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Development Aid and Climate Finance

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Abstract

This paper discusses the implications of climate change for official transfers from rich countries (the North) to poor countries (the South) when the motivation for transfers is ethical rather than strategic. Traditional development transfers to increase income and reduce poverty are complemented by new financial flows to reduce greenhouse gas emissions (mitigation transfers) and become climate-resilient (adaptation transfers). We find that in the absence of barriers to adaptation, mitigation or development, climate change will make isolated transfers less efficient: A large part of their intended effect (to increase income, reduce emissions, or boost climate-resilience) dissipates as the South reallocates its own resources to achieve the mitigation, adaptation and consumption balance it prefers. Only in the case of least-developed countries, which are unable to adapt fully due to income constraints, will adaptation support lead to more climate resilience. In all other cases, if the North wishes to change the balance between mitigation, adaptation and consumption it should structure its transfers as "matching grants", which are tied to the South's own level of funding. Alternatively, the North could provide an integrated "climate-compatible development" package that recognizes the combined climate and development requirements of the South. If the aim is to increase both mitigation and adaptation in the South, development assistance that increases the income level, can an effective measure, but only if there is an international agreement and the recipient country is not income constrained. If the recipient country is very poor, development aid may reduce adaptation effort.

Keywords: inequality aversion; mitigation; adaptation; climate finance; development assistance; institutional barriers

JEL classification: D63, Q50, Q54, Q56

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1. Introduction

The twin needs of poverty alleviation and environmental protection have long been recognized as complementary challenges. There is by now an extensive body of work that documents the close links between environment and development, a literature to which Anil Markandya has made wide-ranging contributions (e.g. Pearce et al. 1990; Markandya and Pearce 1991; Markandya 1998, 2002, 2008; Markandya and Nurty 2004).

Perhaps less appreciated in the academic literature is the fact that environment-development links also extend to questions of finance. Official development assistance has been subject to extensive research in particular about aid effectiveness (e.g., Dollar and Easterly 1999; Collier and Dollar 2002, 2004; Bourguignon and Sundberg 2007), but environmental finance has become a topic of wider academic interest only recently in the context of climate change. Under the Copenhagen Accord of 2009 (UNFCCC, 2010), and reaffirmed in subsequent negotiation documents, developed countries have promised to provide additional climate finance of up to $100 billion a year to help developing countries reduce their emissions and adapt to climate change. Climate finance is to be explicitly provided on top of conventional development assistance, which developed countries have pledged to increase to 0.7% of GDP as part of the Millennium Development Goals.

Fankhauser and Pearce (2014) offer a conceptual discussion of sustainable development finance, while Haites (2013) provides an overview of climate finance issues. Tol (2005) argued early on that development aid can reduce vulnerability to climate change. However, there has been no systematic analysis up to now of how environmental finance and development aid interact, either from a donor perspective (e.g., in terms of overlapping or competing donor objectives) or from a recipients' point of view (e.g., in terms of the incentives that multiple funding streams provide). The aim of this paper is to close this gap, using climate change as a pertinent example.

The paper offers a theoretical model to analyze the ethical motivation of donors in providing three kinds of funding to developing countries: funding to alleviate poverty (development aid), funding to reduce greenhouse gas emissions (mitigation finance) and funding to prepare for unavoidable climate change (adaptation finance). The model also studies how the three funding streams affect the ability and inclination of recipient countries to increase consumption, reduce emissions and strengthen resilience to climate change.

We specify a two period model (present and future), with a rich region (North) and a poor region (South). They play a leader-follower game, where the North calculates the behavior of the South before deciding on the optimal level of transfers. We are not concerned with optimizing global social welfare. Rather, we take the point of view of donor and recipient countries and ask what their social welfare functions imply for the impact of different financial transfers. The main difference between our study and earlier papers on international transfers is threefold: (i) the explicit ethical motivation for giving transfers, (ii) the broad set of transfers we study and (iii) the treatment of market imperfections and institutional barriers for transfers. It is worth elaborating on each of these features.

First, in terms of the ethical motivation of transfers, most of the existing literature on financial transfers focuses on their strategic value, that is, their merit in securing an international agreement (see e.g., Barrett, 2003, 2007 and Hong and Karp, 2012, on forming international environmental agreements). Already in the 1990s, Carraro and Siniscalco (1993) and Kverndokk (1994) argued that side payments mainly from OECD countries to non-OECD countries would be an effective policy instrument for making a limited treaty significant. Eyckmans and Tulkens (2003) show that a proportional surplus- sharing rule can stabilize a grand coalition and secure the first-best global climate policy, and Carraro et al. (2005) demonstrate the importance of monetary transfers as strategic instruments to foster stability of voluntary climate agreements. Further, Hoel (2001) argues that monetary transfers are also important to reduce carbon leakage, while Chatterjee et al. (2003) and Bretschger and Suphaphiphat (2014) study transfers that promote economic growth.

In contrast, the basic tenet in our paper is that transfers reflect the ethical beliefs of those making them. That is, transfers are not made primarily for strategic reasons, but because people in developed countries care about the welfare of people in developing countries.[1] We also assume

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[1] The Copenhagen Accord describes transfers that should "address the needs of developing countries", see UNFCCC (2010).

that these beliefs can be expressed in an appropriately specified welfare function, and study how the level and composition of financial flows depend on the ethical beliefs of developed countries. Fairness issues related to climate finance have been studied by, e.g., Grasso (2010) and Pittel and Rübbelke (2013a). Grasso (2010) studies adaptation finance from the framework of procedural and distributive justice. Pittel and Rübbelke (2013a) focus on how climate finance may support an optimal climate outcome, arguing that international adaptation transfers could help address the perceived unfairness associated with historical emissions. Hence, such transfers may help achieving an international climate agreement. For a further discussion of the ethical dimensions of climate change see Kolstad et al. (2014), Stern (2014a, b) and Kverndokk and Rose (2008).

A second distinguishing feature of our paper is that it analyzes the full range of available transfers, including transfers for mitigation, adaptation and development. In that respect the paper is part of a recent literature on the interplay between adaptation and mitigation (see for instance Ingham et al. 2007; Tulkens and van Steenberghe 2009; Buob and Stephan 2011, 2013; Ebert and Welsch 2012; Heuson et al., 2012; Bréchet et al. 2013). A recurring insight from this body of work is that while the benefits of mitigation are non-excludable, the benefits of adaptation are often excludable. This means adaptation is primarily a private good and the benefits accrue only to the nation doing the adaptation investment (Kane and Shogren, 2000; Barrett, 2008).[2] Thus, nations should have the incentives to do the appropriate adaptation investment themselves in contrast to mitigation. We should thus expect at least some crowding out of adaptation transfers as countries pursue their optimal adaptation strategies.

Another issue in this literature is whether adaptation and mitigation are substitutes or complements (Buob and Stephan, 2013). If the two measures are substitutes, a reduction in the cost of one (say, lower adaptation costs) will reduce demand for the other (less mitigation, since additional low-cost adaptation can reduce the effects of climate change). If the two measures are complements, a reduction in costs will increase demand for both measures. There are examples where this is the case, such as the preservation of peat lands and mangrove forests, which simultaneously sequesters carbon and reduces impacts. However, in most cases mitigation and

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[2] There are examples of adaptation actions with regional public goods features, such as the management of international water systems, and global public good features, such as measures to deal with climate refugees (Heuson et al., 2012), but we can treat these as exceptions from the rule.

adaptation seem to be substitutes (Tol, 2005; Ingham et al., 2005), which is the assumption we make in this paper.[3]

A third important feature of our paper lies in its assumptions about barriers and market imperfections. In the absence of any market imperfections – the climate change externality is fully addressed, there are no financing barriers, transfers are cost-free etc. – the optimal transfer strategy is easy. Donor countries transfer income in accordance with their ethical beliefs and recipient countries allocate funds between income, mitigation and adaptation to maximize their welfare. We take this (unrealistic) case as the starting point, before exploring financing and institutional constraints (see also Bretschger and Suphaphiphat 2014).

The ambition of the international climate negotiations is to achieve a legally binding and universal climate agreement for all nations. An interesting question is how this ambition interacts with mitigation transfers both from the recipient side and the donor side. A universally binding international agreement is therefore a premise for our analysis, although we do not prescribe how constraining the emissions limits might be. An alternative to a carbon constraint is studied by Pittel and Rübbelke (2013b), who develop a two-region model, similar to ours, to explore the merit of financial adaptation transfers that are conditional on mitigation efforts. Conditional transfers are also studied in this paper. However, we also ask whether transfers may be optimal for donor countries without being conditional.

We then introduce financing constraints. Dividing the world into only two regions, rich and poor, is of course a simplification as the developing region consists of countries at different income levels, which may face different financing barriers. We study the case of low income countries, which may face a consumption constraint as they seek to fulfill a subsistence level condition. If they are constrained in available resources we find that the effects of transfers are different. While credit constraints are also studied in Bretschger and Suphaphiphat (2014), they do not study adaptation transfers.

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[3] If mitigation and adaptation are complements, the poor region will boost its mitigation when it receives more adaptation support. This additional mitigation is beneficial for the rich region, given the public good nature of mitigation. So in that case, there are strong incentives for the rich region to voluntarily support adaptation in the poor region. Note that this argument is valid when there is no binding climate agreement.

The paper is structured as follows. Section 2 sets out our theoretical model. It features a two-period leader-follower game of transfers from North to South with utility functions that include the welfare in the other region. We then use this framework to study a series of questions relating to the interplay of development aid and official finance for mitigation and adaptation.

The game is solved by first analyzing the problem of the follower, that is, decision making in the South. Section 3 studies the effect of official transfers on the mitigation decisions of the South, while section 4 studies the impact on adaptation. Section 5 introduces a financing constraint and analyzes the special case of a (least-developed) country whose ability to spend money on climate change is constrained by the need to maintain a subsistence level of consumption.

We turn to the leader and study decision making in the North in section 6, where we analyze the incentive of the North to offer adaptation, mitigation and development transfers, bearing in mind the strategic reaction of the South observed in sections 3 and 4. Section 7 studies the same question but with an institutional constraint: the efficiency of transfers varies, that is, a varying fraction of funding is lost in the course of the transfer. Finally, section 8 concludes.

2. A two-period model of transfers

Our model is structured as a leader-follower game between two regions over two periods ($t = 0,1$). The two regions are called *North* ($j = N$) and *South* ($j = S$), where North is a rich region and South is poor. Each region produces an exogenous output y_j^t, which results in greenhouse gas emissions e_j^t.[4] The combined emissions from both regions result in climate change damage, which reduces output in period 1. Damage in period 0 is assumed to be negligible.

In period 0 each region chooses the amount it wishes to invest in mitigation technology m_j and adaptation technology a_j. The benefit of adaptation is reduced impacts from climate change in period 1. We assume that climate change damage in country *j*, D_j, increases in aggregated

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[4] Thus, we implicitly assume that real capital investments are made optimally.

emissions, is proportional to output, and a fraction, α_j, of this damage can be avoided through adaptation. Investing in adaptation has decreasing returns: $0 \le \alpha_j\left(a_j\right) \le 1$ with $\alpha_j' \ge 0$ and $\alpha_j'' \le 0$. This specification, while simple,is in line with the literature on integrated assessment modelling (see, e.g., Fankhauser, 1994; Kverndokk, 1994; Tol, 2002; Nordhaus, 2008; de Bruin, Dellink and Tol, 2009; de Bruin, Dellink and Agrawala, 2009; for a critique see Pindyck, 2013), and covers both market and non-market damages.[5]

Mitigation capital is long-lived so that the choice of m_j determines emissions over both periods. Emissions are proportional to output, that is, $e_j^t = \sigma_j\left(m_j\right) y_j^t$, where $\sigma_j\left(m_j\right)$ can be interpreted as the emission-to-output ratio. Thus, the benefit of investing in mitigation is a lower emission intensity of output. We assume that mitigation investment has decreasing returns (equivalently, the abatement costs functions is convex): $\sigma_j' < 0$ and $\sigma_j'' \ge 0$.[6]

Each region has its own emission constraints, which one may think of as being part of an international agreement to constrain emissions over both regions:

$$(1) \qquad e_N^0 + e_N^1 \le \hat{e}_N; \;\; e_S^0 + e_S^1 \le \hat{e}_S; \quad \hat{e}_N + \hat{e}_S \le \hat{e}$$

For simplicity we assume that there is no interaction (e.g., through carbon trading) between the two emission spaces. The respective emissions constraints apply separately to each region, although emissions are fungible across time periods.[7] [8]

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[5] For a discussion of the case where consumption and the environment are specified as two different goods in the utility function, see Hoel and Sterner (2007).

[6] Buob and Stephan (2013) define mitigation and adaptation as substitutes if adaptation negatively affects the marginal productivity of mitigation. To see that this is the case in our model, we define a "green GDP function" as in Buob and Stephan; $F(y,a,m) = y - \left[1-\alpha(a)\right] D\left(\sigma(m) y\right) y$. Based on this, the condition for substitution is fulfilled as $\partial^2 F(y,a,m) \big/ \partial m \partial a = \alpha' D' \sigma' y^2 < 0$.

[7] This is not important for the conclusions in this paper, but it simplifies the analyses as we get only one shadow price of carbon in the region, see section 3 below.

[8] Eyckmans et al (2014) explore a global carbon constraint where carbon is traded between regions, thus introducing a strategic element into the game. Another alternative would be to associate the benefit of mitigation directly with reduced damage. This too would introduce strategic considerations into the model and make it difficult to distinguish the equity case for transfers from the strategic case. Moreover, our representation is not unrealistic. Very

The North can make three types of transfer in period 0:

- a productive capital transfer (development assistance), T^i, which will increase the available output (and emissions) of the South in period 1,
- a mitigation transfer, T^m, which helps the South reduce its emissions in both periods,
- an adaptation transfer, T^a, which augments the adaptation capital available to the South.

The transfers introduce some intra- and intergenerational tradeoffs. Mitigation (and mitigation support) has an immediate and lasting impact because it lowers the emission intensity in both periods. Adaptation and productive capital support however, are subject to a time delay. Today's investment only pays off in the next period. Hence, we assume that changing the productive capital base of a country requires more time than curbing its emission intensity. Increasing the adaptation capacity only affects the future as the damage is only felt in the longer term.[9]

The output that is left after transfers and investments in mitigation and adaptation in period 0 is consumed. The consumption levels in each region and period, c_j^t, and the corresponding emissions, e_j^t, can be specified as shown in Table 1.

Table 1: Consumption and emissions levels in each region and period.

	Period 0 (now)	Period 1 (future)
N (North)	$c_N^0 = y_N^0 - m_N - a_N - T^m - T^a - T^i$ $e_N^0 = \sigma_N\left(m_N\right) y_N^0$	$c_N^1 = \left[1 - \left[1 - \alpha_N\left(a_N\right)\right] D_N\left(\hat{e}\right)\right] y_N^1$ $e_N^1 = \sigma_N\left(m_N\right) y_N^1$
S (South)	$c_S^0 = y_S^0 - m_S - a_S$ $e_S^0 = \sigma_S\left(m_S + T^m\right) y_S^0$	$c_S^1 = \left[1 - \left[1 - \alpha_S\left(a_S + T^a\right)\right] D_S\left(\hat{e}\right)\right]\left[y_S^1 + T^i\right]$ $e_S^1 = \sigma_S\left(m_S + T^m\right)\left[y_S^1 + T^i\right]$

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few countries are large enough to influence global emissions significantly. For most, the incentive to reduce emissions comes from an exogenously agreed target, rather than the possibility to reduce damage directly.

[9] In reality, there will also be quick wins in improving adaptation capacity and productivity. At the same time, some mitigation efforts will only curb emission intensity in the long run. We abstract from these possibilities mainly because it allows us to keep the model tractable.

The final, crucial element of the model is each region's utility function. We assume that both regions gain utility from consumption (that also includes feedback from the environment). For simplicity we assume linear utility functions, and we can write the intertemporal utility function of the South as:[10]

(2) $$U_S\left(c_S^0, c_S^1\right) = c_S^0 + \delta_S c_S^1$$

where δ_S is the consumption discount factor of the South, expressing the intergenerational equity preferences of the region.

To be able to study transfers from North to South that are not motivated by strategic reasons, we assume that the North has social preferences. It cares about the intragenerational distribution of consumption, that is, the distribution of consumption between the regions. One way of doing this is to follow Fehr and Schmidt (1999) and assume that the North expresses inequality aversion in consumption;[11] people in the North dislike that the South is poorer than them, but would dislike it even more if the South were richer.[12] In representative democracies, these preferences get reflected in the actions of policy makers (Lee et al. 2004). We can therefore assume that the Fehr-Schmidt utility functions of voters work through in the welfare function of the country as a whole (Kverndokk et al. 2014).

Obviously, as North is the richer region, we have $c_N > c_S$. The utility function of the North can then be written as:

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[10] A linear utility function is of course a simplification. However, we may argue that transfers are not so big that they lead to large changes in the consumption levels of the regions, thus the marginal utility is relatively constant. With this representation, the marginal utility from a change in consumption is equal to one.

[11] We could also introduce the inequality preferences in the welfare function of the South as in Kverndokk et al. (2014). This would give preferences for a higher consumption level in the South. However, as will be obvious from the discussions in Sections 3 and 5 below, equity preferences will not affect the optimal mitigation and adaptation levels, and inequality aversion in the South would not matter for our analysis.

[12] The general case would be $U_N\left(c_N, c_S\right) = c_N - \eta \max\left\{c_S - c_N, 0\right\} - \mu \max\left\{c_N - c_S, 0\right\}, \quad c_j = c_j^0 + \delta_j c_j^1, \; j = N, S$, where η is a parameter representing the negative feeling of being worse off than the South, while μ is the parameter representing the negative feeling of being better off. We then have $\eta \geq \mu$. The second part of the welfare function equals zero as $c_N > c_S$.

(3) $$U_N\left(c_N, c_S\right) = c_N - \mu(c_N - c_S) = (1-\mu)c_N + \mu c_S, \quad c_j = c_j^0 + \delta_j c_j^1, \;\; j = N, S$$

where $\mu > 0$ is a parameter expressing the intragenerational preferences of the North, while δ_N is the discount rate of the North, expressing its intergenerational preferences.

From (3) we see that $\mu < 1$ is required for consumption in the North to add to the North's welfare. In addition, it is reasonable to assume that consumption in the North adds more to the utility of the North than consumption in the South. Thus, we set $\mu < 1/2$.[13]

3. Financial transfers and mitigation in the South

The game is solved by backward induction; we first look at decisions by the follower, that is, the South. The model is structured so that the South's adaptation and mitigation decisions are independent from each other, and we start with mitigation. That is, we first explore how the need to reduce emissions affects how the South reacts to official financial flows from the North.

All optimization problems and first order conditions are specified in Annex 1. Let λ_S be the shadow price on carbon for the South. Assuming the emissions constraint is binding, we find the optimal level of mitigation in the South from the necessary first-order condition (FOC) for an interior solution:

(4) $$-1/\sigma_S'\left[y_S^0 + y_S^1 + T^i\right] = \lambda_S$$

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[13] We could also introduce a consumption transfer from North to South in both periods as a means to reduce consumption inequality. However, as we have assumed that $\mu < 1/2$, no interior solution would be possible from the optimization problem, and there would not be any consumption transfer between the two regions. This is because utility is linear in consumption, and the North will always prefer one extra consumption unit to itself than to the South. A transfer is only welfare improving for the North if it increases consumption more in the South than it reduces consumption in the North. To be more precise: $\Delta C_S > -\left[[1-\mu]/\mu\right]\Delta C_N$. Note, however, that with a concave utility function, it may be welfare improving for the North to transfer consumption to the South if the consumption level is so high that the direct marginal utility of consumption (not considering inequality aversion) is very small. Thus, in this case we may find an optimal consumption transfer. Also, if $\mu = 0$ so that North does not care about the welfare level of the South, there will not be any consumption transfer. The reason is that the consumption transfer has no strategic effect. The only reason to transfer consumption is that the North cares about the welfare of the South.

The FOC tells us that the shadow price of carbon, λ_S, is determined by the marginal cost of mitigation, measured over both periods. Equation (4) together with the binding emissions constraint $e_S^0 + e_S^1 = \hat{e}_S$ from equation (1) constitute a two-equation system with two endogenous variables m_S and λ_S, which are functions of income y_S^0, y_S^1, transfers T^i, T^m and the emissions constraint $\hat{e}_S$. Note that adaptation is not present in the FOC for mitigation effort, which is why we can study the mitigation decision separately.

We solve the system by totally differentiating the two equations. Expressed in matrix form this yields:

(5) $$\begin{bmatrix} \sigma_S'' \breve{y}_S & -1/\lambda_S^{\,2} \\ \sigma_S' \breve{y}_S & 0 \end{bmatrix} \begin{bmatrix} dm_S \\ d\lambda_S \end{bmatrix} = \begin{bmatrix} -\sigma_S'' \breve{y}_S & -\sigma_S' & 0 \\ -\sigma_S' \breve{y}_S & -\sigma_S & 1 \end{bmatrix} \begin{bmatrix} dT^m \\ dT^i \\ d\hat{e}_S \end{bmatrix}$$

where $\breve{y}_S = y_S^0 + y_S^1 + T^i$ is total undiscounted income over both periods. We find that:

(6) $$\frac{dm_S}{d\hat{e}_S} = \frac{1}{\sigma_S' \breve{y}_S} < 0; \quad \frac{dm_S}{dT^m} = -1\,; \quad \frac{dm_S}{dT^i} = \frac{-\sigma_S}{\sigma_S' \breve{y}_S} > 0.$$

The first expression confirms that a more lenient emissions constraint in the South leads to reduced mitigation effort. The second expression suggests that a dedicated mitigation transfer completely crowds out the South’s own mitigation efforts. Since the cap on emissions is fixed, the transfer allows the South to free up its own resources for consumption. As a corollary there is no additional mitigation in the South. A binding emissions constraint in the South renders mitigation transfers ineffective, i.e.[14]

(7) $$\frac{de_S}{dT^m} = \sigma_S' \, \breve{y}_S \left[1 + \frac{dm_S}{dT^m} \right] = 0\,.$$

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[14] It seems likely that a global agreement would be heterogeneous. Some countries may have restrictions on absolute emission levels as in equation (1), while other countries may have restrictions on carbon intensity, i.e. σ. If the latter is true, we have $\sigma_j(m_j) = \bar{\sigma}_j$. However, this will not change conclusions in the no-trade case as this also defines the mitigation level as a function of the exogenous target.

The final expression in equation (6) shows the effect of development assistance on mitigation in the South. It suggests that additional aid will trigger further mitigation. This is because a productive income transfer leads to higher output and therefore more emissions, and additional mitigation is needed to remain within the carbon constraint. Again, the presence of an emissions constraint makes the transfer less effective, in the sense that development assistance now leads to a lower increase in utility in the South, and therefore also the North.[15] To see this we differentiate the utility function of the South with respect to development assistance:

$$\frac{dU_S}{dT^i} = -\frac{dm_S}{dT^i} + \delta_S \left\{1 - \left[1 - \alpha_S\left(a_S + T^a\right)\right] D_S(\hat{e})\right\} \tag{8}$$

The second term of the equation represents the increase in period 1 consumption that a productive transfer would normally have. The first term is negative and reflects the reduction in consumption due to the need for more mitigation. Because wellbeing in the South features in the utility function of the North, utility in the North is affected in the same way. Note that the effect on period 1 consumption depends on climate damages. We will return to this issue in the next section.

Equations (6) to (8) give rise to the following proposition:

Proposition 1: *Mitigation and development transfers become less effective if the South has a binding emissions constraint, in the sense that the transfers result in less additional mitigation or additional consumption, respectively, than the same transfer in the absence of a constraint. This is because each of the transfers focuses on only one objective (emissions cuts and higher output, respectively), and the South will redeploy its own resources to establish its preferred balance between the two goals.*

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[15] However, Bretschger and Suphaphiphat (2014) find that a mitigation transfer may be better for the South than development aid due to its effects on economic growth.

If the North wishes to preserve the full effect of development transfers[16] it will have to recognize the twin importance of both output growth and emissions cuts. The North may then devise a combined package of transfers $\breve{T}$ that includes both development and mitigation assistance. In particular, a package that combines each dollar of development assistance with $-\sigma_S / \sigma'_S \breve{y}_S$ dollars of mitigation transfer (see equation (6) and recall that σ'_S is negative), would be emissions-neutral and not require any further adjustments in the South:

(9) $$\breve{T} = T^i + \frac{-\sigma_S}{\sigma'_S \breve{y}_S} T^m \Rightarrow \frac{de_S}{d\breve{T}} = 0; \quad \frac{dm_S}{d\breve{T}} = 0$$

We can think of such a package as low-carbon development assistance (say, rural electrification based on renewable energy) rather than traditional, high-carbon development aid (access to fossil fuel-based energy), where the incremental cost of the clean solution constitutes the mitigation transfer. The presence of an emissions constraint in the South thus strengthens the case for low-carbon development aid, and raises questions about development support for high-carbon projects like coal.

If the North is intent on increasing mitigation in the South beyond the emissions constraint $\hat{e}_S$, it may wish to structure mitigation transfers as “matching grants”, where for each dollar the South spends on mitigation, the North would pay an additional τ^m dollars for further mitigation.[17] This would provide an incentive to reduce emissions in the South beyond what its carbon constraint requires. Defining $\breve{m}_S = \left[1+\tau^m\right] m_S$ as the total mitigation level in the South, it is easy to show that there is still crowding out but at a lower rate:

(10) $$d\breve{m}_S = dm_S \left[1+\tau^m\right] + m_S d\tau^m = 0 \quad \Rightarrow \quad dm_S / d\tau^m = -m_S \Big/ \left[1+\tau^m\right].$$

Hence, the effect of a slight increase of the matching grant *rate* (from say 10% to 11%) is a decrease in mitigation expenditure in the South of $-m_S \Big/ \left[1+\tau^m\right]$. In order to make this

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[16] Note that this will not necessarily follow from the optimization problem of the North, see Section 5.

[17] Again, this may not necessarily be an optimal policy for the North.

comparable to the effect of the direct grant (which is measured in monetary terms), we have to divide by m_S in equation (10). Therefore, the effect of a slight change in the matching grant is given by $-1/\left[1+\tau^m\right] \in \left[-1,0\right]$, showing that there is incomplete crowding out in the matching grant case.

An incomplete crowding out implies that more is spent on mitigation measures and emissions fall. As the emissions constraint is no longer binding, the shadow price of the constraint is zero and additional mitigation is undertaken if marginal mitigation costs are less than the marginal benefit, which is τ^m, i.e., the additional revenue the South gets from the matching grant.[18] However, unlike in the case of low-carbon development assistance, the matching grant will not result in a welfare maximizing allocation of resources from the perspective of the South as it would allocate resources differently without the matching grant restriction.

We summarize these findings in the following proposition:

Proposition 2: *The North can respond to the impact that an emissions constraint in the South has on the effectiveness of transfers by switching to a low-carbon form of development assistance and / or by offering mitigation assistance in the form of a matching grant. The former would ensure that the twin objectives of output growth and emissions cuts are met simultaneously. The latter would encourage the South to undertake additional mitigation beyond what its emissions constraint requires.*

4. Financial transfers and adaptation in the South

We now turn to the adaptation decision of the South and explore how the adaptation in the South depends on transfers from the North. From the optimization specified in Annex 1, we find the following FOC:

$$(11) \qquad \delta_S \alpha_S'\left(a_S + T^a\right) D_S\left(\hat{e}\right)\left[y_S^1 + T^i\right] = 1$$

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[18] Note that there is an additional effect as the damage in period 1 is no longer given. However, for an individual country this effect will probably be negligible, see footnote 8.

The optimal adaptation effort is found by equalizing the marginal benefits of adaption (the left hand side) and its marginal costs (the right hand side). The FOC determines adaptation effort as an implicit function of adaptation and development transfers and the global emission cap, $\tilde{a}_S\left(T^a, T^i, \hat{e}\right)$.

To determine the signs of the exogenous factors (that is, the impacts of transfers and the emissions constraint on the adaptation level in the South), we totally differentiate equation (11):

$$(12)\qquad \alpha_S''\left[da_S + dT^a\right]D_S\left[y_S^1 + T^i\right] + \alpha_S' D_S'\left[y_S^1 + T^i\right]d\hat{e} + \alpha_S' D_S dT^i = 0$$

It follows straightforwardly that

$$(13)\qquad \frac{\partial}{\partial \hat{e}}\tilde{a}_S\left(\hat{e}, T^a, T^i\right) = \frac{da_S}{d\hat{e}} = \frac{-\alpha_S' D_S'}{\alpha_S'' D_S} > 0$$

A higher global cap on emissions will cause the South to adapt more as the marginal benefit to adaptation is higher. An interpretation of this is that a region would adapt less if a climate agreement is reached. Thus more mitigation would mean less adaptation as in our model mitigation and adaptation are substitutes.

If follows also that

$$(14)\qquad \frac{\partial}{\partial T^a}\tilde{a}_S\left(\hat{e}, T^a, T^i\right) = \frac{da_S}{dT^a} = -1\,.$$

That is, additional adaptation support completely crowds out the South’s own adaptation effort – the South decreases its own adaptation effort by the same amount. In the same way as for mitigation, additional adaptation support frees up resources that the South prefers to use for consumption. The reason for this is seen from the first order condition given by equation (11). Adaptation transfers do not address any exogenous constraints to adaptation but simply offer additional adaptation resources. But since the benefit from adaption is the same before and after the transfer, it will be optimal for the South to maintain its original adaptation level. This is in line with the literature claiming that the benefits of adaptation are excludable, see, e.g., Buob and Stephan (2013).

As in the case of mitigation transfers, the North could increase adaptation in the South, and thus reduce damage in the South, by using a “matching grant” form of support. As before this would lead to incomplete crowding out, but as it changes the allocation of resources, it would result in a welfare loss for the South.

This gives us the following proposition:

Proposition 3: *Adaptation capital transfer from the North to South will completely crowd out adaptation investments in the South, unless a matching grant support function is used, but this will not be a welfare maximizing allocation of resources for the South.*

To study the effect of development assistance on adaptation, it follows from (12) that

$$(15) \qquad \frac{\partial}{\partial T^i}\tilde{a}_S\left(\hat{e},T^a,T^i\right)=\frac{da_S}{dT^i}=\frac{\delta_S\alpha_S' D_S}{\delta_S\left[-\alpha_S''\right]D_S\left[y_S^1+T^i\right]}=\frac{-\alpha_S'}{\alpha_S''\left[y_S^1+T^i\right]}>0,$$

That is, productive capital support leads the South to increase its adaptation effort. Intuitively, by increasing income in the South, more value is at risk in the region due to climate change.[19] This gives an incentive to increase adaptation efforts. Note that this effect hinges on the assumption that damages are proportional to output, a standard assumption in economic studies as mentioned in Section 2. The result can be stated in a Proposition:

Proposition 4: *An increase in development assistance will increase the adaptation level of the South.*

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[19] In addition, higher income may lead to higher demand for climate protection, but we do not model this income effect.

As seen from equations (6) and (15), increasing development assistance has a positive impact on both mitigation and adaptation effort in the South. This is in contrast to climate finance, which does not alter overall adaptation and mitigation levels. However, the result is due to the assumption that there are no barriers. There are no limits to the South's ability to allocate resources between mitigation, adaptation and consumption. We review this assumption in the next section. Institutional barriers in the North will be discussed further in Section 7.

5. Financial transfers when the South is income-constrained

Up to now, we have assumed that the South is sufficiently affluent that it can invest some of its resources in adaptation or mitigation. We now relax this assumption by requiring that consumption in the initial period should be at least equal to some minimal subsistence level $\underline{c}$. This condition may be binding for a least-developed country.

The South's optimization problem is now given by:

$$\max_{m_S, a_S} \quad U_S = c_S^0 + \delta_S c_S^1 \quad \text{s.t.} \quad c_S^0 \geq \underline{c} \quad \text{and} \quad e_S^0 + e_S^1 \leq \hat{e}_S \tag{16}$$

Associating a Lagrange multiplier θ to the minimal consumption requirement and λ_S with the emission constraint as before, we can write the FOC for optimal mitigation (assuming an interior solution[20]) as follows:

$$-[1+\theta] - \lambda_S \sigma_S' \left[y_S^0 + y_S^1 + T^i \right] = 0 \tag{17}$$

The first term denotes the marginal cost of a dollar invested in mitigation in the first period: one unit of consumption forgone plus the shadow price of the subsistence requirement. The second term measures the marginal return of that extra mitigation investment which depends on the shadow value of the emissions constraint. The FOC for optimal adaptation efforts is given by:

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[20] We can do this because we have assumed that the marginal benefits of the first units of mitigation- and adaptation investments are unbounded.

$$-\left[1+\theta\right]+\delta_S\alpha_S' D_S\left[y_S^1+T^i\right]=0 \tag{18}$$

Now, the first term stands for the marginal adaptation cost and the shadow price of the minimal subsistence consumption level. The second term stands for the marginal benefit, i.e., reduction in remaining climate change damages. Compared to the unconstrained case (equation (4) for mitigation and equation (11) for adaptation), we see that marginal cost of investment will be higher in the constrained case (given that the constraint is binding). Hence, the South will mitigate and adapt less if it is constrained in consumption in the initial period which is very intuitive. They would like to mitigate and adapt more but they cannot because otherwise they would starve to death.

The comparative statics and derivations are shown in Annex 2. When both the emissions and consumption constraints are binding, we find exactly the same results for mitigation as in the unconstrained case discussed earlier. In particular, mitigation support is completely crowded out, adaptation support has no impact on mitigation efforts, productive capital support leads to higher mitigation (in order to compensate for higher emissions), a more lenient emission constraint implies less mitigation, and the minimal consumption level (and hence a pure transfer of consumption) has no impact on the mitigation decision.

The comparative statics for adaptation by the South are, however, different from the unconstrained case. First, extra mitigation support leads to more adaptation in the constrained case (remember it did not affect adaptation in the unconstrained case). The transfer of mitigation capital leads to complete crowding out of mitigation as the South will lower its own effort by exactly the same amount. However, this frees resources that can be invested in adaptation which was previously constrained.

Secondly, extra adaptation support has no impact on the adaptation choice of the South in the sense that the South does not change its own adaptation investments. The reason is that the South was constrained in adaptation. Hence, the support alleviates the constraint and increases to total adaptation capital of the South.

Thirdly, productive capital support leads to higher second period emissions which have to be compensated by higher mitigation if the emission constraint is binding. This implies that resources should be drained away from adaptation in order to satisfy the consumption constraint. Note that mitigation investments have to be made in the first period and, therefore, have to be at the expense of adaptation investments as the consumption constraint is binding. In the second period, production will increase, but that will only have an impact on consumption as no investments are made in the second period. Thus, in our model, traditional development assistance leads to lower adaptation investments in the poorest countries. Recall that this was different in the unconstrained case, in which the South reacted with extra adaptation efforts when receiving development assistance.

Fourthly, a more lenient global carbon constraint results in more adaptation investment in the South because the marginal benefit of adaptation increases. This effect is the same as in the unconstrained case.

A final result is that simply transferring consumption goods (i.e., relaxing the consumption constraint) would lead to higher adaptation. The additional consumption is used to direct more resources to constrained adaptation investments.[21]

<u>Proposition 5:</u> *If the South is very poor (i.e. constrained to subsistence consumption in the initial period), adaptation can be boosted by providing (1) targeted adaptation support, (2) mitigation support, or (3) direct consumption transfers. All three routes are equally efficient at boosting adaptation. Productive capital support leads however to lower adaptation.*

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[21] Thus, as opposed to the result in the main model in Section 2, a consumption transfer may be optimal in this case.

6. The financial transfer decisions of the North

To complete the solution to our leader-follower game, we now turn to the problem of the North. First, note that the emissions constraint in the North given by equation (1) determines the need for mitigation in the North, i.e., the optimal level of emissions follows directly from the emissions constraint and is unaffected by the transfers to the South.

Next, to decide on its adaptation level and the transfers to the South, the North wants to maximize its intertemporal welfare function, given all restrictions from Section 2 and subject to its adaptation level (a_N) and transfers (T^a, T^i, T^m). The North takes the optimal responses of the South into account when deciding on the transfers, see also Buob and Stephan (2013). That is, the North decides on transfers, and the South responds to these transfers. The North has the information to calculate the responses of the South.

The optimization problems and the FOCs are given in Annex 1. The first order condition for *adaptation transfers* can be written as:

$$(19) \qquad 1-\mu=\mu\delta_S\left[y_S^1+T^i\right]D_S\left(\hat{e}\right)\alpha_S'\left[\frac{\partial a_S}{\partial T^a}+1\right]$$

This shows that the marginal cost of the transfer in the North, weighted with the equity weight (left hand side), should equal the benefit of increased consumption in the South in the next period, also weighted with the equity weight (right hand side). But from (14) we know that $\frac{\partial a_S}{\partial T^a}=-1$ and the adaptation transfer completely crowds out the South's adaptation effort if there are no other constraints. In this case we see that (19) does not hold, and there is no interior solution. Thus, it will not be optimal for the North to transfer adaptation capital to the South.[22]

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[22] Note that an adaptation transfer in this case would be equal to a pure consumption transfer. As discussed in footnote 13, a consumption transfer will not be optimal with a linear utility function. However, with a concave utility function we would get an interior solution, and it would be optimal with an adaptation transfer even if the adaptation level in the South did not increase. The reason is that consumption in South would increase and the inequality between the two sectors would be lower. This would increase the utility of the North as they express inequality aversion.

However, if there are constraints attached to the adaptation transfers, such that for every dollar used on adaptation in the South, the North transfers τ^a dollars (a matching grant), we know from Section 3 that the crowding out is not complete. Using a matching grant may, therefore, give an interior solution of the optimization problem and a positive adaptation transfer from the North to the South will occur. The magnitude of this transfer is increasing with the equity weight put on the utility of the South, and the transfer would be zero if the weight is set to zero.

If the South is constrained in consumption (Section 5), we know that $\frac{da_S}{dT^a} = 0$, see Annex 2. Equation (19) now becomes:

$$1 - \mu = \mu \delta_S \left[y_S^1 + T^i \right] D_S \left(\hat{e} \right) \alpha_S' \tag{20}$$

Thus, as we do not have crowding out, it may be optimal for the North to transfer adaptation capital to the South.

We know from Section 3 that there is full crowding out of mitigation transfers to the South. Using this in the first order condition for *mitigation transfers* in Annex 1, we get the same result as for adaptation transfers; there is no interior solution to mitigation transfers and the optimal level is equal to zero. The mitigation transfer would just work as a consumption transfer, which is not optimal with the linear utility function. This also holds if the South is income-constrained.

This gives us the following proposition:

<u>Proposition 6:</u> *Due to the complete crowding out of adaptation and mitigation in the South from adaptation and mitigation transfers respectively, these would work as pure income transfers, which will not be optimal with a linear utility function. However, if the South is income-constrained, adaptation transfers would be optimal for the North as they will increase the total adaptation capital in the South.*

The optimal level of *development assistance* follows from its FOC in Annex 1:[23]

$$(21) \qquad 1-\mu=-\frac{\partial m_S}{\partial T^i}\mu-\frac{\partial a_S}{\partial T^i}\left[\mu\left[1-\delta_S\left[y_S^1+T^i\right]\alpha_S' D_S\left(\hat{e}\right)\right]\right]+\delta_S\mu\left[\left[1-\left[1-\alpha_S\left(a_s+T^a\right)\right]\right]D_S\left(\hat{e}\right)\right]$$

Development assistance has impacts on the utility of the North via changes in the mitigation and adaptation efforts in the South, as well as the income increase in the South as the region gets richer. Thus, there may be an interior solution, meaning there may exist an optimal level of development assistance.

For the case where the South is income-constrained, we may still have an interior solution, but should note that the sign of $\frac{\partial a_S}{\partial T^i}$ now turns from positive to negative, which has an impact on the size of the transfer. Whether, transfers increase or decrease is undetermined as adaptation in the South has both a positive (reduces utility in the first period) and negative (increases utility in the second period) impact on the intertemporal utility of the poor region.

7. The decisions of the North when financial transfers are inefficient

We next introduce an institutional barrier. In particular we study the case where international transfers are subject to "leakage", that is, a fraction of transfers does not reach the intended beneficiary. With weak or corrupt institutions, which are prevalent in many developing countries, money may disappear along the road.

In our model, the efficiency of transfers can be modeled in different ways. For instance, the α- and σ-functions describe how adaptation measures and mitigation measures are transferred into reduced damage and emissions respectively. Thus, these functions also describe the efficiency of these transformations. As an example, the α-function may describe the costs of adaptation.

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[23] Note again that the transfer is only welfare improving, i.e., there exists an interior solution, if the cost of the transfer in the North (reduced consumption) is less than the increased consumption in the South that follows from the transfer.

To model how much money actually reaches the targets, we can introduce *efficiency parameters* $0 \leq b^j \leq 1, \quad j = a, i, m$. This means that the North may pay for more than what reaches the South. Thus, while the North's optimization problem is unchanged, these parameters need to be incorporated in *South's* optimization problem.

The introduction of these efficiency parameters only has a modest impact on the qualitative conclusions. However, there will be less crowding out of adaptation and mitigation capital if less money reaches the South, i.e., there is only crowding out of the actual transfer that reaches the target. The optimal sizes of transfers will of course be affected by leakage.

It is also worth exploring to what extent our conclusions hinge on the assumption that development assistance is efficient. In our model development assistance has a positive effect on production in the South; the growth potential of development aid is not crowded out. Some studies suggest that aid does not necessary raise capital stocks in developing countries, and that the outcome depends on domestic policies and institutions, see e.g., Dollar and Easterly (1999); Easterly and Pfutze (2008), but there are also more optimistic views on the effects of development aid (e.g. Sachs (2005); Banerjee and Duflo (2011)). Temple (2010) examines the conditions under which foreign aid will be effective in raising growth. Based on the evidence, he finds that aid can be effective, and that a hypothesis that aid may be harmful does not have backing. Thus, while we have modeled the effect of aid in a simple way, we can conclude that as long as aid is given in a way that promotes growth (not complete crowding out), the effect on mitigation and adaptation effort in the developing countries will be positive in our main model.

Another of our assumptions is more crucial. In the main model with linear utility functions, it is not optimal for the North to transfer mitigation and adaptation capital as we have full crowding out and the transfers go to consumption. With concave utility functions, in contrast, the option for the North would be to increase Southern consumption by either transferring consumption goods directly, or transferring adaptation or mitigation capital. The choice would depend on the transaction costs for each transfer, akin to the "leaky bucket" problem; i.e., the relative efficiency loss in distribution. As a consequence, transferring adaptation or mitigation capital may give different effects on consumption and on who receives the consumption good than a direct transfer of the good itself.

8. Conclusions

This paper discusses the interplay of different types of donor assistance to developing countries: development assistance to boost output and income, mitigation support to reduce greenhouse gas emissions, and adaptation support to increase resilience to climate risks. We assume that the motivation for these transfers is derived solely from the North's concern about well-being in the South. Our model does not include any strategic reasons for mitigation and adaptation transfers, such as the need to secure a global agreement on emissions, or concerns about international trade where countries specializing in an adaptation or mitigation technology seek to expand their market.

The main model does not contain any market distortions that are not internalized. In particular, there are no barriers (such as poor institutions) to effective adaptation, effective economic management and the transfer of funds, and we assume a binding global emissions constraint to address the climate change externality. We may associate this situation with middle income countries, which tend to have fairly advanced institutions.

We find that under these assumptions isolated transfers aimed solely at development, mitigation or adaptation are relatively inefficient: A large part of their intended effect (to increase income, reduce emissions, or boost climate-resilience) dissipates as the South reacts to the transfers by reallocating its own resources until it has established the mitigation, adaptation and consumption balance that optimizes its welfare. In essence, climate change finance works as a pure income transfer and any impacts on mitigation and adaptation are indirect, triggered by the softer budget constraint. The main motivation for transfers in this context would have to be strategic, a topic not studied in this paper.

If the North wishes to change the balance between mitigation, adaptation and consumption in the South it needs to structure its transfers as "matching grants", which vary according to the South's own level of funding. In our model such conditional funding would not lead to a welfare maximizing allocation of resources. Matching grants could only be justified if the North is concerned uniquely about climate security in the South, rather than welfare more broadly.

Development aid can boost both adaptation and mitigation, but this will in turn reduce other capital investments which may have been the initial aim for this transfer. Ultimately if the North wants to preserve the full effect of development transfers, it may recognize how climate change complicates welfare maximization and provide an integrated transfer package that addresses the combined climate and development requirements of the South. The development community has started to call this climate-smart development – or, more catchily green growth (Jacobs, 2013; World Bank, 2012; Bowen and Fankhauser, 2011).

The result changes if we introduce a binding income constraint. We can think of this as the situation of low income countries, which have to secure a subsistence level of income before funds can be allocated for climate change purposes. In this situation financial transfers can have some unexpected consequences. For example, a mitigation transfer may lead to higher levels of adaptation because the South's own mitigation budget is freed up and can be reallocated. In contrast, an adaptation transfer will have the desired effect by easing the constraint on adaptation and increasing climate resilience.

This suggests that adaptation support could usefully be targeted at countries that are income (and therefore adaptation) constrained. In addition to the crowding-out argument made here, there are also compelling equity reasons to prioritize adaptation support for least-developed countries, which tend to be highly vulnerable to the impacts of climate change. In fact, without effective adaptation the development achievements of past decades will be at risk (e.g. World Bank 2010).

Our findings also relate to the widely held view, expressed most prominently by Schelling (1992, 1997) that economic development is an effective way to reduce vulnerability to climate change, although our argumentation is slightly different. Unlike Schelling, we acknowledge the power of dedicated adaptation spending in reducing vulnerability. Our point is that, whatever the nature of the transfers, developing countries will find their own balance between adaptation and development. See also Bowen et al. (2012) for a more nuanced discussion of the links between climate vulnerability, adaptation and development.

The results depend on an international agreement that constrains all global emissions. This may at first glance appear unrealistic. However, a comprehensive agreement on emissions is the explicit aim of the international climate negotiations and the cap on emissions does not need to be strict or environmentally optimal for the model to work. The assumption does not necessarily constrain emissions in the South as their emissions limit may be set close to their business-as-usual level.

The model could be extended in several directions. Output could be modeled as a function of the stock of productive capital, which would hence introduce an endogenous capital investment process as in Bretschger and Suphaphiphat (2014). However, this would complicate the analyses considerably without fundamentally affecting the basic results derived in the simpler formulation.

A more interesting extension would be the introduction of further market imperfections. The barriers to adaptation we have introduced is a potential capital constraint in low income countries where adaptation competes with subsistence consumption, as well as institutional barriers due to, e.g., corruption. Yet, there are many other constraints that could restrain the adaptation potential in the South, related to a lack of adaptive capacity. It would be interesting to investigate how this might affect the results and maybe open up the possibility for other types of assistance (like subsidized loans and technical assistance).

A third set of extensions could involve alternative ways of modeling the equity preferences of the North. One interesting option would be to study the historical responsibility case, where climate damages rather than the consumption level in the South enters North's utility function, or alternatively that the North is only concerned about the size of the transfers and not on the effect. Clearly, many different ethical tenets and formulations are conceivable but are beyond the scope of this paper.

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Annex 1: The optimization problems

Financial transfers and mitigation in the South

The optimization problem of the South with respect to mitigation is given by maximizing the following Lagrangian,

$$(22)\quad \begin{aligned} max_{m_S}\ \mathcal{L}_S &= c_S^0 + \delta_S\, c_S^1 + \lambda_S \left[\hat{e}_S - e_S^0 - e_S^1\right] \\ &= y_S^0 - m_S - a_S + \delta_S \left\{1 - \left[1 - \alpha_S(a_S + T^a)\right] D_S\left(\hat{e}\right)\right\}\left[y_S^1 + T^i\right] + \lambda_S \left\{\hat{e}_S - \sigma_S\left(m_S + T^m\right)\left[y_S^0 + y_S^1 + T^i\right]\right\} \end{aligned}$$

where λ_S is the shadow price on carbon. Assuming the emissions constraint is binding, the necessary first-order condition (FOC) for an interior solution is

$$(23)\quad \begin{aligned} &\frac{\partial \mathcal{L}_S}{\partial m_S} = -1 - \ \lambda_S\, \sigma_S' \left[y_S^0 + y_S^1 + T^i\right] = 0 \\ &\Rightarrow \quad -1 / \sigma_S' \left[y_S^0 + y_S^1 + T^i\right] = \lambda_S \end{aligned}$$

Financial transfers and adaptation in the South

The maximization problem of the South with respect to adaptation is given by:

$$(24)\quad \begin{aligned} max_{a_S}\ \mathcal{L}_S &= c_S^0 + \delta_S\, c_S^1 + \lambda_S \left\{\hat{e}_S - e_S^0 - e_S^1\right\} \\ &= y_S^0 - m_S - a_S + \delta_S \left\{\left[1 - \left[1 - \alpha_S\left(a_S + T^a\right)\right] D_S\left(\hat{e}\right)\right]\left[y_S^1 + T^i\right]\right\} + \lambda_S \left\{\hat{e}_S - \sigma_S\left(m_S + T^m\right)\left[y_S^0 + y_S^1 + T^i\right]\right\} \end{aligned}$$

The necessary first-order condition for a maximum (interior solution[24]) with respect to adaptation effort, a_S, is given by:

$$(25)\quad -1 + \delta_S \alpha_S' D_S \left[y_S^1 + T^i\right] = 0.$$

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[24] Sufficient conditions for an interior solution are that the first unit of investment in adaptation has a very large effect on the residual damages ($\lim_{a_j \to 0} \alpha_j'\left(a_j\right) = +\infty$) and that this effect vanishes for very large investments ($\lim_{a_i \to +\infty} \alpha_i'\left(a_i\right) = 0$).

The financial transfer decisions of the North

The optimization problem for the North can then be written as

$$\begin{aligned}\max_{T^a,T^i,T^m} \mathcal{L}_N &= [1-\mu]\left[y_N^0 - m_N - a_N - T^a - T^i - T^m\right] + \mu\left[y_S^0 - m_S - a_S\right] \\ &+[1-\mu]\delta_N y_N^1\left[1-\left[1-\alpha_N\left(a_N\right)\right]\right]D_N\left(\hat{e}\right) \\ &+\mu\delta_S\left[y_S^1+T^i\right]\left[1-\left[1-\alpha_S\left(a_S+T^a\right)\right]\right]D_S\left(\hat{e}\right) \\ &+\lambda_N\left[\hat{e}_N-\sigma_N\left(m_N\right)\left[y_N^0+y_N^1\right]\right],\end{aligned} \tag{26}$$

where λ_N is the shadow price of carbon in the North. The Kuhn-Tucker conditions, where the choices of the South are taken as given, are

$$\frac{\partial \mathcal{L}_N}{\partial T^a} = -[1-\mu] + \mu\delta_S\left(y_S^1+T^i\right)D_S\left(\hat{e}\right)\alpha_S'\left(\frac{\partial a_S}{\partial T^a}+1\right) \le 0 \tag{27}$$

$$\frac{\partial \mathcal{L}_N}{\partial T^m} = -[1-\mu] - \mu\left(\frac{\partial m_S}{\partial T^m}\right) \le 0 \tag{28}$$

$$\frac{\partial \mathcal{L}_N}{\partial T^i} = -[1-\mu] - \mu\left[\frac{\partial m_S}{\partial T^i}+\frac{\partial a_S}{\partial T^i}\right] + \mu\delta_S\left[\left[1-\left[1-\alpha_S\left(a_s+T^a\right)\right]\right]D_S\left(\hat{e}\right)+\left[y_S^1+T^i\right]\alpha_S'\frac{\partial a_S}{\partial T^i}D_S\left(\hat{e}\right)\right] \le 0, \tag{29}$$

where equality holds for interior solutions of the respective endogenous variables.

Annex 2: Mitigation and adaptation in an income-constrained South

Consider the case where the South is constrained in the sense that a minimal consumption level $\underline{c}$ is required in every period, see the optimization problem in equation (16) and the first order conditions (FOCs) in equations (17) and (18).

Combining the two FOCs above and totally differentiating yields:

$$\begin{aligned}(30)\qquad &\delta_S\alpha''_S\left[da_S+dT^a\right]D_S\left[y_S^1+T^i\right]+\delta_S\alpha'_S D'_S d\hat{e}\left[y_S^1+T^i\right]+\delta_S\alpha'_S D_S dT^i=\\ &-d\lambda_S\sigma'_S\left[y_S^0+y_S^1+T^i\right]-\lambda_S\sigma''_S\left[dm_S+dT^m\right]\left[y_S^0+y_S^1+T^i\right]-\lambda_S\sigma'_S dT^i\end{aligned}$$

Combining this with the differentiated minimal consumption constraint and emission constraint, we can write the following system of three equations in three endogenous variables:

(31)

$$\begin{cases}-da_S-dm_S=d\underline{c}\\ \sigma'_S\left[y_S^0+y_S^1+T^i\right]\left[dm_S+dT^m\right]+\sigma_S dT^i=d\hat{e}_S\\ \delta_S\alpha''_S\left[da_S+dT^a\right]D_S\left[y_S^1+T^i\right]+\delta_S\alpha'_S D'_S d\hat{e}\left[y_S^1+T^i\right]+\delta_S\alpha'_S D_S dT^i=\\ \qquad -d\lambda_S\sigma'_S\left[y_S^0+y_S^1+T^i\right]-\lambda_S\sigma''_S\left[dm_S+dT^m\right]\left[y_S^0+y_S^1+T^i\right]-\lambda_S\sigma'_S dT^i\end{cases}$$

Reorganizing and defining $\breve{y}_S=y_S^0+y_S^1+T^i$ and $\bar{y}_S=y_S^1+T^i$, we get:

$$(32)\qquad\begin{cases}-dm_S-da_S=d\underline{c}\\ \sigma'_S\breve{y}_S dm_S=-\sigma'_S\breve{y}_S dT^m-\sigma_S dT^i+d\hat{e}_S\\ \lambda_S\sigma''_S\breve{y}_S dm_S+\delta_S\alpha''_S D_S\bar{y}_S da_S+\sigma'_S\breve{y}_S d\lambda_S=\\ \qquad -\lambda_S\sigma''_S\breve{y}_S dT^m-\delta_S\alpha''_S D_S\bar{y}_S dT^a-\delta_S\alpha'_S D_S dT^i-\lambda_S\sigma'_S dT^i-\delta_S\alpha'_S D'_S\bar{y}_S d\hat{e}\end{cases}$$

Rewriting in matrix notation:

$$\begin{pmatrix} -1 & -1 & 0 \\ \sigma'_S\breve{y}_S & 0 & 0 \\ \lambda_S\sigma''_S\breve{y}_S & \delta_S\alpha''_S D_S\bar{y}_S & \sigma'_S\breve{y}_S \end{pmatrix} \cdot \begin{pmatrix} dm_S \\ da_S \\ d\lambda_S \end{pmatrix} =$$

(33)

$$\begin{pmatrix} 0 & 0 & 0 & 0 & 1 \\ -\sigma'_S\breve{y}_S & 0 & -\sigma_S & 1 & 0 \\ -\lambda_S\sigma''_S\breve{y}_S & -\delta_S\alpha''_S D_S\bar{y}_S & -\delta_S\alpha'_S D_S - \lambda_S\sigma'_S & -\delta_S\alpha'_S D'_S\bar{y}_S & 0 \end{pmatrix} \begin{pmatrix} dT^m \\ dT^a \\ dT^i \\ d\hat{e}_S \\ d\underline{c} \end{pmatrix}$$

It can easily be checked that the determinant of the coefficient matrix is positive and equal to

(34) $$\det \begin{pmatrix} -1 & -1 & 0 \\ \sigma'_S\breve{y}_S & 0 & 0 \\ \lambda_S\sigma''_S\breve{y}_S & \delta_S\alpha''_S D_S\bar{y}_S & \sigma'_S\breve{y}_S \end{pmatrix} = \left[\sigma'_S\breve{y}_S\right]^2 \geq 0$$

The full comparative statics for *mitigation* are shown below.

(35) $$\frac{dm_S}{dT^m} = \frac{1}{\left[\sigma'_S\breve{y}_S\right]^2} \det \begin{pmatrix} 0 & -1 & 0 \\ -\sigma'_S\breve{y}_S & 0 & 0 \\ -\lambda_S\sigma''_S\breve{y}_S & \delta_S\alpha''_S D_S\bar{y}_S & \sigma'_S\breve{y}_S \end{pmatrix} = \frac{-\left[\sigma'_S\breve{y}_S\right]^2}{\left[\sigma'_S\breve{y}_S\right]^2} = -1 < 0$$

(36)

$$\frac{dm_S}{dT^a} = \frac{1}{\left[\sigma'_S\breve{y}_S\right]^2} \det \begin{pmatrix} 0 & -1 & 0 \\ 0 & 0 & 0 \\ -\delta_S\alpha''_S D_S\bar{y}_S & \delta_S\alpha''_S D_S\bar{y}_S & \sigma'_S\breve{y}_S \end{pmatrix} = 0$$

(37)

$$\frac{dm_S}{dT^i} = \frac{1}{\left[\sigma'_S\breve{y}_S\right]^2} \det \begin{pmatrix} 0 & -1 & 0 \\ -\sigma_S & 0 & 0 \\ -\delta_S\alpha'_S D_S - \lambda_S\sigma'_S & \delta_S\alpha''_S D_S\bar{y}_S & \sigma'_S\breve{y}_S \end{pmatrix} = \frac{-\sigma_S}{\sigma'_S\breve{y}_S} \geq 0$$

(38)
$$\frac{dm_S}{d\hat{e}_S} = \frac{1}{\left[\sigma_S'\breve{y}_S\right]^2} \det\begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ -\delta_S\alpha_S' D_S'\bar{y}_S & \delta_S\alpha_S'' D_S\bar{y}_S & \sigma_S'\breve{y}_S \end{pmatrix} = \frac{\sigma_S'\breve{y}_S}{\left[\sigma_S'\breve{y}_S\right]^2} = \frac{1}{\sigma_S'\breve{y}_S} \leq 0$$

(39)
$$\frac{dm_S}{d\underline{c}} = \frac{1}{\left[\sigma_S'\breve{y}_S\right]^2} \det\begin{pmatrix} 1 & -1 & 0 \\ 0 & 0 & 0 \\ 0 & \delta_S\alpha_S'' D_S\bar{y}_S & \sigma_S'\breve{y}_S \end{pmatrix} = 0$$

The full comparative statics for *adaptation* are shown below.

(40)
$$\frac{da_S}{dT^m} = \frac{1}{\left[\sigma_S'\breve{y}_S\right]^2} \det\begin{pmatrix} -1 & 0 & 0 \\ \sigma_S'\breve{y}_S & -\sigma_S'\breve{y}_S & 0 \\ \lambda_S\sigma_S''\breve{y}_S & -\lambda_S\sigma_S''\breve{y}_S & \sigma_S'\breve{y}_S \end{pmatrix} = \frac{\left[\sigma_S'\breve{y}_S\right]^2}{\left[\sigma_S'\breve{y}_S\right]^2} = +1 > 0$$

(41)
$$\frac{da_S}{dT^a} = \frac{1}{\left[\sigma_S'\breve{y}_S\right]^2} \det\begin{pmatrix} -1 & 0 & 0 \\ \sigma_S'\breve{y}_S & 0 & 0 \\ \lambda_S\sigma_S''\breve{y}_S & -\delta_S\alpha_S'' D_S\bar{y}_S & \sigma_S'\breve{y}_S \end{pmatrix} = 0$$

(42)
$$\frac{da_S}{dT^i} = \frac{1}{\left[\sigma_S'\breve{y}_S\right]^2} \det\begin{pmatrix} -1 & 0 & 0 \\ \sigma_S'\breve{y}_S & -\sigma_S & 0 \\ \lambda_S\sigma_S''\breve{y}_S & -\delta_S\alpha_S' D_S - \lambda_S\sigma_S' & \sigma_S'\breve{y}_S \end{pmatrix} = \frac{\sigma_S\sigma_S'\breve{y}_S}{\left[\sigma_S'\breve{y}_S\right]^2} = \frac{\sigma_S}{\sigma_S'\breve{y}_S} \leq 0$$

(43)
$$\frac{da_S}{d\hat{e}_S} = \frac{1}{\left[\sigma_S'\breve{y}_S\right]^2} \det\begin{pmatrix} -1 & 0 & 0 \\ \sigma_S'\breve{y}_S & 1 & 0 \\ \lambda_S\sigma_S''\breve{y}_S & -\delta_S\alpha_S' D_S'\bar{y}_S & \sigma_S'\breve{y}_S \end{pmatrix} = \frac{-\sigma_S'\breve{y}_S}{\left[\sigma_S'\breve{y}_S\right]^2} = \frac{-1}{\sigma_S'\breve{y}_S} \geq 0$$

(44)
$$\frac{da_S}{d\underline{c}} = \frac{1}{\left[\sigma_S'\breve{y}_S\right]^2} \det\begin{pmatrix} -1 & 1 & 0 \\ \sigma_S'\breve{y}_S & 0 & 0 \\ \lambda_S\sigma_S''\breve{y}_S & 0 & \sigma_S'\breve{y}_S \end{pmatrix} = \frac{-\left[\sigma_S'\breve{y}_S\right]^2}{\left[\sigma_S'\breve{y}_S\right]^2} = -1 < 0$$