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Altruistic Foreign Aid and Climate Change Mitigation

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Abstract

This paper emphasizes the value of jointly addressing environmental and development objectives. We consider one altruistic developed country and several heterogeneous developing countries. We demonstrate that the lack of coordination between countries in tackling climate change finds a simple solution if developing countries can expect to receive development aid transfers from the developed country. The timing of the decision is central to the mechanism: development aid transfers should be determined after pollution abatement levels. The main restriction of our result is that it only holds if the developed country is altruistic enough to make positive development aid transfers to developing countries. Nevertheless, even from a purely selfish point of view, it may be profitable for the developed country to be more altruistic, leading to higher welfare for all countries.

Keywords: Public good provision; Altruism; Climate change; Development aid.

JEL codes: D6; Q5; O1.

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1 Introduction

In a world of rising inequalities and climate change, development and environmental policies are of crucial importance and represent a major challenge for governmental and international institutions. Combating climate change requires efforts from all countries, even if they differ in terms of wealth. Determining and achieving these efforts will require coordination between countries. The public-good aspect of pollution emissions abatement is such that coordination failures typically lead to insufficient abatement. Moreover, emissions reduction efforts are extremely demanding for developing countries, which face several other challenges such as health, education, and peace. Ambitious development policies are hence a prerequisite if the poorest countries are to have the capacity to implement environmental policies. Yet development and environmental policies are often considered separately. The United Nations, for example, splits its activities into two separate initiatives: the United Nations Development Programme and the United Nations Environment Programme. In the United States, development and environmental affairs are delegated to two powerful independent agencies, the US Agency for International Development and the Environmental Protection Agency. In recent years only, attempts have been made to link the two aspects. For instance, the United Nations launched the Poverty-Environment Initiative to connect its Development and Environment Programmes. Similarly, in 2018 at the COP 24 (24th Conference of the Parties on climate change), the World Bank Group announced that it would invest 200 billion US dollars to support developing countries' actions against climate change from 2021 to 2025.

The current paper emphasizes the value of addressing both environmental and development objectives in a single framework. In particular, it is shown that the well-designed interconnection of development and environmental policies can help to solve coordination problems between developed and developing countries. Our model comprises one developed country and several heterogeneous developing countries. All countries are assumed to be concerned about their own consumption and the sum of all emissions abatement. In addition, the developed country is altruistic and hence cares about the welfare of the developing countries. Countries fail to properly internalize the benefits of their emissions abatement on other countries, which typically generates inefficient abatement decisions.[1]

This paper shows that the coordination problem finds a simple solution if developing countries can expect to receive development aid transfers from the developed country. Although the developing countries take no interest in other countries' welfare, they anticipate that making sub-optimal environmental efforts will lower the transfers they receive from the developed country through two effects. First, the developed country will be more affected by pollution and will therefore increase its abatement efforts, leaving fewer resources for development aid purposes. Second, other developing countries will be more affected by pollution and will thus attract a greater share of the development aid. Once the endogeneity of development aid transfers is properly taken into account, the best strategy for the developing countries is to abate exactly the socially optimal level. This strategy provides the developing countries with the best combination of monetary transfers and environmental benefits.

The timing of the decision is central to the mechanism. For incentives to work properly, development aid transfers should be determined after all abatement decisions have been made. In practice, this means that developed countries should not commit to a given amount of aid, but rather communicate on their degree of altruism, which will determine the transfers they will make once all abatement decisions have been made. The coordination problem is ultimately solved thanks to developing countries' anticipation of the forthcoming development aid transfer.

An interesting aspect of the mechanism is that there is no need to observe each country's abatement effort and its related cost. In the first stage, each country only needs to observe the aggregate abatement effort to make its abatement decision. In the second stage, the developed country only needs to observe the available wealth of each developing country to make its transfer decision.

The main restriction of our result is that it only holds if the developed country is altruistic enough to make positive development aid transfers to the developing countries. Otherwise, the developing countries will anticipate that they will receive no aid and will tend to reduce their efforts. This restriction relates to a serious problem in today's world where key players are increasingly inclined to reduce their transfers to developing countries. However, a final interesting result of our paper is that more al-

[1] The difficulties that countries experience when attempting to agree emissions reduction levels during the various rounds of the United Nations Climate Change Conferences highlight this coordination problem.

truistic behavior may be profitable even from a purely selfish point of view. If altruism increases the amount of development aid, it may also enhance private utility (i.e. without accounting for the altruistic part of the utility), since positive aid transfers solve the coordination problem.

To the best of our knowledge, no other papers have examined this particular issue. The current paper contributes to several strands of literature such as development economics with altruistic transfers (for instance, Azam and Laffont (2003) and Svensson (2000)) and environmental economics on multilateral externalities and international agreements (for instance, Barrett (2001), Helm and Wirl (2014, 2016) and Martimort and Sand-Zantman (2016)). It adds to the literature at the intersection of development and environmental economics (for instance, Bretschger and Suphaphiphat (2014) and Chambers and Jensen (2002)). The paper is also connected to the literature on household behavior, and more specifically the Rotten Kid Theorem introduced by Becker (1974) and further investigated by Bergstrom (1989), which relates to the impact of altruistic transfers in sequential games.

The remainder of the paper is structured as follows. Section 2 presents our modeling assumptions. In Section 3, we determine the Pareto optimal allocations. Section 4 analyzes the interaction between abatement and transfer decisions and compares two decision processes: simultaneous and sequential decisions. Section 5 examines how our results depend on the degree of altruism. Finally, Section 6 concludes.

2 Setting

We consider $n+1$ countries indexed by $i \in \{0,..,n\}$. Each country $i \in \{0,..,n\}$ has an exogenous endowment $w_i \in \mathbb{R}_+$ and emits greenhouse gases (GHG), which generate global pollution. Countries can abate an amount $a_i \in \mathbb{R}_+$ of GHG emissions at a cost of $c_i(a_i)$. The function $a_i \to c_i(a_i)$ is twice continuously differentiable, increasing and convex. We assume $c_i(0) = 0$ and $c_i'(0) = 0$ to avoid corner solution for emissions abatement (i.e. $a_i = 0$).[2] We denote the vector of emissions abatement by $\boldsymbol{a} = (a_0, \cdots, a_n)$. The total amount of emissions abatement is $A = \sum_{i=0}^{n} a_i$, which benefits all countries. More precisely, each country $i \in \{0, \cdots, n\}$ is assumed to obtain a benefit

[2] Extending the analysis to allow for corner solutions for emissions abatement would be rather straightforward. This would however lengthen the mathematical parts without offering additional insights.

$b_i(A)$ from global emissions abatement, where the function $b_i(.)$ is twice continuously differentiable, increasing, and concave, with $b_i'(\infty) = 0$. The aggregate benefit function is $B(.) = \sum_{i=0}^{n} b_i(.)$.

Country 0 differs from the others by being altruistic. This may lead country 0 to transfer an amount m_i to country i. We denote the vector of transfers paid by country 0 by $\boldsymbol{m} = (m_1, \cdots, m_n)$ and the aggregate level of transfers by $M = \sum_{i=1}^{n} m_i$. For the sake of simplicity, we will generally use the adjective "developed" to refer to country 0 and the adjective "developing" to refer to countries $1, \cdots, n$, although our analysis does not require us to make formal assumptions about the distribution of w_i.

The developing countries ($i \in \{1, .., n\}$) are selfish and derive a utility

$$U_i = u_i \left(w_i - c_i(a_i) + b_i(A) + m_i \right), \tag{1}$$

where the function u_i is increasing and concave. The developed country is altruistic and derives a utility

$$U_0 = u_0 \left(w_0 - c_0(a_0) + b_0(A) - M \right) + \sum_{i=1}^{n} \lambda_i U_i, \tag{2}$$

where the function u_0 is increasing and concave. The U_i are the utilities of the developing countries detailed in equation (1) and the weight $\lambda_i \geq 0$ determines the degree of altruism that country 0 has for country i. All utility functions (u_i, $i \in \{0, .., n\}$) are assumed to be twice continuously differentiable.

The setting described above is one in which a "public good" (aggregate abatement) is individually provisioned (through individual abatement activities). For the model to be fully specified, we need to assume a decision-process structure. We will in fact consider two decision processes and compare the outcomes they generate. In the first one, the "simultaneous choice model", abatement and transfer decisions are made simultaneously, generating a Nash-equilibrium. In the second one, the "sequential choice model", all countries first determine the level of abatement, solving a Nash equilibrium, and in a second stage the developed country determines the level of transfers. In this sequential choice model, decisions made in the first stage properly account for what will happen in the second stage. As we are interested in discussing how inefficient these decision processes may be, we start by characterizing the set of Pareto optimal allocations.

3 Pareto optimal allocations

The notion of Pareto optimality is standard and does not need to be introduced. Proposition 1 shows that all Pareto optimal allocations are characterized by the same emissions abatement vector. Pareto optimal allocations therefore only differ by the distribution of wealth across all countries. This distribution must, in any case, be such that consumption is non-negative in any country and the developed country could not be made better off by increasing its transfer to a developing country. Formally:

Proposition 1 *A pair* $(\boldsymbol{a}, \boldsymbol{m})$ *of abatement and transfer vectors achieves a Pareto optimal allocation if and only if:*

1. $\boldsymbol{a} = \boldsymbol{a}^{opt}$, *where* $\boldsymbol{a}^{opt}$ *is the unique solution of:*

$$\sum_{j=0}^{n} b_j'(A) = c_i'(a_i) \quad \textit{for } i \in \{0, \cdots, n\},$$

and:

2. $\boldsymbol{m}$ *is any vector of transfers such that:*

$$\sum_{j=1}^{n} m_j \leq w_0 - c_0(a_0^{opt}) + b_0(A^{opt})$$

and for all $i \in \{1, \cdots n\}$:

$$w_i - c_i(a_i^{opt}) + b_i(A^{opt}) + m_i \geq 0,$$
$$u_0'\Big(w_0 - c_0(a_0^{opt}) + b_0(A^{opt}) - \sum_{j=1}^{n} m_j\Big) \geq \lambda_i u_i'\Big(w_i - c_i(a_i^{opt}) + b_i(A^{opt}) + m_i\Big).$$

Proof. See Appendix A.1. ■

The optimal abatement levels are such that the effects of each country's abatement on all other countries are internalized. The fact that all Pareto optimal allocations involve the same abatement levels directly results from the assumption that wealth, abatement costs, and benefits are perfect substitutes. The result cannot be generalized to settings where the utility of country i would be a more complex function of w_i, a_i, and A. Such general frameworks are unfortunately relatively intractable, not to mention the calibration issues involved. Our simplified setting has the advantage of providing a simple understanding of the sub-optimalities that can result from non-cooperative decision processes.

It is noteworthy that some Pareto optimal allocations may require negative transfers, when resources flow from developing countries to the developed country. In the following, we will constrain transfers to be non-negative, reflecting the fact that the developed country cannot decide to take resources from the developing countries.

4 Interaction between aid and abatement decisions

We now compare two decision processes that may yield sub-optimal allocations, since they both use the concept of a Nash equilibrium. We find that sub-optimality is systematic with one of these decision processes (the "simultaneous choice model" considered in Section 4.1), while this is not the case with the other (the "sequential choice model" considered in Section 4.2). In our setting, we hence show that a way to avoid the sub-optimalities that typically arise in a Nash equilibrium with a public good is to choose an appropriate sequence of abatement and transfer decisions.

4.1 Simultaneous choice model

The first decision process we consider is one where abatement and transfer decisions are taken simultaneously. The outcome is assumed to form a Nash equilibrium. We use the subscript "sim" to refer to the outcome of the simultaneous decision model. The developed country takes the abatement levels $(a_1^{sim}, \cdots, a_n^{sim})$ of the developing countries as given, and chooses abatement a_0^{sim} and transfers $\boldsymbol{m}^{sim}$ to maximize its utility:

$$
\begin{aligned}
(a_0^{sim}, \boldsymbol{m}^{sim}) = \arg\max_{\boldsymbol{m}, a_0} u_0\Big(w_0 - c_0(a_0) + b_0(A) - \sum_{k=1}^{n} m_k\Big) + \sum_{i=1}^{n} \lambda_i U_i \\
\text{s.t.} \quad A = a_0 + \sum_{k=1}^{n} a_k^{sim}; \quad m_i \geq 0 \ \ \forall i \in \{1,..,n\}; \\
U_i = u_i\Big(w_i - c_i(a_i^{sim}) + b_i(A) + m_i\Big) \ \ \forall i \in \{1,..,n\}.
\end{aligned} \tag{3}
$$

A developing country $i \in \{1, \cdots, n\}$ takes the transfer m_i^{sim} and abatement levels a_j^{sim} for $j \neq i$ as given and chooses its own abatement to maximize its utility:

$$a_i^{sim} = \arg\max_{a_i} u_i\Big(w_i - c_i(a_i) + b_i(A) + m_i^{sim}\Big)$$
$$\text{s.t.} \quad A = a_i + \sum_{\substack{j=0 \\ j \neq i}}^{n} a_j^{sim}. \tag{4}$$

A Nash equilibrium is obtained when equations (3) and (4) hold simultaneously. Existence and uniqueness will be discussed in Section 5 (in the case where there is only one developing country). Independent of this technical aspect, such an equilibrium has the following property:

Proposition 2 *In the simultaneous choice model, aggregate abatement is strictly lower than in the Pareto optimal allocations ($\sum_{i=0}^{n} a_i^{sim} < \sum_{i=0}^{n} a_i^{opt}$). In the case where transfers are not strictly binding in 0 (i.e. when $m_i^{sim} > 0$ for all i), the abatement of the developed country is strictly larger than at the optimum ($a_0^{sim} > a_0^{opt}$).*

Proof. See Appendix A.2. ■

Proposition 2 shows that the simultaneous choice model yields an inefficiently low level of abatement. This reflects the fact that a Nash equilibrium typically provides a sub-optimal provision of public good. Interestingly, we see that when the developed country is wealthy and altruistic enough to provide positive transfers to developing countries, its own abatement level is above the level it needs to be at the optimum. The sub-optimality is therefore double-faceted. First, there is a low aggregate level of abatement involving a level of pollution higher than at the optimum. Second, this aggregate abatement is obtained through a mis-allocation of individual abatements, with too much abatement by the developed country and too little by the developing countries.

A way to restore optimality would be to allow a form of contracting where each transfer given to a developing country (m_i) is conditional on its level of abatement (a_i).[3] However, in this case, the developed country would have to observe the individual

[3] There is ongoing debate in the development economics literature as to whether foreign aid should be conditional on developing countries' efforts. Svensson (2000, 2003) and Azam and Laffont (2003), for instance, analyze whether it is efficient and feasible to implement conditional aid, without considering international environmental issues. Another area of debate in the environmental economics

abatement a_i and have perfect knowledge of both the cost functions $a_i \to c_i(a_i)$ and the benefit functions $A \to b_i(A)$. This assumption is questionable. Furthermore, committing to an allocation rule can be costly. The sequential game we develop below aims to solve sub-optimality without requiring individual abatement decisions and the related abatement costs to be observable.

4.2 Sequential choice model

We now consider a two-stage decision process. In the first stage, all countries choose their emissions abatement simultaneously, determining an abatement vector $\boldsymbol{a}^{seq}$ that solves a Nash equilibrium. The subscript "*seq*" is used to refer to the outcome of the sequential decision model. In the second stage, the developed country determines the transfers $\boldsymbol{m}^{seq}$. Importantly, all countries anticipate the second stage of the decision process when they choose their level of abatement $\boldsymbol{a}^{seq}$ in the first stage. The decision process can be formalized as follows:

Stage 2: At this stage, the developed country takes the abatement vector $\boldsymbol{a}^{seq}$ as given and chooses the transfer vector $\boldsymbol{m}^{seq}$ to maximize its utility:

$$\begin{aligned} \boldsymbol{m}^{seq} = \arg\max_{\boldsymbol{m}} \ & u_0\Big(w_0 - c_0(a_0) + b_0(A^{seq}) - \sum_{k=1}^{n} m_k\Big) + \sum_{i=1}^{n} \lambda_i U_i \\ & \text{s.t.} \quad A^{seq} = \sum_{k=0}^{n} a_k^{seq}; \quad m_i \geq 0 \ \ \forall i \in \{1,..,n\}; \\ & U_i = u_i\Big(w_i - c_i(a_i^{seq}) + b_i(A^{seq}) + m_i\Big) \ \ \forall i \in \{1,..,n\}. \end{aligned} \tag{5}$$

This optimization problem yields a reaction function $\boldsymbol{a}^{seq} \to \boldsymbol{m}^{seq}(\boldsymbol{a}^{seq})$. The lower the available wealth of a developing country $(w_i - c_i(a_i^{seq}) + b_i(A^{seq}))$, the more aid the developed country will transfer to the latter.

Stage 1: At this stage, all countries simultaneously choose their abatement levels, anticipating that altruistic transfers will adjust to abatement decisions through the function $\boldsymbol{a}^{seq} \to \boldsymbol{m}^{seq}(\boldsymbol{a}^{seq})$. The developed country takes the abatement levels

literature regards the form of the contracts to be implemented with multilateral externalities. Helm and Wirl (2014, 2016) and Martimort and Sand-Zantman (2016), for instance, analyze optimal conditional transfers in this context, without considering development aid motives.

$(a_1^{seq}, \cdots, a_n^{seq})$ of the developing countries as given, and implements a level of abatement provided by:

$$\begin{aligned} a_0^{seq} = \arg\max_{a_0} u_0\Big(w_0 - c_0(a_0) + b_0(A) - \sum_{k=1}^{n} m_k^{seq}(\boldsymbol{a})\Big) + \sum_{i=1}^{n} \lambda_i U_i \\ \text{s.t. } \; A = a_0 + \sum_{k=1}^{n} a_k^{seq}; \quad \boldsymbol{a} = (a_0, a_1^{seq}, \cdots, a_n^{seq}); \\ U_i = u_i\Big(w_i - c_i(a_i^{seq}) + b_i(A) + m_i^{seq}(\boldsymbol{a})\Big) \;\; \forall i \in \{1, .., n\}. \end{aligned} \tag{6}$$

The developing country $i \in \{1, \cdots, n\}$ takes abatement a_j^{seq}, for $j \neq i$, as given, and implements a level of abatement provided by:

$$\begin{aligned} a_i^{seq} = \arg\max_{a_i} u_i\Big(w_i - c_i(a_i) + b_i(A) + m_i^{seq}(\boldsymbol{a})\Big) \\ \text{s.t. } \; A = a_i + \sum_{\substack{j=0 \\ j \neq i}}^{n} a_j^{seq}; \quad \boldsymbol{a} = (a_0^{seq}, \cdots, a_i, \cdots, a_n^{seq}). \end{aligned} \tag{7}$$

A Nash equilibrium is obtained when equations (6) and (7) hold simultaneously. Existence and uniqueness will also be discussed in Section 5. Resolution of the sequential choice model is relatively complicated. In particular, we need to consider the non-negativity constraint imposed on transfers. This constraint means that the functions $a_i \to m_i^{seq}(a_0^{seq}, \cdots, a_i, \cdots, a_n^{seq})$ are, in general, not concave (these functions are typically flat and equal to zero for low values of a_i and then positive when a_i is above some threshold). This in turn implies that the maximization problems of developing countries are typically not convex, with multiple solutions in some cases. The impact of these non-convexities will be further investigated in Section 5. We can, however, state an important result, which holds when all transfers are positive.

Proposition 3 *In the sequential choice model, if all transfers are strictly positive, then the allocation is Pareto optimal (i.e. $m_i^{seq} > 0$ for all $i \Rightarrow \boldsymbol{a}^{seq} = \boldsymbol{a}^{opt}$).*

Proof. See Appendix A.3. ■

Proposition 3 shows that even if all countries are engaged in a non-cooperative game of public good provision (abatement decisions follow from a Nash equilibrium), altruistic transfers may play the role of a coordinating device, providing a Pareto-efficient outcome. The outcome obtained in this sequential model is actually the one that the developed country would choose if it had perfect knowledge of all abatement cost and benefit functions, and if it could determine all actions (including the abatement of developing countries). What is remarkable, though, is that the sequential choice model is able to implement such an outcome, without the developed country observing the abatement levels of developing countries and their related costs. In addition to its own cost function $c_0(.)$, the developed country needs to know the aggregate benefit function $B(.)$ and must be able to observe the aggregate abatement A in order to choose its abatement level a_0. It must also be able to observe the available wealth $w_i - c_i(a_i^{seq}) + b_i(A^{seq})$ of each developing country to determine the transfers $\boldsymbol{m}$. This is less restrictive than imposing knowledge of a_i and the functions $c_i(.)$. In addition to their own cost functions, developing countries need to know that the developed country is sufficiently wealthy and altruistic to make strictly positive transfers. Developing countries also need to know the aggregate benefit function and must be able to observe the aggregate abatement in order to choose their abatement level a_i.

From a theoretical point of view, Proposition 3 is closely related to the Rotten Kid Theorem, initially introduced by Becker (1974) in a specific setting and more broadly investigated by Bergstrom (1989). The Rotten Kid Theorem states that, if a household head cares about other household members (i.e. "kids") and can reallocate wealth between household members, then it is in the interest of all household members to pursue measures that maximize the utility of the household head. Our analytical framework differs from the latter in two aspects. First, in the Rotten Kid Theorem, the household head can reallocate wealth between children with no constraints, while in our scenario, the developed country can only transfer some of its private wealth to developing countries, which implies that transfers might be binding in 0. Second, in the Rotten Kid Theorem, all the children play first and the household head only plays after. In our model, all countries, including the developed country, determine their abatement at the same time. The follower (the developed country in our scenario, the household head in Becker's setting) is thus assumed to make a decision from the first stage of the game. These two differences compared with the Rotten Kid Theorem generate significant differences, such as the possibility of multiple equilibria (see Section 5).

A key property known from Bergstrom (1989) and required for the Rotten Kid Theorem to hold is that of transferable utilities, which in our setting comes from the assumption that wealth, costs, and benefits are perfect substitutes. While this assumption may appear reasonable if we see abatement costs and benefits as variations on production levels, it would no longer be the case if we introduced other forms of benefits, such as changes in health and mortality. This is certainly an important limitation of our analysis, although it is also found in most of the economics literature on climate change.

A significant restriction of Proposition 3 is that it only holds in the case where the transfers m_i^{seq} are strictly positive. This may not reflect today's reality, where transfers remain limited and where they are not exclusively motivated by altruistic purposes.[4] This is a legitimate source of concern, especially in a period where altruistic policies appear to be declining in popularity. In the next section, however, we explain why our framework could provide an argument for being more altruistic.

5 Considerations on altruism

In this section, we aim to explain the effects of being more or less altruistic. In order to simplify the analysis, we focus on a scenario where there is only one developed country and one developing country (which corresponds to the case where $n = 1$). Most of the insights would actually extend to the case where many countries are at play, though the analysis would be much more cumbersome. Instead of having a single source of non-convexity, there would be n sources, which would complicate our discussion of equilibrium existence and multiplicity.

In all of the following, we consider the wealth levels w_0 and w_1 as given and we denote the developed country's degree of altruism by λ_1. We discuss the impact of λ_1 on the outcome of the sequential and simultaneous choice models. We first state a result about the existence of a Nash equilibrium in the simultaneous choice model, which holds for all values of λ_1.

Proposition 4 *In the simultaneous choice model with two countries, a unique Nash equilibrium exists for all* $\lambda_1 \geq 0$.

Proof. See Appendix A.4. ■

We now state a result regarding the existence of a Nash equilibrium in the sequential choice model and its properties.

[4] According to Alesina and Dollar (2000), donors are driven by several motives, such as altruism, past history, or geographical proximity.

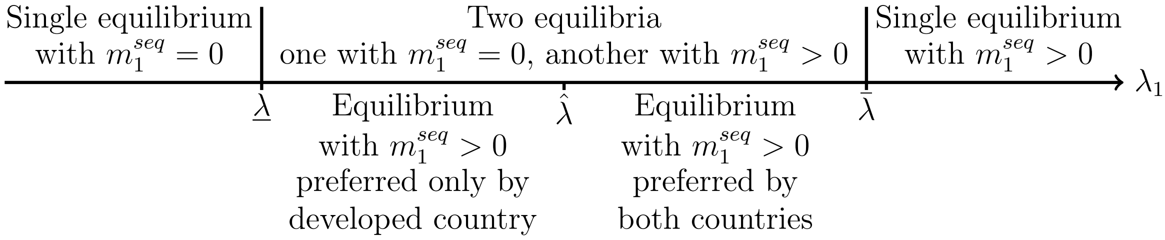

Figure 1: Equilibria characteristics in function of the degree of altruism in the sequential choice model.

Proposition 5 *In the sequential choice model with two countries (subject to three technical conditions detailed at the beginning of Appendix A.5), scalars $\underline{\lambda} < \hat{\lambda} < \bar{\lambda}$ exist such that:*

1. *If $\lambda_1 < \underline{\lambda}$, a single Nash equilibrium exists and the transfer level is $m_1^{seq} = 0$.*

2. *If $\underline{\lambda} \leq \lambda_1 \leq \bar{\lambda}$, two Nash equilibria exist, an equilibrium with a transfer level of $m_1^{seq} = 0$ and an other equilibrium such that $m_1^{seq} > 0$.*

3. *If $\bar{\lambda} < \lambda_1$, a single Nash equilibrium exists and the transfer level is $m_1^{seq} > 0$.*

Moreover, if $\underline{\lambda} \leq \lambda_1 < \hat{\lambda}$, the Nash equilibrium with $m_1^{seq} > 0$ is preferred by the developed country to the Nash equilibrium with $m_1^{seq} = 0$, but this is not the case for the developing country. If $\hat{\lambda} \leq \lambda_1 \leq \bar{\lambda}$, the Nash equilibrium with the $m_1^{seq} > 0$ Pareto-dominates the Nash equilibrium with $m_1^{seq} = 0$.

Proof. See Appendix A.5. ■

Figure 1 summarizes the finding of Proposition 5, indicating which equilibrium (or equilibria) exists depending on the degree of altruism λ_1. For low levels of altruism ($\lambda_1 < \underline{\lambda}$), the transfer is always equal to zero and there is no gain in announcing that transfers are possible at the second stage. The developing country anticipates that there will be no transfer, and has no incentive to choose the socially optimal abatement level as in the simultaneous choice model. For high levels of altruism ($\lambda_1 > \bar{\lambda}$), the transfer is always strictly positive. The sequential choice model delivers the virtuous outcome described in Proposition 3, as the transfer incentivizes the developing country to choose the socially optimal abatement level. For intermediate levels of altruism ($\underline{\lambda} < \lambda_1 < \bar{\lambda}$), two equilibria exist, one with and one without transfer. Moreover, the developed country always prefers the equilibrium with transfer, while the preference of the developing country depends on the level of altruism. When λ_1 is below $\hat{\lambda}$, the developing country prefers the equilibrium without transfer. When λ_1 is above $\hat{\lambda}$, the developing country prefers the equilibrium with transfer, which implies that this equilibrium Pareto-dominates the equilibrium without transfer.

Interestingly, this equilibrium multiplicity implies the existence of possible "climate traps", where transfers are null and aggregate abatement low, while a Pareto-dominating equilibrium with positive transfer and higher aggregate abatement could exist. We also see that, regardless of the equilibrium selection mechanism assumed, the outcome will be a discontinuous function of λ_1.

Our result highlights how more altruistic behavior can help countries to move from the inefficient equilibrium without transfer to the Pareto optimal equilibrium with transfer. Assume, for example, that in case of multiple equilibria the selected one is always the one preferred by the poor country. In this case, if $\lambda_1 < \hat{\lambda}$, countries are stuck in the inefficient equilibrium without transfer. If the level of altruism λ_1 increases, the shift to the Pareto optimal equilibrium occurs when λ_1 crosses the threshold $\hat{\lambda}$, leading to a significant efficiency gain. At this threshold, the comparison of the efficient and inefficient Nash equilibria shows that all utility gains are attributed to the developed country, since the utility of the developing country remains the same. This means that more altruistic behavior may be profitable for the developed country, even from a purely selfish point of view.

To illustrate Proposition 5, we develop a simple numerical exercise. The specification is detailed in Appendix A.6. Figure 2 displays five figures representing the transfer level (m_1), the abatement levels (a_0 and a_1), and the selfish utility levels (u_0 and u_1) with respect to the developed country's degree of altruism (λ_1). Each of the five figures shows two lines, respectively characterizing the inefficient equilibrium, which only exists when $\lambda \leq \bar{\lambda}$, and the Pareto optimal equilibrium, which only exists when $\lambda \geq \underline{\lambda}$. Between $\underline{\lambda}$ and $\bar{\lambda}$, where the two Nash equilibria coexist, the two lines are represented in dash form. Figure 2a displays the transfer level (m_1) and shows that the inefficient equilibrium is characterized by the absence of any transfer, while the Pareto optimal equilibrium is characterized by a strictly positive transfer. In the latter case, the more the developed country cares about the developing country, the higher the transfer will be. Figures 2b and 2c depict the abatement levels (a_0 and a_1) of the developed country and the developing country, respectively. In the inefficient equilibrium, an increase in altruism drives the developed country to further internalize the marginal abatement benefit of the developing country. This leads to an increase in abatement a_0 by the developed country and thus to a decrease in abatement a_1 by the developing country through free-riding. In the Pareto optimal equilibrium, an increase in altruism does not affect abatement levels since all Pareto optimal allocations involve the same abatement levels. Moreover, the abatement a_1 of the developing country is higher in the Pareto optimal equilibrium than in the inefficient equilibrium (and conversely for the abatement a_0 of the developed country). In the Pareto optimal equilibrium, the developing country internalizes the marginal abatement benefit of the developed country thanks to the operational transfer.

Figures 2d and 2e display the selfish utility levels (u_0 and u_1) of the developed country and the developing country, respectively. In the inefficient equilibrium, the selfish utility u_0 of the developed country decreases with altruism as its contribution a_0 increases (and conversely, the selfish utility u_1 of the developing country increases with altruism). In the Pareto optimal equilibrium, the selfish utility u_0 of the developed country also decreases with altruism because of the transfer increase with altruism (and conversely the selfish utility u_1 of the developing country increases with altruism). Moreover, $\hat{\lambda}$, which is located between $\underline{\lambda}$ and $\bar{\lambda}$, characterizes the degree of altruism at which the utility u_1 of the developing country is identical in the two equilibria. The developing country prefers the inefficient equilibrium below $\hat{\lambda}$ and the Pareto optimal equilibrium above $\hat{\lambda}$. Thanks to the significant efficiency gain, the developed country prefers the Pareto optimal equilibrium over $[\underline{\lambda}, \bar{\lambda}]$, which illustrates the idea that the developed country can gain from being more altruistic.

6 Conclusion

This short paper aims to deliver two messages. First, development and environmental policies should be considered together rather than separately. Our result emphasizes that transfers related to development policies can serve as a coordination device, avoiding sub-optimalities arising in the non-cooperative provision of environmental goods. This involves using an appropriate decision process, where transfers are determined after pollution abatement levels. However, the coordination mechanism only works if the developed country is sufficiently altruistic (or wealthy), so that positive transfers actually flow from the developed country to developing countries.

The second point is that even if the developed country is not sufficiently altruistic, the efficiency gains arising from being more altruistic may be larger than the "cost" of helping developing countries. Development policies thus appear to be more than a transfer of wealth from developed to developing countries that reduces inequality, but also a way to address global environmental challenges, in particular those related to climate change.

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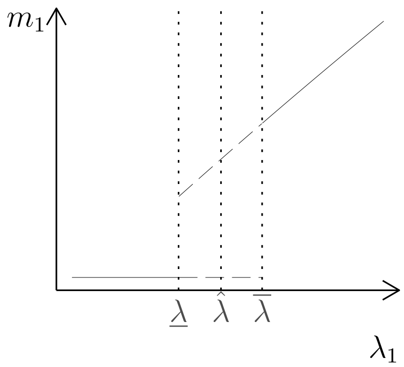
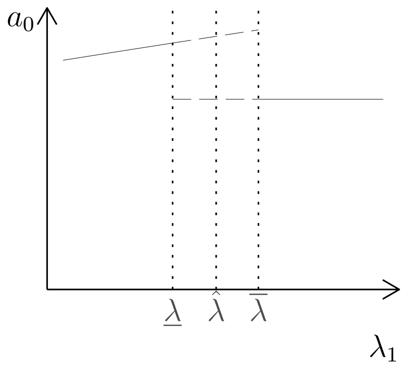
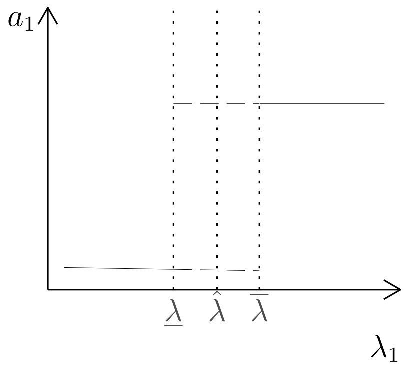


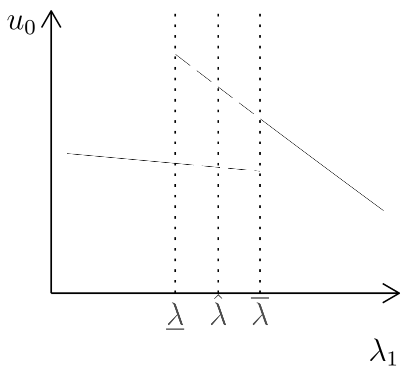
(a) Transfer m_1 w.r.t. altruism λ_1



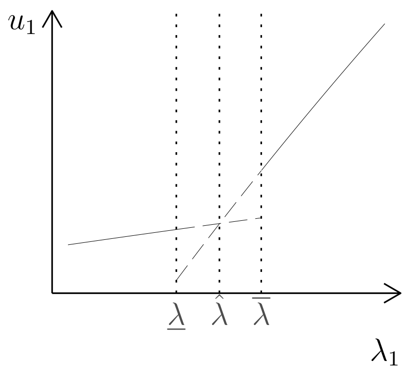
(b) Developed country abatement a_0 w.r.t. altruism λ_1



(c) Developing country abatement a_1 w.r.t. altruism λ_1



(d) Developed country selfish utility u_0 w.r.t. altruism λ_1



(e) Developing country selfish utility u_1 w.r.t. altruism λ_1

Figure 2: The impact of altruism in the sequential game with one developed country and one developing country ($n = 1$).

A Appendices

A.1 Proof of Proposition 1

A feasible allocation is Pareto optimal if it maximizes a convex combination of all countries' utilities. Accounting for the fact that country 0 is altruistic, we obtain the result that a feasible allocation is Pareto optimal if $\gamma_i \in [\lambda_i, +\infty[$ exists, for all $i \in \{1, .., n\}$, such that:

$$\begin{aligned} &\max_{\boldsymbol{m},\boldsymbol{a}} u_0\Big(w_0 - c_0(a_0) + b_0(A) - \sum_{k=1}^{n} m_k\Big) + \sum_{j=1}^{n} \gamma_j u_j\Big(w_j - c_j(a_j) + b_j(A) + m_j\Big) \\ &\qquad \text{s.t.} \quad A = \sum_{k=0}^{n} a_k; \qquad w_0 - c_0(a_0) + b_0(A) - \sum_{k=1}^{n} m_k \geq 0; \\ &\qquad w_j - c_j(a_j) + b_j(A) + m_j \geq 0 \qquad \forall j \in \{1, .., n\}. \end{aligned} \tag{8}$$

The first order condition of (8) relative to m_i implies that:

$$u_0'\Big(w_0 - c_0(a_0) + b_0(A) - \sum_{k=1}^{n} m_k\Big) \geq \lambda_i u_i'\Big(w_i - c_i(a_i) + b_i(A) + m_i\Big). \tag{9}$$

The first order conditions of (8) relative to a_0 and a_i ($i \in \{1, .., N\}$) are respectively:

$$\sum_{j=0}^{n} b_j'(A) = c_0'(a_0), \tag{10}$$

$$\sum_{j=0}^{n} b_j'(A) = c_i'(a_i). \tag{11}$$

This concludes the proof.

A.2 Proof of Proposition 2

The first order condition of (3) relative to m_i gives either:

$$m_i = 0 \quad \text{and} \quad \lambda_i u_i'\Big(w_i - c_i(a_i) + b_i(A)\Big) < u_0'\Big(w_0 - c_0(a_0) + b_0(A) - \sum_{\substack{k=1 \\ k \neq i}}^{n} m_k\Big), \tag{12}$$

or:

$$m_i \geq 0 \quad \text{and} \quad \lambda_i u_i'\Big(w_i - c_i(a_i) + b_i(A) + m_i\Big) = u_0'\Big(w_0 - c_0(a_0) + b_0(A) - \sum_{k=1}^{n} m_k\Big). \quad (13)$$

The first order condition of (3) relative to a_0 and the first order condition of (4) relative to a_i are respectively:

$$\sum_{j=1}^{n} \lambda_j \frac{u_j'(.)}{u_0'(.)} b_j'(A) + b_0'(A) = c_0'(a_0), \quad (14)$$

$$b_i'(A) = c_i'(a_i). \quad (15)$$

We show by contradiction that $\sum_{i=0}^{n} a_i^{sim} < \sum_{i=0}^{n} a_i^{opt}$. Assume that $\sum_{i=0}^{n} a_i^{sim} \geq \sum_{i=0}^{n} a_i^{opt}$. Then, (10) and (14) imply $a_0^{sim} \leq a_0^{opt}$ (given that $\lambda_j \frac{u_j'}{u_0'} \leq 1$ in (14)). Moreover, (11) and (15) imply $a_i^{sim} < a_i^{opt}$. Thus, $\sum_{i=0}^{n} a_i^{sim} < \sum_{i=0}^{n} a_i^{opt}$, which contradicts our hypothesis, and thus proves the first part of the proposition.

Regarding the second part of the proposition, now assume that none of the m_i are strictly binding in zero, which means that $\lambda_j \frac{u_j'}{u_0'} = 1$ in (14). Given that $\sum_{i=0}^{n} a_i^{sim} < \sum_{i=0}^{n} a_i^{opt}$, (10) and (14) imply $a_0^{sim} > a_0^{opt}$.

A.3 Proof of Proposition 3

The first order conditions of (5) relative to m_i are identical to (12) and (13), which implicitly defines a function $\boldsymbol{a} \rightarrow m_i^{seq}(\boldsymbol{a})$. This function is continuously differentiable at all points where it is strictly positive.

The first order condition of (6) relative to a_0 and the first order condition of (7) relative to a_i are, respectively:

$$\sum_{j=1}^{n} \lambda_j \frac{u_j'(.)}{u_0'(.)} b_j'(A) + b_0'(A) = c_0'(a_0), \quad (16)$$

$$b_i'(A) + \frac{dm_i^{seq}}{da_i} = c_i'(a_i). \quad (17)$$

The comparative statics of (13) relative to a_j give:

$$\lambda_i u_i''(.)\left[-\delta_{ij} c_i'(a_i) + b_i'(A) + \frac{dm_i^{seq}}{da_j} \right] = u_0''(.)\left[b_0'(A) - \sum_{k=1}^{n} \frac{dm_k^{seq}}{da_j} \right] \quad (18)$$

in which $\delta_{ij} = 1$ if $i = j$ and $\delta_{ij} = 0$ otherwise. By taking equations (17) and (18), and setting $i = j$, we find that for any $j \in \{1, .., n\}$:

$$b_0'(A) - \sum_{k=1}^{n} \frac{dm_k^{seq}}{da_j} = 0. \tag{19}$$

Using equations (18) and (19), we then obtain $b_i'(A) + \frac{dm_i^{seq}}{da_j} = 0$ for any $i \neq j$, which can be summed to:

$$\sum_{\substack{k=1\\k\neq j}}^{n} b_k'(A) + \sum_{\substack{k=1\\k\neq j}}^{n} \frac{dm_k^{seq}}{da_j} = 0. \tag{20}$$

The sum of (19) and (20) gives $\frac{dm_j^{seq}}{da_j} = \sum_{\substack{k=1\\k\neq j}}^{n} b_k'(A) + b_0'(A)$, which together with (17) gives:

$$b_i'(A) + \sum_{\substack{k=1\\k\neq i}}^{n} b_k'(A) + b_0'(A) = c_i'(a_i). \tag{21}$$

Equations (13), (16), and (21) imply that the allocation in this game is Pareto optimal if no m_i is binding in 0.

A.4 Proof of Proposition 4

With only one developing country, the first order condition of (3) relative to m_1 shows that either $m_1 = 0$ and $\lambda_1 u_1'(.) < u_0'(.)$, or $m_1 \geq 0$ and $\lambda_1 u_1'(.) = u_0'(.)$. Moreover, the first order condition of (3) relative to a_0 and the first order condition of (4) relative to a_1 are, respectively:

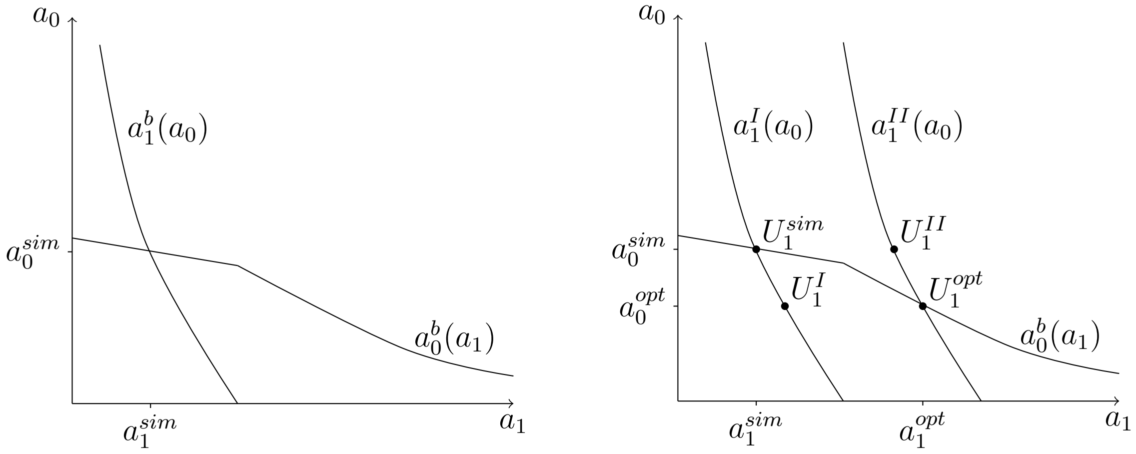
$$\lambda_1 u_1'(.) b_1'(A) = u_0'(.)\big(c_0'(a_0) - b_0'(A)\big), \tag{22}$$

$$b_1'(A) = c_1'(a_1), \tag{23}$$

which determine the best response functions $a_0^b(a_1)$ and $a_1^b(a_0)$, respectively (represented in Figure 3(a)). We show below that the slope of the function $a_0^b(a_1)$ is larger than -1 and that the slope of the inverse function of $a_1^b(a_0)$ is lower than -1, which means that they cross at most once. Moreover, by looking at extreme values ($a_0 = 0$ and $a_0 = \infty$), we see that they necessarily cross. In summary, $a_1^b(a_0)$ and $a_0^b(a_1)$ cross once and only once in (a_1^{sim}, a_0^{sim}), and there is a unique Nash equilibrium.

To complete the proof, let us analyze the slopes of best response functions $a_0^b(a_1)$ and $a_1^b(a_0)$. The derivation of (22) relative to a_1 states how $a_0^b(a_1)$ evolves with a_1:

$$\frac{da_0^b}{da_1} = \frac{-1 + \beta}{1 + \alpha}, \tag{24}$$



(a) Simultaneous choice model

(b) Sequential choice model

Figure 3: Abatement best response functions in the simultaneous and sequential choice models with one developing country

in which we have: $\alpha = -\frac{c_0''}{b_1''+b_0''} > 0$ and $\beta = 0$ when m_1 is not binding in 0, and $\alpha = -\frac{u_0'.c_0''-\lambda_1 u_1''.b_1'^2-u_0''.(c_0'-b_0')^2}{\lambda_1 u_1'.b_1''+u_0'.b_0''} > 0$ and $\beta = \frac{u_0''.b_0'.(c_0'-b_0')}{\lambda_1 u_1'.b_1''+u_0'.b_0''} > 0$ when m_1 is binding in 0. Thus, the slope of $a_0^b(a_1)$ is larger than -1. Note that $a_0^b(a_1)$ goes from $(a_1, a_0) = (0, a_0^b(0))$ to $(a_1, a_0) = (\infty, 0)$. The derivation of (23) relative to a_0 states how $a_1^b(a_0)$ evolves with a_0:

$$\frac{da_1^b}{da_0} = \frac{-1}{1-\frac{c_1''}{b_1''}}. \tag{25}$$

Thus, the slope of $a_1^b(a_0)$ is between -1 and 0, and the slope of the inverse function of $a_1^b(a_0)$ is lower than -1. Note that the inverse function of $a_1^b(a_0)$ goes from $(a_1, a_0) = (0, \infty)$ to $(a_1, a_0) = (a_1^b(0), 0)$.

A.5 Proof of Proposition 5

As shown below, proposition 5 is valid under three technical conditions (where $R_f = |\frac{x.f'(x)}{f(x)}|$ by definition):

$$\frac{R_{u_0'}.R_{b_0}}{R_{b_1'}}.\frac{b_0}{w_0-c_0+b_0} < 1, \tag{26}$$

$$\frac{R_{b_1}.R_{u_1'}}{R_{c_0'}}.\frac{b_1}{0.25.(w_1-c_1+b_1+m_1)} < 1, \tag{27}$$

$$\frac{R_{c_0}.R_{u_0'}}{R_{c_0'}}.\frac{c_0}{0.25.(w_0-c_0+b_0-m_1)} < 1, \tag{28}$$

which are true when b_0 and c_0 are small relative to the wealth of country 0, b_1 is small relative to the wealth of country 1, and the elasticities $R_f = |\frac{x.f'(x)}{f(x)}|$ are reasonable for the functions u'_0, b_0, c_0, c'_0, u'_1, b_1, and b'_1.

Let us now proceed with the proof. With only one developing country, the first order condition of (5) relative to m_1 shows that we have either:

$$m_1 = 0 \quad \text{and} \quad \lambda_1 u'_1\Big(w_1 - c_1(a_1) + b_1(A)\Big) < u'_0\Big(w_0 - c_0(a_0) + b_0(A)\Big), \tag{29}$$

or:

$$m_1 \geq 0 \quad \text{and} \quad \lambda_1 u'_1\Big(w_1 - c_1(a_1) + b_1(A) + m_1\Big) = u'_0\Big(w_0 - c_0(a_0) + b_0(A) - m_1\Big), \tag{30}$$

which implicitly defines a function $(a_0, a_1) \to m_1^{seq}(a_0, a_1)$. Moreover, the first order condition of (6) relative to a_0 and the first order condition of (7) relative to a_1 are respectively:

$$\lambda_1 u'_1(.) b'_1(A) = u'_0(.)\big(c'_0(a_0) - b'_0(A)\big), \tag{31}$$

$$b'_1(A) + \frac{dm_1^{seq}}{da_1} = c'_1(a_1), \tag{32}$$

where $\frac{dm_1^{seq}}{da_1} = 0$ if m_1^{seq} is binding in 0 and $\frac{dm_1^{seq}}{da_1} = b'_0(A)$ if m_1^{seq} is not binding in 0. Equations (31) and (32) respectively determine the best response functions $a_0^b(a_1)$ (continuous) and $a_1^b(a_0)$ (discontinuous). In Figure 3(b), we represent $a_0^b(a_1)$ and two curves $a_1^I(a_0)$ and $a_1^{II}(a_0)$, representing $b'_1(A) = c'_1(a_1)$ and $b'_1(A) + b'_0(A) = c'_1(a_1)$, respectively. Note that $a_1^I(a_0) < a_1^{II}(a_0)$. Note also that the best response function $a_1^b(a_0)$ is composed partly of $a_1^I(a_0)$ and partly of $a_1^{II}(a_0)$, such that for any a_0 the utility of country 1 is the highest possible. Similarly to Appendix A.4, we can show that $a_0^b(a_1)$ crosses $a_1^I(a_0)$ and $a_1^{II}(a_0)$ once and only once, at the points (a_1^{sim}, a_0^{sim}) and (a_1^{opt}, a_0^{opt}), respectively.

Are (a_1^{sim}, a_0^{sim}) and (a_1^{opt}, a_0^{opt}) Nash equilibria? In what follows, as represented in Figure 3(b), we denote by U_1^{sim}, U_1^{II}, U_1^{opt}, and U_1^I the utility levels reached by country 1 for abatement (a_1^{sim}, a_0^{sim}), $(a_1^{II}(a_0^{sim}), a_0^{sim})$, (a_1^{opt}, a_0^{opt}), and $(a_1^I(a_0^{opt}), a_0^{opt})$, respectively. We also denote by W_1^{sim}, W_1^{II}, W_1^{opt}, and W_1^I the corresponding wealth levels reached by country 1. Abatement (a_1^{sim}, a_0^{sim}) is a Nash equilibrium if $U_1^{sim} \geq U_1^{II}$, and abatement (a_1^{opt}, a_0^{opt}) is a Nash equilibrium if $U_1^{opt} \geq U_1^I$. Let us analyze when this is the case.

The aggregate wealth is larger in the Pareto optimal allocation (a_0^{opt}, a_1^{opt}) than in $(a_1^{II}(a_0^{sim}), a_0^{sim})$. Moreover, in these two allocations, weighted marginal utilities are equalized across countries as m_1 is not binding in 0. This implies that $U_1^{II} < U_1^{opt}$.

With condition (26), we have β (defined in Appendix A.4) smaller than 1 and the function $a_0^b(a_1)$ decreases with a_1. In this case, we have $a_1^{sim} < a_1^{opt}$ and $a_0^{sim} > a_0^{opt}$. Given that there is no transfer in the context of $a_1^I(a_0)$, $a_0^{opt} < a_0^{sim}$ implies that $U_1^I < U_1^{sim}$.

With conditions (27) and (28), we can show as explained further below that W_1^{opt} and W_1^{II} increase with λ_1 at a higher rate than W_1^{sim} and W_1^I. In this case, scalars $\underline{\lambda}$, $\hat{\lambda}$, and $\overline{\lambda}$ exist such that $\underline{\lambda} < \hat{\lambda} < \overline{\lambda}$ and:

i) For $\lambda_1 < \underline{\lambda}$, $U_1^{opt} < U_1^I$. In this case, $U_1^{opt} < U_1^I$ and $U_1^{II} < U_1^{opt} < U_1^I < U_1^{sim}$ imply that there is one and only one Nash equilibrium, which is (a_1^{sim}, a_0^{sim}).

ii) For $\underline{\lambda} < \lambda_1 < \hat{\lambda}$, $U_1^I < U_1^{opt} < U_1^{sim}$. In this case, $U_1^I < U_1^{opt}$ and $U_1^{II} < U_1^{opt} < U_1^{sim}$ imply that there are two Nash equilibria. Moreover, no equilibrium Pareto-dominates the other ($U_1^{opt} < U_1^{sim}$ and $U_0^{opt} > U_0^{sim}$).

iii) For $\hat{\lambda} < \lambda_1 < \overline{\lambda}$, $U_1^{II} < U_1^{sim} < U_1^{opt}$. In this case, $U_1^{II} < U_1^{sim}$ and $U_1^I < U_1^{sim} < U_1^{opt}$ imply that there are two Nash equilibria. Moreover, one equilibrium Pareto-dominates the other ($U_1^{opt} > U_1^{sim}$ and $U_0^{opt} > U_0^{sim}$).

iv) For $\overline{\lambda} < \lambda_1$, $U_1^{sim} < U_1^{II}$. In this case, $U_1^{sim} < U_1^{II}$ and $U_1^I < U_1^{sim} < U_1^{II} < U_1^{opt}$ imply that there is one and only one Nash equilibrium, which is (a_1^{opt}, a_0^{opt}).

To complete the proof, let us explain why W_1^{opt} and W_1^{II} increase with λ_1 at a higher rate than W_1^{sim} and W_1^I under conditions (27) and (28). Given that a change of λ_1 does not affect the wealth of country 1 through a_1 under the envelope theorem and that a_0^{opt} does not depend on λ_1, we have:

$$\frac{dW_1^{sim}}{d\lambda_1} = b_1'(A)\frac{da_0^{sim}}{d\lambda_1}, \tag{33}$$

$$\frac{dW_1^{II}}{d\lambda_1} = \left(b_1'(A) + \frac{\partial m_1^{seq}}{\partial a_0}\right)\frac{da_0^{sim}}{d\lambda_1} + \frac{\partial m_1^{seq}}{\partial \lambda_1}, \tag{34}$$

$$\frac{dW_1^{opt}}{d\lambda_1} = \frac{\partial m_1^{seq}}{\partial \lambda_1}, \tag{35}$$

$$\frac{dW_1^I}{d\lambda_1} = 0. \tag{36}$$

Computing $\frac{\partial m_1^{seq}}{\partial \lambda_1}$ with the derivation of (30) relative to λ_1, we get $\frac{\partial m_1^{seq}}{\partial \lambda_1} = \frac{-u_1'}{\lambda_1 u_1'' + u_0''}$. Computing $\frac{da_0^{sim}}{d\lambda_1}$ with derivations of (31) and (32) relative to λ_1 gives $\frac{da_0^{sim}}{d\lambda_1} < \frac{1}{\lambda_1}\frac{b_1'}{c_0''}$. Moreover, $|b_1'| < c_0'$ and $|b_1' + \frac{\partial m_1^{seq}}{\partial a_0}| < c_0'$ in (a_1^{sim}, a_0^{sim}) and $(a_1^{II}(a_0^{sim}), a_0^{sim})$. Thus, to have W_1^{opt} and W_1^{II} increasing with λ_1 at a higher rate than W_1^{sim} and W_1^I, we just need $2\frac{c_0'}{\lambda_1}\frac{b_1'}{c_0''} < \frac{-u_1'}{\lambda_1 u_1'' + u_0''}$, which is the case if conditions (27) and (28) are satisfied.

A.6 Specification of the illustration for Proposition 5

For the numerical exercise, we chose $u_i(.) = log(.)$, $c_i(a_i) = \alpha_i \frac{a_i^{\delta_i}}{\delta_i}$, $b_i(A) = \beta_i A^{\eta_i}$. The developed country is indexed by 0 and the developing country is indexed by 1. The parameters used to simulate the graphs in Figure 2 are detailed in the following table:

Parameters	α_0	α_1	δ_0	δ_1	η_0	η_1	β_0	β_1	w_0	w_1
Value	0.1	0.1	2	2	0.5	0.5	5	5	50	15