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Abstract

This paper focuses on two equity dimensions of climate policy, intra- and intergenerational equity, and analyzes the implications of equity preferences on climate policy, and on the production and consumption patterns in rich and poor countries. We develop a dynamic two-region model, in which each region suffers from local pollution and global warming, but also has an inequality aversion over current consumption allocations. Inequality aversion lifts the consumption path of the poor region, while the rich region must take a greater share of the climate burden. Furthermore, with inequality aversion, the optimal climate policy leads to higher investment in clean capital in the North and in dirty capital in the South, thereby allowing the South to pollute more and develop faster. The optimal policy may even require the poor region to increase emissions relative to the uncoordinated business-as-usual case. Introducing transfers between the regions reinforces these effects. However, loans to poor countries to reduce inequality may result in a debt crisis, and hence, debt remittance may be part of the optimal climate policy.

JEL-Code: C630, D310, D630, Q540.

Keywords: intragenerational equity, intergenerational equity, inequality aversion, climate policy, economic development, international transfers, debt crisis.

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1. Introduction

While climate change has been recognized as a threat to the future by most scientists and politicians for many years, there is still an ongoing debate as to what to do about it. Researchers may not agree on the optimal emission reductions even if they agree on the natural science background, the impacts and the costs of abating greenhouse gas emissions. The reason for this is to a considerable extent that optimal emission reductions depend on equity issues, and our discounting of the future climate impacts is particularly important.¹ However, ethical issues have not been fully explored in economic analyses, as greenhouse gas abatement not only affects the welfare distribution between present and future generations, but also the distribution within a generation, such as between rich and poor countries. These two equity aspects are important when studying optimal emissions reductions, and as we explain below, they may work in different directions.

The purpose of our study is to analyze the trade-off between the two dimensions of equity in climate policy. We ask the following question: How should we design climate policies when policy makers have preferences for both intra- and intergenerational equity, and what are the implications for emissions and energy investments?

The two dimensions of equity in climate polices can be referred to as *intra-* and *intergenerational*. The first is primarily about how we should distribute the burdens within a generation, either within the generation living today or within future generations, see Kverndokk and Rose (2008). Two examples of this can be: who would suffer from climate change (inaction), and how should the burdens of mitigation (action) be distributed? In the years to come, the world may face large climatic changes such as increased temperatures, sea level rise, changed wind and precipitation patterns, more extreme weather, etc. (IPCC, 2007a). Nevertheless, the damages associated with climate change will not be evenly distributed among countries nor within a given country. Studies such as those by Tol et al. (2000), Tol (2002a,b) and Yohe et al. (2007) show that some sectors will lose from climate change while others will benefit, with poorer countries likely facing relatively stronger negative impacts than richer countries. Several economic studies also reveal that the costs of action will vary among countries and sectors, and that it is generally more expensive to abate

¹ See Dasgupta (2008) for an overview and Anthoff and Tol (2009) for illustrations.

the more energy efficient the economy is (IPCC, 2007b). Policy instruments implemented to reduce greenhouse gas emissions will impose different burdens on people, and economic instruments such as carbon taxes will often be regressive, i.e., the burden will be the highest for the poorest (see, e.g., Bye et al., 2002).

While intragenerational equity is important, most of the equity debate on climate change issues in the economic literature has been on intergenerational equity issues, i.e., distribution across generations, focusing on how large emissions reductions we should be aiming for, or how high the atmospheric greenhouse gas concentration or global mean temperature ceiling should be. This affects the distribution of burdens between the current generation and future generations, as the burdens of mitigation - the costs - have to be taken by the present generation, while future generations benefit from mitigation.

There are several reasons for extensive mitigation today, such as attitudes toward risk and concerns about catastrophic events (Weitzman, 2007a). However, most of the discussions have been about the appropriate discount rate for climate policy decisions, as the optimal level of abatement is sensitive to the value of this parameter. Discount rates can be thought of as weights put on the future benefits of climate change policies to compare them to present costs. If we measure the costs and benefits in consumption units, the main reasons for discounting are that we may treat different generations differently (the pure rate of time preferences), and that the benefit of a consumption unit differs depending on the consumption level. The second argument is that a higher level of consumption gives a lower marginal utility of an additional unit, represented by the elasticity of the marginal utility of consumption, termed marginal elasticity of felicity by Dasgupta (2008). Thus, a high consumption level for future generations may be an argument for paying less attention to these generations. The consumption discount rate used in economic analyses combines these two arguments, which both represent ethical choices. However, the choice of the appropriate discount rate has been a controversial issue for many years. For instance, the Stern Review (Stern, 2007) use a fairly low consumption discount rate, and therefore finds a high level of optimal abatement compared to other studies, such as those by Nordhaus (1993) and Nordhaus and Boyer $(2000)^2$

 $^{^{2}}$ This created a lively debate in which, e.g., Nordhaus (2007) and Weitzman (2007b) argued against the choice of the low discount rate based on the observed values of the long-run return to capital. However, Heal (2009)

Most studies focus on either intra- or intergenerational equity, thereby implicitly assuming that the two dimensions can be treated separately. However, choices that affect intergenerational distribution also affect the intragenerational distribution between rich and poor countries. As Heal (2009) points out, there are two ways in which preferences for equality affect the choice of climate action. First, a high elasticity of the marginal utility of consumption leads to less aggressive action if we believe that consumption increases over time. The reason is that this makes future generations richer, and if we care about inequality between the present and future generations, we place a lower value on the richer future generations (intergenerational equity). There is, however, an additional effect. The rich countries are primarily responsible for the aggregate level of greenhouse gases in the atmosphere, while as mentioned above, the poor countries are likely to suffer the most from climate change. Hence, if we put a low weight on future outcomes, climate change is more likely to occur, and poor countries may suffer more (intragenerational equity). Consequently, the gap between the welfare levels of the rich and the poor may be higher, and based on the latter effect, stronger preferences for equality should go in the direction of more action to help prevent climate change.

These two effects of inequality aversion work in different directions, and the impacts of stronger preferences for equity on the level of greenhouse gas abatement are ambiguous. The problem is that global models used to determine the optimal level of greenhouse gas emissions focus on the first effect (intergenerational), implying that stronger preferences for equality actually induce low abatement (see e.g., Nordhaus and Boyer, 2000).

Thomas Schelling suggested one solution to this (see, e.g., Schelling, 1992) by arguing that development of the poor region is the best way to reduce the impacts of global warming.

shows that equality between the consumption discount rate and the return to capital only holds under idealized conditions such as a one-good model and perfect market assumptions including no external effects, which obviously do not hold in the case of climate change. The one-good model has also been criticized by Hoel and Sterner (2007) and Sterner and Persson (2008). They point out that if consumers consume an environmental good in addition to a produced good, the environmental good will become relatively scarcer over time as we experience more climate change. This is an argument for using a low and even negative consumption discount rate for environmental services. Lastly, Nævdal and Vislie (2008) show that the discount rate has a negligible impact on the stabilization target to avoid crossing catastrophic tipping points.

According to his argument, the developed world is not as vulnerable to climate change due to their high level of economic development. We can, therefore, reduce the vulnerability of developing countries by letting them grow as well. The end results may then be that the world is not hit as hard by climate change, and economic differences between the regions may be reduced. Apart from Schelling, few economists have discussed the linkages between the two equity dimensions. However, recently, Baumgärtner et al. (2012) provide a general discussion about the trade-offs between inter- and intragenerational justice in economic analysis, while Glotzbach and Baumgärtner (2012) analyze the relationship between these two aspects of justice in ecosystem management. Nonetheless, we are not aware of any studies of optimal climate policy that take both types of inequality aversion into account and investigate the impacts on emissions and investments in clean and dirty capital. Our paper closes this gap.

We investigate how to design climate policies when people have preferences for both intraand intergenerational equity, and what the implications are for emissions and energy investments. To do so, we set up a simple model with two regions, one rich and one poor, to explicitly account for equity preferences along the two dimensions. The intergenerational aspect is represented by the trade-offs between welfare in the present and future generations due to the impact of global warming, while the intragenerational equity concern is purely a developmental issue, as we compare the consumption levels of the poor and the rich. We use the Fehr and Schmidt (1999) framework to express this concern as it is supported by a recent experiment with participants who have been involved in international climate policy (Dannenberg et al., 2010).

We do not study differences in vulnerability to climate damage across countries as discussed by Schelling (1992). Instead, we study the implications of economic development in the poor region for emissions and capital investments. Our main finding is that preferences for intragenerational equality shift the climate burden toward the rich region. We should let the poor region use more productive but dirty capital to speed up its development, while the rich region should carry most of the abatement burden. Since clean capital is less productive by assumption, the consumption of the rich region falls, while the poor region can increase consumption. This result supports the claims made by developing countries in global climate negotiations, where they argue against emissions reductions on the basis that this would cause setbacks on the road to development. The paper is organized in the following way. In the next section, we study the optimal climate policy when people have preferences for both intra- and intergenerational equity, while Section 3 compares this outcome to the case of Business-as-Usual (no social contract). In Section 4 we introduce more possibilities for interaction between the regions, when we analyze the implications of direct transfers and international trade for the social contract. We illustrate our results with numerical simulations in Section 5. The final section concludes.

2. Deciding on a Social Contract: A Model of Inequality Aversion

As a starting point, we study the optimal global climate contract. To do this, we take a consequentialist standpoint and consider the aggregate welfare of individuals as the social objective. Hence, the social contract maximizes a social welfare function.

2.1 The Basics of the Model

Consider two regions *n* and *s*, where *n* denotes the developed region (North) and *s* the developing region (South). The welfare of a representative consumer/country in region r = n, s at time *t* is:

$$U_{r,t} = u(c_{r,t}, D_{r,t}, S_t) - \alpha_r \max(c_{k,t} - c_{r,t}, 0) - \beta_r \max(c_{r,t} - c_{k,t}, 0), r, k = n, s, r \neq k.$$
(1)

where $c_{r,t}$ is consumption, D is local pollution, and S is the state of the global environment, while k denotes the other representative region. u(c, D, S) is a standard utility function, which is increasing in c and S, but falling in D, and with: $\frac{\partial u(c, D, S)}{\partial c} \rightarrow \infty$ for $c \rightarrow 0$, $\frac{\partial^2 u(c, D, S)}{\partial c \partial D} \leq 0$ and $\frac{\partial^2 u(c, D, S)}{\partial D^2} \leq 0$. The latter condition implies that local pollution becomes increasingly damaging as the pollution level rises. As mentioned above, we do not consider different degrees of vulnerability to climate change within the two regions.

We model preferences for equality as inequality aversion following Fehr and Schmidt (1999). This implies that people dislike having higher consumption than others, but they dislike even more to consume less than others.³ This streamlines the economic development perspective as the intragenerational aspect. In contrast, the climate change perspective is the intergenerational aspect in our model. The Fehr and Schmidt framework has primarily been used to describe preferences for income equality among individuals, but may also be useful as a description of the social preferences of policy makers in different regions, as long as the transfers between regions are not due to strategic reasons only.⁴

Following this, let α be a parameter representing the negative feeling of being worse off than others, while β is the parameter representing the negative feeling of being better off. We then have that $\alpha \ge \beta$.⁵ We ignore strategic interactions by assuming that each region, North and South, consists of many identical countries that do not have any market power and cannot individually affect the overall level of global environmental quality.

Note that since the utility function is increasing and concave in consumption, a social planner seeking to maximize the sum of welfare over the two regions will want to reduce inequality in consumption as this increases aggregate welfare. Hence, even without the Fehr-Schmidt inequality aversion in the utility function (1), there are gains from eliminating intragenerational inequality. However, this is not driven by aversion towards inequality per se, but by the desire to maximize aggregate utility. Also, these gains are only present in the social planner case: the concavity of the utility function does not give individual countries incentives to reduce intragenerational inequality, as countries only care about their own welfare, not aggregate global welfare.

³ This assumption is in contrast to the result from one experiment with participants who have been involved in international climate policy. Dannenberg et al. (2010) find that participants dislike to a considerable extent being better off than others, while their aversion to being worse off than others is moderate. However, this does not have any implications for the analyses below.

⁴ Other alternative social preferences could be used, but this is not crucial to our conclusions as long as they express preferences for equality in payoffs such as consumption. One example is Charness-Rabin preferences (Charness and Rabin, 2002) applied by Kolstad (2011) to study coalitions in public goods provision.

⁵ An additional constraint on the utility preferences of the North that affects the inequality parameter β is that there exists an optimal consumption level in the North that is larger than zero, i.e., it is not always preferred to transfer a unit of consumption to the South.

Without loss of generality, let us assume that the population sizes of the two regions are equal and normalized to unity. Therefore, c_r is per capita consumption in region r.

Furthermore, each representative country produces an aggregate good, $Y_{r,t}$, using two types of inputs, clean and dirty, which are perfect substitutes:⁶

$$Y_{r,t} = Y_{r,c,t} + Y_{r,d,t}$$
(2)

$$Y_{r,c,t} = A_{c,t} K_{r,c,t}^{\gamma_c}$$
(3)

$$Y_{r,d,t} = A_{d,t} K_{r,d,t}^{\gamma_d}$$

$$\tag{4}$$

where subscripts *c* and *d* denote clean and dirty. Hence, the clean input is produced using clean capital, while the dirty input is produced using dirty capital. We assume that $\gamma_j \in \langle 0,1]$ for j = c,d, which implies diminishing marginal returns. The productivity of dirty capital is higher than for clean capital, i.e., $A_{d,t} > A_{c,t}$ for all *t*. For simplicity, we assume constant total factor productivities. Within this framework, however, we can easily introduce technological development as a positive trend in the total factor productivities.

Initially, the North has more of both types of capital than the South: $K_{n,j,1} > K_{s,j,1}$, for j = c, d. Indeed, given that preferences and technology are the same for both regions, it is North's larger stock of capital at time 0 that defines it as the initially rich region.

Each country can invest in clean and dirty capital, with capital dynamics given by:

$$K_{r,j,t+1} = \left(1 - \delta_j\right) K_{r,j,t} + I_{r,j,t}, \ r = n, s, \ j = c, d,$$
(5)

where δ_i is the capital depreciation rate.

⁶ One example can be electricity.

The countries' resource constraints are:⁷

$$Y_{r,t} = c_{r,t} + I_{r,c,t} + I_{r,d,t}, \quad r = n,s$$
(6)

By substituting for investment, $I_{r,c,t}$ and $I_{r,d,t}$, from equation (5), the resource constraint of a country in region r can be rewritten as:

$$Y_{r,t} = \left[K_{r,c,t+1} - (1 - \delta_c)K_{r,c,t}\right] + \left[K_{r,d,t+1} - (1 - \delta_d)K_{r,d,t}\right] + c_{r,t}.$$
(7)

Following Silva and Zhu (2009), we assume that there is co-production of local and global pollution from the use of dirty capital.⁸ As a result, these pollutants are correlated. Assume that κ_i is a coefficient that reflects the local pollution per unit of dirty capital used, while κ_g reflects the global pollution (greenhouse gas emissions) per unit of dirty capital. This yields the following flow of local pollution:

$$D_{r,t} = \kappa_l K_{r,d,t}, \quad r = n, s.$$
(8)

We model the global environment as a stock variable that deteriorates with global pollution, which follows from the aggregate use of the dirty capital, and regenerates naturally at a rate $\sigma > 0$:

$$S_{t+1} = \sigma \overline{S} + (1 - \sigma) S_t - \kappa_g \sum_r K_{r,d,t}$$
⁽⁹⁾

The equation implies that the global environmental quality satisfies the following constraint: $S_t \in [0, \overline{S}]$, where \overline{S} is the long-run level in absence of pollution. Note that without

⁷ Note that we do not explicitly model markets. This can be justified by imagining a sequence of spot markets that are renewed across generations.

⁸ Silva and Zhu (2009) assume that pollution follows from the production of the dirty good. In our model, it follows from the use of dirty capital. In the long run (steady state), however, there is a constant relationship between production and the capital stock.

pollution, S converges asymptotically to \overline{s} . We therefore treat climate change as a reversible process in the very long run.

Lastly, since the North is endowed with more productive capital than the South, the North initially consumes more than the South: $c_{n,1} > c_{s,1}$. Hence, we can write the welfare functions of the two regions at time t = 1 as:

$$U_{n,1} = u(c_{n,1}, D_{n,1}, S_1) - \beta_n(c_{n,1} - c_{s,1})$$
(10)

$$U_{s,1} = u(c_{s,1}, D_{s,1}, S_1) - \alpha_s(c_{n,1} - c_{s,1})$$
(11)

2.2 The Social Contract

Within this framework, consumption in the South will never exceed consumption in the North (per capita). This follows from the fact that the two regions are identical in every respect apart from their initial capital endowments. Hence, in the social optimum, the South can at most catch up with the North. If it is optimal with inequality in the long run, it cannot be optimal to let the initially poorer region catch up with and exceed the initially richer region, since we can reach such equilibrium faster if the North remains richer than the South. Hence, we use the simplified welfare functions (10) and (11) also for t > 1.

The social planner seeks to maximize the sum of discounted welfare across regions, where welfare in period t is given by:

$$W_{t} = u(c_{n,t}, D_{n,t}, S_{t}) + u(c_{s,t}, D_{s,t}, S_{t}) - (\beta_{n} + \alpha_{s})(c_{n,t} - c_{s,t})$$
(12)

The maximization problem can then be expressed as:

$$\max_{\{c_{nt}, c_{st}, K_{nct+1}, K_{sct+1}, K_{ndt+1}, K_{sdt+1}, S_{t+1}\}} \sum_{t=0}^{\infty} \rho^{t} \left(\sum_{r} u(c_{r,t}, D_{r,t}, S_{t}) - \phi(c_{n,t} - c_{s,t}) \right),$$
(13)

subject to (2)-(4) and (7)-(9), where ρ is the time preference rate and $\phi = (\beta_n + \alpha_s)$ is a constant. These parameters represent the main preferences for inter- and intragenerational equity in the model.

We can now express the Lagrangian of the maximization problem as:

$$L_{so} = \sum_{t=1}^{\infty} \rho^{t-1} \left\{ \sum_{r} u(c_{r,t}, D_{r,t}, S_t) - \phi(c_{n,t} - c_{s,t}) + \sum_{r} \lambda_{r,t} \left[Y_{r,t}(K_{r,c,t}, K_{r,d,t}) - K_{r,c,t+1} + (1 - \delta_c) K_{r,c,t} - K_{r,d,t+1} + (1 - \delta_d) K_{r,d,t} - c_{r,t} \right] + \mu_t \left[S_{t+1} - \sigma \overline{S} - (1 - \sigma) S_t + \kappa_g \sum_{r} K_{r,d,t} \right] \right\}$$
(14)

Where λ_r is the shadow price of capital in region *r*, while μ is the shadow price of the environmental quality.

First order conditions include:

$$[c_{n,t}]: \qquad \qquad \frac{\partial u(c_{n,t}, D_{n,t}, S_t)}{\partial c_{n,t}} - \phi = \lambda_{n,t}$$
(15)

$$[c_{s,t}]: \qquad \qquad \frac{\partial u(c_{s,t}, D_{s,t}, S_t)}{\partial c_{s,t}} + \phi = \lambda_{s,t}$$
(16)

$$[K_{r,d,t+1}]:\kappa_l \frac{\partial u(c_{r,t+1}, D_{r,t+1}, S_{t+1})}{\partial D_{r,t+1}} + \lambda_{r,t+1} \left[\frac{\partial Y_{r,t+1}}{\partial K_{r,d,t+1}} + 1 - \delta_d \right] + \mu_{t+1}\kappa_g = \rho^{-1}\lambda_{r,t}, \ r = n,s$$
(17)

$$[K_{r,c,t+1}]: \qquad \qquad \lambda_{r,t+1} \left[\frac{\partial Y_{r,t+1}}{\partial K_{r,c,t+1}} + 1 - \delta_c \right] = \rho^{-1} \lambda_{r,t}, \ r = n,s$$
(18)

$$[S_{t+1}]: \qquad \sum_{r} \frac{\partial u(c_{r,t+1}, D_{r,t+1}, S_{t+1})}{\partial S_{t+1}} = \mu_{t+1} (1 - \sigma) - \rho^{-1} \mu_{t}$$
(19)

Clearly, an important question when analyzing the optimal solution is whether consumption in the two regions will converge to the same level in the long run. In Appendix 1, we show that this will be the case, which gives us the following Lemma:

<u>Lemma 1:</u> In the long run, the socially optimal consumption levels of North and South will converge independently of inequality aversion.

n

Proof: See Appendix 1.

Note that the result is independent of inequality aversion in consumption. As we discussed above, in the social planner case, diminishing marginal utility of consumption alone will eliminate inequality in the long run. However, inequality aversion accelerates the convergence process, see discussion below and the simulation results in Section 5.

2.3 Optimal Policy

Let us now consider how inequality aversion affects the optimal consumption and capital paths of the two regions. We summarize our main results in Proposition 1.

<u>Proposition 1:</u> Inequality aversion within a generation affects the optimal capital and consumption paths of the North and the South:

- a. The **South** invests more in dirty capital and less in clean capital, causing an upward shift in all or most of its consumption path.
- *b. The North invests more in clean capital and reduces its investment in dirty capital. This causes a downward shift in all or most of its consumption path.*

With discounting, it may be optimal to reduce North's consumption and/or increase South's consumption in the short run by increasing and/or reducing their capital stocks, respectively. Later this results in a temporary increase in consumption inequality, which can imply a positive shift in the North's consumption path and/or a negative shift in the South's consumption path for a period of time, as the regions adjust their capital stocks toward the long-run equilibrium.

Proof: Inequality aversion gives an incentive to reduce consumption in the North and increase consumption in the South. Each region's consumption level is given by its resource constraint (6). As is evident from (6), the basic model contains no direct mechanism for transferring consumption from North to South. Instead, the current capital levels (production) and investment in clean and dirty capital determine each region's consumption level. By assumption, clean capital is less productive than dirty capital. Hence, the only way to achieve

equity in the long run is by shifting investments toward more clean capital in the North, and more dirty capital in the South. However, from the resource constraint we know that consumption can be quickly scaled up or down through capital investment or disinvestment. In the short run, the social planner can achieve equality by increasing investments in the North and/or reducing investments in the South. Both options compromise equity in the longer run, as more (less) capital means higher (lower) production that must affect consumption at some point of time. This temporary solution to the equity issue is optimal when future differences in consumption are discounted, so that it pays to sacrifice future equality to achieve more equality today. This is compounded by the fact that as South increases consumption, the cost of inequality in consumption is smaller. Hence, at some finite time interval in the future, consumption must rise in the North and/or drop in the South, so that consumption levels may be higher (North) or lower (South) than the consumption path without inequality aversion. Regardless of how inequality aversion affects consumption paths in the short run, it will lead to more investment in clean capital in the North, and more investment in dirty capital in the South over time to ensure equality in the long run (cf. Lemma 1). n

Proposition 1 describes the effect of inequality aversion on the investments in clean and dirty capital in the long run. While the North in the long run invests relatively more in clean capital, the South invests relatively more in dirty capital. It follows that the North is taking a bigger hit to improve the environment. We can think of this shift in investments as an indirect transfer of welfare from North to South. By letting the South invest more in dirty capital, the region consumes more (grows faster).

While inequality aversion has the anticipated effect on regional consumption and capital paths in the long run, the short-run effects may seem puzzling at first. Why would the (poor) rich region invest more (less) today to temporarily reduce equality at the cost of more inequality in the future? As stated in Proposition 1, this is the result of discounting. Hence, it represents yet another example of the conflict between inter- and intragenerational equity. The less weight we put on future generations relative to those living today (high discount rate), the stronger the incentive to immediately eliminate inequality between people living today through investment. However, this means sacrificing intragenerational equity for certain future generations as the capital stocks of the two regions must converge toward the same level (Lemma 1). For the North, this implies that the capital that was accumulated to reduce shortrun consumption must be consumed, leading to a temporary bump in consumption. Hence, inequality aversion does not necessarily shift the consumption path of the North below the initial consumption path for all time periods. We return to this in our numerical analysis in Section 5.

Proposition 1 emphasizes the close relationship between climate action and development/growth. In international negotiations aimed at reaching a global climate agreement, developing countries have long expressed a concern that limiting their greenhouse gas emissions will hamper their development opportunities. On this basis, they argue that the developed world must bear the majority of the cost of reducing global emissions. Proposition 1 may justify this claim made by developing countries, and suggests that if we all care about equality, the poorer region should be allowed to invest more in dirty capital, and thus pollute more. Consequently, the rich region should bear the majority of the costs of better environmental quality. In other words, Proposition 1 says that the solution to balancing the trade-off between intra- and intergenerational equity is to transfer emissions from North to South through their capital investments.

To see how the transition towards equality works in the long run, consider the optimal capital paths. To simplify the notation, we define: $MP_{r,j,t} = \frac{\partial Y_{r,t}}{\partial K_{r,j,t}}$ as the marginal productivity of

capital *j* in region *r*, and $MU_{r,t}^x = \frac{\partial u(c_{r,t}, D_{r,t}, S)}{\partial x_{r,t}}$, with $x_t = (c_{r,t}, D_{r,t}, S)$, as the marginal

utility of consumption, local pollution, and global environmental services, respectively, in region r. Now by eliminating common terms from the two regions' optimality conditions for clean capital (18) and rearranging, we obtain the following condition:

$$MP_{s,c,t} - MP_{n,c,t} = \rho^{-1} \left(\frac{\lambda_{s,t}}{\lambda_{s,t+1}} - \frac{\lambda_{n,t}}{\lambda_{n,t+1}} \right).$$
(20)

In the short run, before the two regions converge, we know that the North is richer and therefore has a higher utility than the South, while the difference between the two regions is decreasing over time. Regardless of whether the optimal steady-state policy involves a reduction or an increase in the North's utility relative to the initial state, it must be the case that $MU_{n,t}^c/MU_{n,t+1}^c < MU_{s,t}^c/MU_{s,t+1}^c$ until the South has caught up with the North. In addition, we know from (15) and (16) that $\lambda_{n,t} = MU_{n,t}^c - \phi$ and $\lambda_{s,t} = MU_{s,t}^c + \phi$. With this information, we can show that the following inequality must hold until the regions converge:

$$\frac{\lambda_{s,t}}{\lambda_{n,t}} > \frac{\lambda_{s,t+1}}{\lambda_{n,t+1}}.$$
(21)

Inequality (21) shows that the difference in the shadow values of capital between the South and the North decreases over time, and implies that the right-hand side of (20) is positive. Hence, while the South catches up with the North, the marginal product of clean capital is higher in the South than in the North, which implies a higher stock of clean capital in the North than in the South, $K_{n,c,t} > K_{s,c,t}$.

Finally, let us consider the optimal investment in clean and dirty capital in the long run. To do this, we rewrite the first order conditions (15)-(19) for the steady-state levels of the variables:

$$MU_n^c - \phi = \lambda_n \tag{22}$$

$$MU_s^c + \phi = \lambda_s \tag{23}$$

$$\kappa_l M U_r^D + \lambda_r \left[M P_{r,d} + 1 - \delta_d \right] + \mu \kappa_g = \rho^{-1} \lambda_r, \ r = n, s$$
(24)

$$\lambda_r \left[MP_{r,c} + 1 - \delta_c \right] = \rho^{-1} \lambda_r, \ r = n, s$$
⁽²⁵⁾

$$\sum_{r} MU_{r}^{S} = \mu \left(1 - \sigma - \rho^{-1} \right)$$
(26)

By substituting for the steady-state shadow prices of capital ((22)-(23)) and the environment (26) in the optimality conditions for clean and dirty capital ((24)-(25)), we obtain the following relationships that the marginal productivities must satisfy in equilibrium:

$$MP_{r,d} = \delta_d + v - \kappa_l \frac{MU_r^D}{MU_r^C + \psi_r} + \left(\frac{\kappa_g}{\sigma + v}\right) \frac{MU_n^S + MU_s^S}{MU_r^C + \psi_r}$$
(27)

$$MP_{r,c} = \delta_c + v \tag{28}$$

where $(\psi_n, \psi_s) = (-\phi, \phi)$ captures the effect of inequality aversion for both North and South, and $v = \rho^{-1} - 1$ is the discount rate. The optimal level of clean capital requires its marginal productivity to equal the sum of the depreciation and discount rates. These terms enter the condition for the marginal productivity of dirty capital, but when considering the optimal level of dirty capital we must also account for the welfare effects of local and global pollution. Consequently, the marginal productivity of dirty capital must equal the sum of depreciation and discount rates, the value of reduced local pollution, and the value of improved global environmental quality. We measure the two latter effects in terms of increased consumption, with inequality considerations (ψ_r) accounted for as consumption levels converge. Once convergence occurs, the marginal productivity of dirty capital must be the same in all countries.

Note that every term in the optimality condition for dirty capital (27) is positive. Hence, even if the capital depreciation rates for clean and dirty capital are equal, we will require a higher marginal productivity from dirty than clean capital to invest. As discussed above, this is because an investment in dirty capital must also compensate for the welfare effects of local and global environmental damage. Note that the inequality aversion parameters enter into the denominators of equation (27), thus partially decreasing the marginal productivity of dirty capital in the North while increasing it in the South. However, as consumption converges in the long run, and as the effect of global pollution enters equally in the utility functions, we find that the levels of dirty capital in the two countries converge.

How does inequality aversion across a generation affect greenhouse gas emissions? Let us rearrange and express the steady-state condition for global environmental quality in terms of the shadow price of the environment:

$$\mu = \frac{MU_n^{s} + MU_s^{s}}{1 - \sigma - \rho^{-1}}$$
(29)

It follows that the steady-state value of the shadow price of the global environment (μ) increases with the marginal utility of environmental quality given by the numerator in

equation (29). Furthermore, it increases with the replenishment rate of the environment and decreases with the discount factor. Equation (29) also reveals that the steady-state level of global environmental quality does not depend on the regions' preferences for equality (ϕ). The steady-state level of global environmental quality is given by:

$$S^* = \overline{S} - \frac{\kappa_g}{\sigma} \sum_r K^*_{r,d}$$
(30)

The environmental quality path towards the steady state depends on the aggregate level of dirty capital in the two regions. As seen above, inequality aversion reduces emissions in the North, while increasing emissions in the South before the system reaches steady state. If the emission reduction in the North exceeds the increase in the South, the environmental quality path shifts upwards (better environment). However, without specifying functional forms, it is not clear which of the two effects dominates: the decrease in the North or the increase in the South. Hence, the impact of inequality aversion on environmental quality is ambiguous. We return to this in the numerical analysis in Section 5.

3. What if a Contract is Not Possible? The Business-as-Usual Case

The next question is what the actions of the two regions of the world would be if the social contract cannot be reached. Without an enforcement mechanism in place, the regions are better off following their own interest and maximizing the welfare of a representative consumer. We refer to this as the Business-as-Usual problem (BAU), i.e., the optimization problem of local policy makers when there is no coordinated action or global environmental agreement.

As above, the North initially consumes more than the South: $c_{n,1} > c_{s,1}$. Countries are identical in all respects other than initial consumption and capital stock levels. Hence, following the same reasoning as above, the South can at most catch up with the consumption level of the North, but never exceed the North. Therefore, we can express the BAU optimization problem as consumers maximizing:

$$\sum_{t=1}^{t=\infty} \rho^{t-1} U_{n,t} = \sum_{t=1}^{t=\infty} \rho^{t-1} \left[u \left(c_{n,t}, D_{n,t}, S_t \right) - \beta_n \left(c_{n,t} - c_{s,t} \right) \right],$$
(31)

$$\sum_{t=1}^{t=\infty} \rho^{t-1} U_{s,t} = \sum_{t=1}^{t=\infty} \rho^{t-1} \left[u \left(c_{s,t}, D_{s,t}, S_t \right) - \alpha_s \left(c_{n,t} - c_{s,t} \right) \right],$$
(32)

respectively, given the technology (2)-(4), the resource constraint (7), and the local environmental constraints (8). We set the time preference rate, ρ , equal for the two regions to avoid having the effects of inequality aversion confounded by the effects of discounting.

To find the non-cooperative Nash equilibria for the two regions, we first define the Lagrangians. The North's Lagrangian is:

$$L_{BAU} = \sum_{t=1}^{\infty} \rho^{t-1} \left\{ \left[u(c_{n,t}, D_{n,t}, S_t) - \beta_n \left(c_{n,t} - c_{s,t} \right) \right] + \lambda_{n,t} \left[Y_{n,t}(K_{n,c,t}, K_{n,d,t}) - K_{n,c,t+1} + (1 - \delta_c) K_{n,c,t} - K_{n,d,t+1} + (1 - \delta_d) K_{n,d,t} - c_{n,t} \right] \right\}$$
(33)

where $\lambda_{n,t} > 0$ is the shadow price of capital. Recall that we made the assumption that each representative country is so small that its impact on the dynamics of global environmental quality is approximately zero. As a result, we maximize (33) over consumption and dirty and clean capital stocks, taking the effect of dirty capital on the local environment into account, while taking global environmental quality as given. The first order conditions then become:

$$[\mathcal{C}_{n,t}]: \qquad MU_n^c - \beta_n = \lambda_{n,t} \tag{34}$$

$$[K_{r,c,t+1}]: \qquad \lambda_{n,t} = \rho \lambda_{n,t+1} \left[M P_{n,c,t+1} + 1 - \delta_c \right]$$
(35)

$$[K_{r,d,t+1}]: \qquad \lambda_{n,t} = \rho \left[M U_{n,t+1}^D \kappa_t + \lambda_{n,t+1} \left(M P_{n,d,t+1} + 1 - \delta_d \right) \right]$$
(36)

The first order conditions for the optimization problem of the South are similar, but with consumption determined by:

$$[\mathcal{C}_{s,t}]: \qquad MU_{s,t}^c + \alpha_s = \lambda_{s,t} \tag{37}$$

Equations (34) and (37) show that in the optimum, the present marginal benefit from increased consumption should equal the opportunity cost of increasing consumption, which is given by the shadow price of capital. Compared to standard preferences (no inequality aversion: $\alpha_r = \beta_r = 0$, r = n,s), the marginal benefit of consumption is lower in the North and higher in the South. This implies lower consumption in the North and higher consumption in the long run. However, just like under the social planner case, the regions can reduce inequality in consumption in the short run through investments. We summarize this in Lemma 2:

<u>Lemma 2</u>: With business-as-usual, inequality aversion within a generation leads to reduced consumption in the North and higher consumption in the South compared to standard preferences. However, with discounting, it may be optimal to reduce North's consumption and/or increase South's consumption in the short run by increasing and/or reducing their capital stocks, respectively. Later this results in a temporary increase in consumption inequality, as the regions adjust their capital stocks toward the long-run equilibrium.

Proof: From equations (34) and (37), we know that the two regions have incentives to reduce inequality. Hence, over time and in the long run, inequality aversion leads to a reduction in North's consumption and an increase in South's consumption. As in the social planner case, the North can reduce inequality permanently by investing relatively more in the less productive clean capital or temporarily by accumulating more capital. Similarly, the South can reduce inequality permanently by investing relatively more in the more productive dirty capital, or temporarily by disinvesting in capital (consuming the capital stock). Hence, following the proof of Proposition 1, the North (South) may increase (decrease) consumption temporarily in the medium run, to adjust capital stocks to the long-run levels after the initial short-run reduction in inequality in the case of positive discounting.

Let us now compare the optimal consumption levels under BAU to the socially optimal levels by comparing equations (15) and (16) to equations (34) and (37). The difference in the optimality conditions for consumption is that each region under the social contract takes into account both regions' disutility from inequality, and not just its own disutility. In BAU the regions only take into account own disutility, not the disutility they impose on the other region, which represents an equality externality. Hence, over time the North reduces and the South increases consumption more under the social contract than in the BAU case, all else equal. As under the social contract, there may be a temporary increase in the consumption path of the North in BAU. However, due to the equality externality, this effect is not as strong as under the social contract.

In addition to the equality externality, we have an environmental externality in the BAU case. Countries do not take into account their impact on the global environment, which leads to lower consumption in both regions under the optimal policy compared to BAU. For the North, both incentives lead to lower consumption under the social contract compared to BAU. For the South, however, we have opposing incentives. We summarize this result in Proposition 2:

<u>Proposition 2:</u> Over the long run, inequality aversion within a generation leads to a larger consumption reduction in the North under the social contract than with business-as-usual, while the effect on consumption in the South is ambiguous.

Proof: See text.

Equations (35) and (36) determine investments in clean and dirty capital, respectively. The interpretations of these equations are that the benefits of increased capital in period t must equal the social costs of the capital investments. For both types of capital, the alternative cost of investment is lower consumption in the current period, while for the dirty capital the cost also includes lower utility due to a worsening of the local environment.

By combining equations (35) and (36), we can eliminate $\lambda_{n,t+1}$ and ρ , which yields the following relationship between clean and dirty capital in region **r**:

$$MP_{r,d,t} - MP_{r,c,t} = \delta_d - \delta_c - \lambda_{r,t}^{-1} M U_{r,t}^D \kappa_l.$$
(38)

Equation (38) states that a country should adjust its stocks of clean and dirty capital so that the difference in marginal productivities between the two equals the difference in capital

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depreciation rates and the marginal social cost of dirty capital on the local environment. Note that the last term in equation (38) is positive. Consequently, if clean capital and dirty capital depreciate at the same rate, the country will require a higher marginal productivity of dirty capital than for clean to invest.

How would inequality aversion affect investments in clean and dirty capital in the two regions, respectively? Consider first the North, where, over the long run, inequality aversion leads to lower consumption, lower investments in dirty capital, and higher investments in clean capital. Lower consumption can be achieved with more investments, and investments in the least effective capital (clean) ensure lower consumption also in the future. Less investment in dirty capital and more in clean capital reduce local pollution. A better local environment increases utility and therefore works as a substitute to lowering consumption in the utility function in the North. We can use the same intuition for the South but with opposite signs. Investments in dirty capital increase, while investments in clean capital fall. Thus, inequality aversion increases the climate burden on the North, while reducing the burden on the South also with BAU.

Let us next compare regional capital stocks between the social contract and BAU. This involves comparing optimality conditions (17) and (18) to conditions (35) and (36). The optimality condition for clean capital is the same in the two cases. However, the optimality condition for dirty capital under the social contract includes an additional term compared to the BAU case. This term represents the marginal effect of more dirty capital on global environmental quality. The inclusion of this term in the social contract case implies a lower investment in dirty capital compared to BAU since the environmental externality is internalized. This, in turn, affects investment in clean capital.

Hence, we find that while inequality aversion yields a lower stock of dirty capital in the North under the social contract than under BAU, we cannot determine the effect on the capital stock in the South. Hence, poor countries should not necessarily have a pollution constraint under a global climate treaty. Under certain conditions it may actually be optimal to let poor countries increase their emissions under a climate treaty. We summarize this result in Proposition 3.

<u>Proposition 3:</u> Over the long run, inequality aversion within a generation leads to a reduction in emissions in the North under the social contract compared to business-as-usual, while for the South the result is ambiguous, and emissions may actually be higher under the social contract.

Proof: See text.

Our analysis of the Business-as-Usual case shows that even without a social planner, the rich countries should finance more of the actions to combat climate change they have preferences for equality. In fact, our results show that we in some cases should encourage poorer countries to use more dirty capital than they otherwise would to speed up their development (cf. Proposition 3). Even if poor countries ignore the negative externality of their own dirty production on the global climate, they may be reluctant to use enough dirty capital because of the negative implications for local pollution. However, the use of more dirty capital in the South speeds up this region's development, which also benefits the North because of the equality externality. Consequently, the North may be better off subsidizing technologies that reduces local pollution in the South, rather than trying to convince the South to use more clean capital to cut global emissions. The BAU results confirm our main results from the previous section, and offer support for claims often made by developing countries in climate talks. If people care about equality, most of the climate burden should be placed on developed countries, while poorer countries should be allowed to continue using dirty capital to speed up economic growth.

4. Interactions between the Regions

Let us now turn once again to the social contract. Thus far, the only interaction between the regions has come through the impact of pollution on the global environment. In this section we will analyze the implications of opening up for international transfers, such as development aid from the rich to the poor region, and international trade.

Recall from our analysis in Section 2 that without the possibility for direct transfers between the regions, it may be optimal in the short run to let the North lower its consumption level by investing more, while the South increases consumption by investing less. Later on for a period of time, the North must increase consumption, while the South must reduce consumption, to

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adjust capital stocks to their steady-state levels. This leads to increased inequality for some time, before the regions converge toward equality in equilibrium (cf. Proposition 1). When the social planner faces such restriction on transfers between the regions, the optimal contract is a second-best policy. Consequently, when we relax the constraint by allowing for some or unlimited international transfers, the result must be that we get closer to the first-best solution and achieve higher aggregate welfare. In the following, we analyze two specific and policy relevant cases: international transfers and international trade.

4.1 International Transfers

We introduce transfers between the two regions by adding the term τ_t , which represents transfers from North to South in period *t*, to the regions' resource constraints. The two regions' modified resource constraints then become:

$$Y_{n,t}(K_{n,c,t},K_{n,d,t}) = c_{n,t} + \tau_t + K_{n,c,t+1} - (1 - \delta_c)K_{n,c,t} + K_{n,d,t+1} - (1 - \delta_d)K_{n,d,t}$$
(39)

$$Y_{s,t}(K_{s,c,t},K_{s,d,t}) = c_{s,t} - \tau_t + K_{s,c,t+1} - (1 - \delta_c)K_{s,c,t} + K_{s,d,t+1} - (1 - \delta_d)K_{s,d,t}$$
(40)

In addition, we introduce a constraint on North-South transfers such that $\tau_t \leq M$ in every time period. Now, the social planner must also determine the optimal size of the transfers τ_t , and hence, we obtain an additional first order condition for this variable. The first order conditions of the modified optimization problem include the optimality conditions for the case without transfers ((15)-(19)), along with the following condition for the North-South transfer:

$$\lambda_{n,t} + \omega_t = \lambda_{s,t},\tag{41}$$

where $\omega_t \ge 0$ is the shadow price of the transfer constraint $(\tau_t \le M)$.

The optimal transfer policy is a most rapid approach path towards equality. In the case of unlimited transfers, which means that $\omega_t = 0$ for all *t* in (41), there should be a transfer from North to South in the first period that completely eliminates inequality. From the second period onwards, all countries are equal and there is no disutility from inequality. If the transfer constraint binds, condition (41) shows that the shadow price in the North is higher than the

shadow price in the South. Hence, the optimal policy is to transfer as much as possible from North to South ($\tau_t = M$) until the consumption paths of the two regions converge. The positive shadow price of the transfer constraint illustrates the social value of development aid (direct transfers) from the rich to the poor region.

Allowing for transfers from North to South enables the social planner to eliminate inequality sooner. Furthermore, the social planner wants to eliminate inequality between the two regions regardless of whether the countries have inequality preferences. First, due to the concavity of the regional welfare functions, the aggregate welfare is higher if consumption levels are equalized, all else equal. Second, the best use of available resources (capital) requires that marginal productivities are equal across all countries at all times. Hence, ideally both regions should have the same levels of clean and dirty capital. This finding also supports the result that inequality aversion implies higher consumption and more dirty production in the South.

We summarize the results on transfers in Lemma 3:

<u>Lemma 3:</u> Transfers between the regions speeds up the convergence process under the social contract. Transfers from North to South should follow the most rapid approach path to equality between the regions. As a result, transfers increase pollution in the South and decrease pollution in the North.

Proof: See text.

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4.2 International Trade: Transfers Must Be Paid Back

Above, we discussed pure transfers from North to South. Let us now investigate how the results change if we allow for international trade in input factors. Define $E_{d,t}$ as export of the dirty input factor from North to South, while $E_{c,t}$ is export of the clean input factor from North to South. Consequently, the South's export equals to $-E_{d,t}$ and $-E_{c,t}$, respectively. The available amounts of inputs are then:

$$Y_{n,j,t} = Y_{n,j,t}(K_{n,j,t}) - E_{j,t}, \quad j = c,d$$
(42)

$$Y_{s,j,t} = Y_{s,j,t}(K_{s,j,t}) + E_{j,t}, \quad j = c,d$$
(43)

In this simple setup, we impose market clearing without considering prices. This can be justified in the social planner case, as we do not consider any strategic interactions that may affect prices. The temporal budget constraints then become:

$$c_{n,t} = Y_{n,d,t}(K_{n,d,t}) - E_{d,t} + Y_{n,c,t}(K_{n,c,t}) - E_{c,t} - K_{n,c,t+1} + (1 - \delta_c)K_{n,c,t} - K_{n,d,t+1} + (1 - \delta_d)K_{n,d,t}(44)$$

$$c_{s,t} = Y_{s,d,t}(K_{s,d,t}) + E_{d,t} + Y_{s,c,t}(K_{s,c,t}) + E_{c,t} - K_{s,c,t+1} + (1 - \delta_c)K_{s,c,t} - K_{s,d,t+1} + (1 - \delta_d)K_{s,d,t}(45)$$

Finally, the following intertemporal trade balance must hold:

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$$\sum_{t=1}^{\infty} (1+i)^t \left(E_{d,t} + E_{c,t} \right) = 0$$
(46)

where i is the interest rate. Note that in this model the interest rate equals the time preference rate, see equation (18). This means that the international trade balance can be written as:

$$\sum_{t=1}^{\infty} \rho^{1-t} \left(E_{d,t} + E_{c,t} \right) = 0 \tag{47}$$

Under the social contract, the social planner directly determines trade. As a result, we can think of trade as transfers that must be paid back with interest. Introducing this into our model yields the following first order condition, where $\phi > 0$ is the shadow price of the intertemporal trade balance:

$$\lambda_{s,t} - \lambda_{n,t} = \rho^{2(1-t)}\varphi \tag{48}$$

Note that without the trade balance constraint, we find that $\lambda_{n,t} = \lambda_{s,t}$, i.e., the result with unlimited transfers.

The evolution of the consumption paths is as follows. At time t = 1, we have $\lambda_{s,t} - \lambda_{n,t} = \varphi$, which implies that the difference in regional shadow prices of capital is at its minimum and equal to the shadow price of the trade balance, where the latter represents the payback from South to North. However, note that with positive discounting, the right-hand side of (48)

increases exponentially and converges to ∞ as $t \to \infty$. Therefore, we obtain a "Greek disease" result, in which it is better to equalize consumption as much as possible now while postponing the costs of paying back, even though these costs will explode over time. Yet once again, this finding reinforces our main result: the South should increase its dirty capital stock and pollute more, thereby allowing the region to consume more and pay back its debt. The North, on the contrary, should invest more in clean capital, which helps improve the local and global environment, but comes at the cost of lower consumption. This gives us our final proposition:

<u>Proposition 4:</u> Under the social contract, international trade will reduce the difference in consumption between the regions in the near term, but with a positive discount rate, the gap in consumption will increase over time toward its equilibrium level.

Proof: Let us start with the left-hand side of (48), which must converge to infinity as $t \to \infty$. This means that the difference in the shadow prices of capital between the South and the North must approach infinity. We know that in the long run, the South must export goods to the North for the trade balance constraint to hold. As a consequence, the South's consumption level declines, while North's consumption increases over time. From the first order conditions for consumption (equations (15) and (16)) and the assumption $\lim_{c\to 0} MU_{r,t}^c = \infty$, it is clear that for the term $(\lambda_{s,t} - \lambda_{n,t})$ to approach infinity as $t \to \infty$, consumption in the South must approach zero. Hence, in the long run, consumption approaches zero in the South, while it increases towards a finite upper bound in the North.

The discount factor is a critical determinant of the consumption dynamics of the two regions. However, regardless of the discount factor, trade from North to South should be used to reduce inequality today. Figures 1 and 2 illustrate this. In the special case without discounting ($\rho = 1$), the optimality condition for trade simplifies to $\lambda_{s,t} - \lambda_{n,t} = \varphi$. As with discounting, there should be trade from North to South in the first period so that the difference between the two shadow prices of capital equals the shadow price of balanced trade. To eliminate the two regions' trade balance surpluses and deficits in the long run, the South must export goods to the North from period 2 onward. As a result, the two regions never fully converge. Instead, trade allows the two regions to immediately adjust to a long-run level where there is some inequality, which is then maintained over time to achieve balanced trade, as illustrated in Figure 2. Note that the less trade we need initially to eliminate inequality, the less constraining the trade balance constraint will be, and the smaller the difference between the countries in the long run (i.e., smaller φ).

As we introduce discounting, the South's consumption level will not just be lower than that of the North, it will approach zero in the long run. A higher discount rate means that we care less about future consumption and inequality, but it also implies that the South must reduce consumption more when it pays back its trade debt in the future. Thus, it is socially optimal to help the South today to eliminate inequality between the regions, even though the South will collapse in the very long run. It follows that even when people care about equality and such preferences are accounted for by a welfare maximizing social planner, trade does not ensure equality in the long run. Note also that with trade, we no longer get short-run elimination of consumption inequality through temporary changes in the regions' capital investment, cf. Proposition 1.



Figure 1. Greek disease (positive discount rate).

Figure 2. Greek disease (no discounting).

Clearly, the introduction of an additional constraint in the optimization problem of the social planner can only worsen the outcome. Unlimited transfers without a (binding) trade balance constraint would therefore yield higher welfare than the trade solution discussed above. This has several policy implications. First, this supports debt remittance to developing countries to help reduce inequality. The developed world can then transfer wealth to the developing world,

both by remitting debt and by using more clean capital, thereby allowing poorer countries to use more of the productive but dirtier capital to develop faster. Eventually, however, as the inequality between different regions diminishes, the poor region must also use more clean capital to reduce aggregate pollution. Second, our findings confirm that wealth transfers from rich to poor countries, such as development aid and foreign direct investment, can be welfare improving, particularly in the short run to help speed up the process of eliminating inequality between countries, which involves faster development in the South.

5. Numerical Simulations

To illustrate our results, we carry out a number of simulations where we examine how inequality aversion affects the social contract. In these simulations we assume the North and the South have the same utility function given by:

$$U(c_{t}, D_{t}, S_{t}) = c_{t}^{a} \frac{1}{(1+D)^{b}} S_{t}^{c}$$
(49)

Furthermore, we simulate the social contract for three values of aggregate inequality aversion $\phi = (0,1,1.5)$ over a time horizon of 150 years. As these simulations are for illustrations only, we choose parameter values based on best guess, apart from the total factor productivities in the production functions (3) and (4), which are from Acemoglu et al. (2012). See Appendix 2 for parameter values.⁹

Consumption levels in the North and the South are plotted in Figure 3. The simulations confirm that consumption levels in the North and the South converge over time, and the point of time when inequality is completely eliminated decreases with the level of inequality aversion, ϕ . Also, the simulations confirm our theoretical results presented in Proposition 1 that inequality leads to an immediate adjustment in consumption levels. For example, we see a dip in North's consumption, followed by a temporary increase ("bump").

⁹ The MatLab code used to run the simulations are available from the authors upon request.



Figure 3. Consumption in North and South as a function of time.

The initial adjustment in consumption becomes more pronounced as ϕ increases. Note that given our parametric choices, both regions choose to build down their stocks of dirty capital. When $\phi = 0$, the initial dip in consumption is caused by depreciation of dirty capital before the stock of clean capital has accumulated sufficiently to compensate. As we increase ϕ , it becomes more and more important to reduce the difference in consumption between the North and the South. When $\phi = 1.5$, we get rapid convergence between the two regions' consumption levels. However, in this particular case, after an initial period of equality in consumption, consumption levels diverge before finally converging at a later point in time. This divergence occurs because the North has accumulated excess capital that it needs to consume at some point in time (cf. Figure 4). In general, increased inequality aversion yields higher consumption in the South and lower consumption in the North. However, to achieve this, North engages in excessive saving that leads to an accumulation of capital. This capital must at some point be consumed. The reason that North postpones its consumption is discounting, which means that the cost of large differences in consumption today, *ceteris*

paribus, is lower than in the future, and that capital accumulation in South implies that South's consumption increases as a function of time. This is in line with Proposition 1.

Figure 4 shows the evolution of clean and dirty capital stocks in the two regions. This figure confirms the theoretical result that inequality aversion leads to higher levels of dirty capital in the South. Although dirty capital initially depreciates at the same rate regardless of region and inequality aversion due to the initial values we imposed, we later get a transfer of emissions from North to South, and more so the stronger the inequality aversion. Finally, Figure 4 confirms our theoretical result of long-run convergence in the regions' clean and dirty capital stocks.



Figure 4. Time paths of accumulation of clean and dirty capital under different degrees of inequality aversion.

Figure 5 illustrates the effect of inequality aversion on the evolution of global environmental quality. Because of increasing emissions in the South with more inequality aversion (see Figure 4), the quality of the global environment falls in the inequality aversion. This effect is, however, transitory. In the long run, environmental quality is independent of inequality aversion, which also confirms our theoretical results.



Figure 5. Global environmental quality as a function of time.

6. Conclusions

This paper studies the trade-off between intra- and intergenerational equity as represented by preferences to reduce future climate damage and to increase economic development in the poor world today. We find that inequality aversion within a generation will reduce consumption and greenhouse gas emissions in the rich region of the world, while consumption and emissions will increase in the poor region. This happens as the rich region shifts towards more clean capital, while the poor region is allowed to use more of the dirty and more productive capital to develop faster. This result emphasizes the close relationship between development and climate policy, and justifies transferring emissions from North to South to promote economic development. Introducing monetary transfers between the regions reinforces this result. Whether total greenhouse gas emissions increase as a result of income

inequality aversion within a generation depends on the size of the emissions reductions in the North relative to the increases in the South.

If we consider the Kyoto Protocol in light of our findings, the division between Annex I and non-Annex I countries is justified. The first group consists of rich countries that committed to reducing their greenhouse gas emissions, while the latter group consists of poorer developing countries that do not have to undertake emissions reductions. Hence, the division between Annex I- and non-Annex I countries was a way to transfer wealth from North to South by imposing the use of cleaner capital in the richest region, while poor countries could use dirty though more productive capital to speed up their development. This is in line with the optimal climate policy we have characterized in this paper. The Kyoto Protocol also defines a mechanisms that support capital transfers from rich to poor countries, the clean development mechanism, but does not include debt remittance or similar direct financial transfers as ways to further reduce the inequality between regions. Finally, our results suggest that while poor countries should be allowed to pollute more in the short run when they catch up with the North. In the long run, however, all countries must contribute to improved environmental quality by restricting their emissions. There is no mechanism in the Kyoto Protocol to commit non-Annex I countries to reduce emissions as they become richer.

Our work suggests that future climate agreements should contain mechanisms for wealth transfers to developing countries to speed up their development and reduce inequality. These mechanisms could be in the form of lower emissions reductions for developing countries, or direct transfers, such as debt remittance or development aid. There should also be explicit mechanisms that define how and when to limit the emissions of these countries as they become more developed. Moreover, our results show that in certain situations, climate agreements should require poor countries to increase their use of dirty capital in the short run to speed up their development, even if this yields higher levels of both local and global pollutants. This result is driven by the equality externality, as poor countries do not take into account the welfare loss of rich countries from inequality, and may therefore pollute too little and develop too slowly without emissions restrictions. In such situation, the developed countries can assist by funding technologies to reduce the negative effects of increased local pollution in the South.

There are many possibilities for extending the current work. Our work abstracts from strategic considerations since all countries are assumed to be sufficiently small to take both prices and global environmental quality as given. In recent climate negotiations, it is quite clear that there are several big players in the game that exert a significant impact, both in the relevant markets and on the climate. These include large countries such as the United States and China, as well as groups of countries that coordinate their actions (e.g., the European Union). Extending our analysis to allow for strategic interaction between countries and regions therefore seems highly relevant. Another possibility for future work is to investigate the implications of limited substitutability between clean and dirty capital. While we have assumed perfect substitution between clean and dirty capital, restrictions on the substitutability may affect the results.

Appendix 1: Will consumption levels converge in the long run?

In the long run, the economy will enter a steady state in which there will be no growth in any of the variables (in the absence of technological progress. We can therefore rewrite the first order conditions (15)-(19) for the steady-state levels of the variables:

$$\frac{\partial u(c_n, D_n, S)}{\partial c_n} - \phi = \lambda_n \tag{50}$$

$$\frac{\partial u(c_s, D_s, S)}{\partial c_s} + \phi = \lambda_s \tag{51}$$

$$\kappa_{l} \frac{\partial u(c_{r}, D_{r}, S)}{\partial D_{r}} + \lambda_{r} \left[\frac{\partial Y_{r}}{\partial K_{r,d}} + 1 - \delta_{d} \right] + \mu \kappa_{g} = \rho^{-1} \lambda_{r}, \ r = n, s$$
(52)

$$\lambda_r \left[\frac{\partial Y_r}{\partial K_{r,c}} + 1 - \delta_c \right] = \rho^{-1} \lambda_r, \ r = n, s$$
(53)

$$\sum_{r} \frac{\partial u(c_r, D_r, S)}{\partial S} = \mu \left(1 - \sigma - \rho^{-1} \right)$$
(54)

From equation (53), it is clear that the long-run clean capital level must be the same in the two regions. Since ρ and δ_c are the same for both countries, the marginal product of clean capital must be the same in the two regions, and with a production function that is monotonically increasing in clean capital, this implies that $K_{n,c} = K_{s,c} = K_c^*$ in equilibrium.

Next, let us consider the long-run levels of dirty capital given by equation (52), which can be rewritten as follows:

$$\lambda_r \left(\frac{\partial Y_r}{\partial K_{r,d}} + 1 - \delta_d - \frac{1}{\rho} \right) + \kappa_l \frac{\partial u(c_r, D_r, S)}{\partial D_r} = -\mu \kappa_g, \ r = n, s$$
(55)

Note that the right-hand side of this expression is the same for both the North and South. Consequently, we can write:

$$\lambda_n \left(MP_{n,d} + 1 - \delta_d - \rho^{-1} \right) - \lambda_s \left(MP_{s,d} + 1 - \delta_d - \rho^{-1} \right) = \kappa_l \left(MU_s^D - MU_n^D \right), \tag{56}$$

where $MP_{r,j} = \frac{\partial Y_r}{\partial K_{r,j}}$ is the marginal productivity of capital *j* in region *r*, and $MU_r^D = \frac{\partial u(c_r, D_r, S)}{\partial D_r}$ is the marginal utility of local pollution in region *r*.

Let us first assume that the South never catches up with the North, so that $c_n > c_s$ in steady state. However, introducing this into condition (56) shows that the condition cannot hold for $c_n > c_s$. To see this, let us rewrite equation (56) as follows:

$$\left(\lambda_{s}-\lambda_{n}\right)\left(1-\delta_{d}-\rho^{-1}\right)+\left(\lambda_{s}MP_{s,d}-\lambda_{n}MP_{n,d}\right)+\kappa_{l}\left(MU_{s}^{D}-MU_{n}^{D}\right)=0.$$
(57)

We know from (50) and (51) that the shadow price of capital must be lower in the North than in the South ($\lambda_n < \lambda_s$) since the North has a higher consumption level, and therefore a lower marginal utility from goods consumption, than the South. Thus, the first term of (57) must be positive for $c_n > c_s$. If $c_n > c_s$ it must also be the case that $K_{n,d} > K_{s,d}$, as we have already established that the level of clean capital is the same in the two regions in the long run. Since the marginal productivity is decreasing in the level of dirty capital, this implies that $MP_{n,d} < MP_{s,d}$. For this reason, the second term of (57) is also positive. As a result, condition (57) can only hold if its third term is negative. To evaluate the sign of the third term, note first that we know from equation (8) that $D_n > D_s$ if $K_{n,d} > K_{s,d}$. Next, from the assumptions $u_{cD}^n \leq 0$ and $u_{DD}^n \leq 0$, we have that MU_r^D is declining, both in consumption and local pollution. Since the North has higher levels of consumption and local pollution, it must be the case that $MU_s^D > MU_n^D$, which means that the third term of (57) is positive when $c_n > c_s$. Hence, condition (56) cannot hold unless $c_n = c_s$, which means that the consumption level of the two regions must converge in the long run.

Appendix 2: Parameters used in the simulations

a	Exponent in utility function (consumption)	0.5
b	Exponent in utility function (local environment)	0.2
c	Exponent in utility function (global environment)	0.4
ф	Aggregate inequality aversion	0, 1, 1.5
A _c	Total factor productivity in clean input production	0.9848
A _d	Total factor productivity in dirty input production	1.2933
Υ _c	Exponent in clean input production function	0.5
Υ _d	Exponent in dirty input production function	0.5
δ _c	Depreciation rate of clean capital	0.05
δ _d	Depreciation rate of dirty capital	0.05
K _{n,c,0}	Initial capital stock of clean capital in the North	20
K _{n,d,0}	Initial capital stock of dirty capital in the North	20
K _{s,c,0}	Initial capital stock of clean capital in the South	10
K _{s,d,0}	Initial capital stock of dirty capital in the South	10
κ _l	Local pollution per unit of dirty capital	0.5
κ _g	Global pollution per unit of dirty capital	0.4
σ	Regeneration rate of global environmental quality	0.25
\overline{S}	Initial environmental quality	100
v	Time preference rate	0.05
Т	Time horizon	150

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