 0 \\ F\left(\underline{n}\right) &= a\left(-dq_1\right)^b\left(b\frac{q_2\sigma^{b-1}}{q_1\delta} - \sigma^b\,(b-1) - \left(\frac{q_2}{q_1}\frac{1}{\delta}\right)^b\right) + CF_{MC} < 0 \\ &\Longleftrightarrow CF_{MC} < a\left(-dq_1\right)^b\left(\sigma^b\,(b-1) + \left(\frac{q_2}{q_1}\frac{1}{\delta}\right)^b - b\sigma^{b-1}\frac{q_2}{q_1\delta}\right) = \widehat{CF} \end{aligned}$$

Then if $CF < \widehat{CF}$, there exists a $\widehat{\widehat{n}} \in [\underline{n}, \overline{n}]$ such that $F\left(\widehat{\widehat{n}}\right) = 0$ ($C_2 = C_3$) and if $CF > \widehat{CF}$ we have $C_2 > C_3\ \forall\, n > \underline{n}$.

C. Proof of Proposition 2

Rewriting the cost function in MC for $MC > 0$ according to (17) gives

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

Which is clearly concave in MC for $b < 1$. Minimizing the cost leads to $MC = 0$ (condition (8)). The value of dq_2 is then derived from (18) which corresponds to Regime 3 if $\sigma < \frac{q_2}{q_1\delta}$ and to Regime 4 otherwise.[20]

[20] Condition $\sigma < \frac{q_2}{q_1\delta}$ ensures $dq_2 > -dq_1\sigma$ for $dq_2 = \frac{-dq_1}{q_1}\frac{q_2}{\delta}$

Rewriting the cost function in dq_2 for $MC > 0$ according to (17) gives

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

which is clearly concave in dq_2 for $b < 1$ so that the only solution which minimizes the cost is again a corner solution. According to condition (7) minimizing the cost requires $dq_2 = -dq_1\sigma$. The value of MC is derived from (17), which corresponds to Regime 1 if $\sigma < \frac{q_2}{q_1\delta}$ and to Regime 4 otherwise.[21]

We now compare Regime 1 and Regime 3.

Under Regime 3, the cost reduces to

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

whereas under Regime 1, the cost reduces to

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

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

D. Proof of Proposition 3

Similarly to the Proof of Proposition 1, conditions (7) and (8) imply:

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

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

both conditions can be fulfilled iff

$$\overline{\overline{n}} > \underline{\underline{n}} \iff \frac{q_1}{q_2} < \frac{1}{\delta\sigma}$$

The comparison of costs gives

$$C_1 < C_3 \iff n < \frac{a\left(-dq_1\right)^b\left(\left(\frac{q_2}{q_1}\frac{1}{\delta}\right)^b - \sigma^b\right) - CF_{MC}}{\left(-dq_1\frac{(1-\alpha)\frac{\overline{W}}{I_W}}{\alpha(1+\delta)}\right)\left(\frac{1}{q_1} - \frac{\delta}{q_2}\sigma\right)} = \widehat{\underline{\underline{n}}}$$

[21] Condition $\sigma < \frac{q_2}{q_1\delta}$ ensures $MC > 0$ when $MC = -dq_1 W\frac{(1-\overline{\alpha})}{\overline{\alpha}(1+\delta)}\left(\frac{1}{q_1} - \frac{\delta}{q_2}\sigma\right)$

with

$$\underline{\underline{\widehat{n}}} < \underline{\underline{n}} \Longleftrightarrow CF_{MC} > \widehat{CF}$$

and

$$C_2 < C_3 \Longleftrightarrow n\frac{(1-\alpha)\left(-\frac{dq_1}{q_1}\right)\frac{\overline{W}}{I_W}}{(1+\delta)\,\alpha} + n^{\frac{b}{b-1}} a\,(1-b)\left(\frac{(1-\alpha)W\delta}{\alpha(1+\delta)q_2 ab}\right)^{\frac{b}{b-1}} + CF_{MC} < a\left(\frac{q_2}{q_1}\frac{1}{\delta}\,(-dq_1)\right)^b$$

With

$$\begin{aligned}
G\,(n) &= n\frac{(1-\alpha)\left(-\frac{dq_1}{q_1}\right)\frac{\overline{W}}{I_W}}{(1+\delta)\,\alpha} - n^{\frac{b}{b-1}} a\,(b-1)\left(\frac{(1-\alpha)W\delta}{\alpha(1+\delta)q_2 ab}\right)^{\frac{b}{b-1}} + CF_{MC} - a\left(\frac{q_2}{q_1}\frac{1}{\delta}\,(-dq_1)\right)^b \\
G'\,(n) &= \frac{(1-\alpha)\left(-\frac{dq_1}{q_1}\right)\frac{\overline{W}}{I_W}}{(1+\delta)\,\alpha} - n^{\frac{1}{b-1}} ab\left(\frac{(1-\alpha)W\delta}{\alpha(1+\delta)q_2 ab}\right)^{\frac{b}{b-1}} < 0 \Longleftrightarrow n > \overline{\overline{n}} \\
G\,(\overline{n}) &= CF_{MC} > 0 \quad \text{and} \quad G\,(\underline{n}) < 0 \Longleftrightarrow CF_{MC} < \widehat{CF}
\end{aligned}$$

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