

# The Dynamic Impact of Unilateral Environmental Policies

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## Abstract

This paper builds a two-country, two-sector (polluting, nonpolluting) trade model with directed technical change, examining whether unilateral environmental policies can ensure sustainable growth. The polluting good generates more or less emissions depending on its relative use of a clean and a dirty input. I show that a unilateral policy combining clean research subsidies and a trade tax can ensure sustainable growth, while unilateral carbon taxes alone increase innovation in the polluting sector abroad and generally cannot ensure sustainable growth. Relative to autarky and exogenous technical change respectively, the mechanisms of trade and directed technical change accelerate environmental degradation either under laissez-faire or with unilateral carbon taxes, yet both help reduce environmental degradation under the appropriate unilateral policy. I characterize the optimal unilateral policy analytically and numerically using calibrated simulations. Knowledge spillovers have the potential to reduce the otherwise large welfare costs of restricting policy to one country only.

### *Key words:*

climate change, environment, directed technical change, innovation, trade, unilateral policy

*JEL:* F18, F42, F43, O32, O33, O41, Q54, Q55

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## 1. Introduction

Despite the signature of the Kyoto protocol in 1997, annual carbon dioxide ( $\text{CO}_2$ ) emissions increased by 39% between 1997 and 2010. Meanwhile, climate negotiations have stalled and no global agreement is in sight. In response, several countries have undertaken unilateral environmental policies with varying degrees of ambition and success. For instance, the European Union implemented a cap-and-trade system (EU ETS) in 2005 which covers around 45% of the EU's greenhouse gas emissions. However, such policies generate a pollution haven effect, as the production of tradable and polluting goods moves to countries with laxer policies, which leads to an increase in their emissions. Could unilateral policies nevertheless achieve the necessary reduction in  $\text{CO}_2$  emissions? If so, how should they be designed? These questions are fundamentally about the economy's long-run behavior. Over the time period relevant to climate change, comparative advantages evolve with innovation, which itself responds to environmental policies. Yet, the economic literature on unilateral environmental policies has largely ignored the role played by innovation. This paper builds a trade model featuring directed technical change and a global pollution externality, and thereby highlights the crucial role that innovation plays in the positive and normative analysis of unilateral climate change policies.

More formally, I consider a dynamic Ricardo–Heckscher–Ohlin model with two countries, North and South, and two sectors, polluting and non-polluting. The North represents countries willing to implement an environmental policy, and the South, countries that are not—a division which need not fall along the lines of developed versus developing countries. The polluting good represents the tradable goods with a high  $\text{CO}_2$  emission intensity, typically energy-intensive sectors. It is produced using clean inputs (e.g., renewable and nuclear energy or bioplastics) and/or dirty inputs (e.g., fossil fuel energy or traditional petroleum products). Innovation is undertaken in both countries by profit-maximizing firms that hire scientists. It can be directed at the nonpolluting sector, or, within the polluting sector, at clean or dirty technologies. For most of the analysis, innovation is completely local.

In *laissez-faire*, the allocation of innovation favors the exporting sector and therefore reinforces comparative advantage over time. This results from a market size effect: a country exports the good that it produces relatively

more, such that the market for innovation in that sector is relatively larger. As in Acemoglu et al. (2012a; henceforth AABH), the allocation of innovation within the polluting sector exhibits path-dependence, also because of a market size effect (a more advanced technology has a larger market which increases the profits of subsequent innovators). If clean technologies are initially less advanced than dirty ones, the laissez-faire equilibrium leads the economy toward an environmental disaster, as the quality of the environment falls below a critical threshold. In other words, economic growth is not sustainable. The paper analyzes whether this disaster can be prevented by specific policies in the North only, and doing so, makes two important points.

First, carbon taxes are generally unable to prevent an environmental disaster and may even be counterproductive. A carbon tax in the North leads to a reallocation of some of the polluting good's production from the North to the South (a static pollution haven effect). It cannot prevent an environmental disaster if the South initially had a comparative advantage in the polluting sector, since then, the South specializes further in the polluting sector and its emissions keep growing. Moreover, because reallocating production goes hand in hand with reallocating innovation, a Northern carbon tax actually increases dirty Southern innovations (a dynamic pollution haven effect) and thereby may accelerate environmental degradation.

Second, a temporary industrial policy, which combines clean research subsidies and a trade tax, may prove to be more effective. Such a policy can help the North develop a comparative advantage in the polluting sector while making that sector cleaner at the same time. This ensures that emissions eventually start decreasing in both countries. If the initial environmental quality is high enough, an environmental disaster can be averted. Importantly, directed technical change is essential for this result; with exogenous technical change, unilateral policies in the North could still fail to prevent a disaster when the South initially has a sufficiently large comparative advantage in the polluting sector.

The optimal unilateral policy can be decentralized through a carbon tax and research subsidies in the North along with a trade tax on the polluting good. When the social planner values equally consumption in the North and the South, the trade tax typically takes the form of a tariff and then of an export subsidy. Its expression reflects two aims of the social planner: reducing emissions in the South and redirecting Southern innovation toward the nonpolluting sector. To illustrate the results, I conduct a numerical exercise where, in accordance with the literature, the South corresponds to

countries with no binding constraints under the Kyoto protocol. This exercise shows that, even though avoiding a disaster is possible, the welfare costs from not being able to intervene in the South may be very large. It also highlights the double-edged nature of trade and directed technical change. Relative to autarky and exogenous technical change respectively, the mechanisms of trade and directed technical change accelerate environmental degradation either under *laissez-faire* or with unilateral carbon taxes, yet both help reduce environmental degradation under the appropriate unilateral policy.

Finally, the model is enriched by including knowledge spillovers. Unilateral carbon taxes may still fail to prevent an environmental disaster; whereas a combination of clean research subsidies and a carbon tariff can do so for sufficiently high initial environmental quality. In this scenario, however, the diffusion of knowledge can ensure a switch toward clean innovation in the South; hence an environmental disaster can be prevented even though the South still specializes in the polluting good. In addition, the welfare costs from not being able to intervene in the South are much lower.

This paper can be interpreted as a green version of the “infant industry argument,” which claims that trade can be detrimental to growth if it leads countries to specialize in sectors with poor development prospects (Krugman, 1981, Young, 1991, Matsuyama, 1992). Here as well, a country risks specializing in the “wrong” sector, not because that sector offers poor growth prospects, but because this country cannot prevent the environmental externality associated with production in that sector. The idea that free trade may amplify comparative advantages and that a temporary trade policy could permanently reverse the trade pattern was previously touched on by Krugman (1987), and Grossman and Helpman (1991, ch. 8).<sup>1</sup>

It has long been recognized that, in an open world, the pollution haven effect hampers the effectiveness of unilateral policies for reducing world pollution (Pethig, 1976). Empirical evidence is reported by Copeland and Taylor (2004) or Broner, Bustos and Carvalho (2012). Markusen (1975) and Hoel (1996) show that the optimal instrument for addressing the pollution haven effect is a tariff. In the context of global warming, where the pollutant

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<sup>1</sup>Krugman’s (1987) is based on learning-by-doing, and Grossman and Helpman’s (1991) model features endogenous growth in one sector only. A few papers have built models with trade and directed technical change; examples include Acemoglu (2003), who studies the impact of trade on the skill bias of technological change, and Gancia and Bonfiglioli (2008), who show that trade amplifies international wage differences.

(CO<sub>2</sub>) enters at several stages of the production process, several papers use computable general equilibrium (CGE) models to track carbon through the global economy; in this way they determine the pattern of trade and compute the carbon leakage rate (the rate at which emissions abroad increase after a domestic reduction). Developed countries are net carbon importers, which justifies the focus of the paper on the case where the South has a comparative advantage in the polluting sector: Atkinson et al. (2011) find that the net US imports of carbon from China in 2004 amounted to 244 million tons of CO<sub>2</sub> or 0.9 percent of total world emissions that year; the OECD STAN database estimates that for OECD countries net CO<sub>2</sub> imports represent 12.6% of CO<sub>2</sub> emissions from production. Elliott et al. (2010) compute a carbon leakage rate of 20 percent from a reduction in Annex I countries—the countries with binding constraints under the Kyoto protocol—and show that border tax adjustments eliminate half of it.<sup>2</sup> There are comparatively few empirical studies. Aichele and Felbermayr (2012) find that countries which committed to the Kyoto protocol reduced domestic CO<sub>2</sub> emissions by about 7%, but did not change their total CO<sub>2</sub> consumption. While this literature has focused on static models, the novelty of the present paper is to incorporate dynamic aspects. This comes at the expense of a more detailed model of world trade (as in CGE models) and of a study of the strategic interactions between countries (as in Copeland and Taylor, 2005).

A growing literature has shown the importance of taking into account directed technical change when designing climate change policies. On the empirical side, Popp (2002) shows that an increase in energy prices leads to more energy-saving innovation; similar results are found by Newell, Jaffe and Stavins (1999) in the air conditioner industry and by Hassler, Krusell and Olovsson (2012) using macroeconomic US data. Aghion et al. (2012) focus on the car industry and establish that an increase in fuel prices leads to clean innovation at the expense of dirty innovation and that there is path dependence in clean versus dirty innovation—findings in line with the results reported here. On the theoretical side, several papers have integrated directed technical change in the study of climate change policies; here, I build on AABH.<sup>3</sup> The final good in AABH and the polluting sector in this paper

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<sup>2</sup>Among others, Babiker and Rutherford (2005); Böhringer, Fisher and Rosendahl (2010); and Böhringer, Carbon and Rutherford (2011) find similar results.

<sup>3</sup>Earlier work on the environment and directed technical change includes Bovenberg and Smulders (1995) Goulder and Schneider (1999), van der Zwaan et al. (2002) , Popp

are produced similarly with a clean and a dirty input, which are substitutes for each other. Yet, AABH focus on a closed economy and does not feature a “non-polluting sector” as in this paper. Therefore, in AABH carbon taxes can still prevent an environmental disaster by redirecting innovation towards clean technologies. This result, which would still hold if there was only one country, collapses in an open economy, as carbon taxes are often insufficient and sometimes counterproductive. Acemoglu, Aghion and Hémous (2014) present a simple North-South extension of AABH, where countries trade a polluting and a non-polluting goods. Crucially, the two goods are assumed to be substitute and there is no innovation which can make the polluting input less polluting (therefore the two goods are similar to the clean and dirty inputs in this set-up). Besides the South cannot innovate even if it reaches the technological frontier. In that paper, carbon taxes necessarily reduce the amount of emissions in the long-run (contrary to here), but may be unable to prevent an environmental disaster (yet this result rests on the assumption that Southern imitators coordinate on a bad equilibrium). The present paper reverses these assumptions, which provides a more realistic and richer framework. Di Maria and Smulders (2004) and Di Maria and van der Werf (2008) also study the allocation of innovation between an energy-intensive sector and a non-energy-intensive sector in a directed technical change model with trade, but they also overlook that innovations within the energy-intensive sector could either reduce or increase pollution.<sup>4</sup>

Finally, this paper relates to the large “integrated assessment models” (IAMs) literature which builds dynamic models of the economy and the climate to evaluate the impact of climate change policies on welfare. This literature has been pioneered in particular by Nordhaus (1994), who developed the DICE model for a world economy, and Nordhaus and Boyer (2000), who developed the RICE model for a multi-regions economy. It aims at deriving (quantitatively) the optimal policy, which generally takes the form of a carbon tax schedule (see, for instance, Golosov et al., 2014, for a recent treatment, or Krusell and Smith, 2009, for an ongoing project with highly

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(2004) and Grimaud and Rouge (2008). See also Acemoglu et al. (2012b).

<sup>4</sup>In Di Maria and Smulders (2004), the North develops technologies and the South imitates. Opening up to trade leads to a reallocation of innovation toward the sector that the North exports. Carbon leakage is reduced when the goods are substitutes and amplified otherwise. In Di Maria and van der Werf (2008), both countries innovate and carbon leakage is always reduced by the innovation response to a unilateral cut in emissions.

disaggregated regions). While this literature generally ignores endogenous innovation, this paper shows that in the presence of externalities in knowledge creation, green R&D subsidies are a crucial part of the optimal climate policy (a point also made by AABH). In addition, it also derives the optimal unilateral policy in the presence of trade in goods, which neither this literature nor the CGE trade literature mentioned above do.<sup>5</sup>

Section 2 presents the model. Section 3 studies the equilibrium, identifies which policies are able to ensure sustainable growth and discusses the model’s main assumptions. Section 4 solves for the second-best policy when the South is constrained to be in *laissez-faire*, both analytically and numerically. Section 5 discusses how the main results generalize when there are knowledge spillovers. An online Appendix contains the proofs and further extensions.

## 2. Model

I consider a discrete-time, infinite-horizon two-country (North,  $N$ , and South,  $S$ ), two-sector (polluting  $P$  and non-polluting  $NP$ ), three-factor (capital, labor and scientists) Heckscher–Ohlin–Ricardo model in which sector  $P$  is similar to the economy of AABH. Each country is endowed with a fixed amount of labor and capital,  $L^N, K^N$  and  $L^S, K^S$ , and a mass 1 of scientists. The North is meant to represent countries which are ambitious in tackling climate change and the South countries which are not. I consider an admittedly extreme scenario in which the North is able to implement strong environmental policies and the South does not carry any policy at all—of course, in reality, most countries lay somewhere between these two extremes. As already mentioned, the division North–South need not fall along the lines of developed versus developing countries, in particular because the United States have not signed the Kyoto protocol. Yet, in the numerical exercise, I follow the CGE literature and identify the North with the countries which were subject to binding constraints under the Kyoto protocol, including the United States, and the South with the rest of the world.

### 2.1. Welfare

The economy admits, for each period  $t$ , a representative agent in the North who lives for one period and a like representative agent in the South.

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<sup>5</sup>Hassler and Krusell (2012) are close to doing so but their model does not feature trade in goods (nor innovation), and they do not explore the full set of policy instruments.

The utility of time- $t$  agent in country  $X \in \{N, S\}$  is given by  $\nu(S_t) C_t^X$ , where  $S_t$  is the quality of the environment (identical in North and South) and  $C_t^X$  is the final good consumption in country  $X$ . The social welfare function aggregates these preferences according to:

$$U = \sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} \frac{(v(S_t) (C_t^N + C_t^S))^{1-\eta}}{1-\eta}; \quad (1)$$

where  $\rho > 0$  is the discount rate and  $\eta \geq 0$  is the inverse elasticity of intertemporal substitution ( $\eta = 1$  corresponds to a logarithmic utility). Therefore, the social planner cares only about the time profile of world consumption and environmental quality. Section 4.2 discusses an alternative set-up where she also cares about the distribution of consumption between North and South.

Consumption,  $C_t^X$ , and environmental quality,  $S_t$ , are weakly positive and  $v$  is increasing in  $S_t$ . There is an upper-bound on  $S_t$ , denoted  $\bar{S}$ , that corresponds to a pristine environment. I define an *environmental disaster* as an instance of environmental quality reaching zero in finite time. I assume that  $v(0) = 0$  so that a disaster is as detrimental to welfare as zero consumption.<sup>6</sup>

## 2.2. Production

Final consumption is a Cobb-Douglas aggregate of the consumption of two goods, polluting,  $P$ , and nonpolluting,  $NP$ :

$$C^X = (C_P^X)^\nu (C_{NP}^X)^{(1-\nu)}, \quad (2)$$

where  $C_Y^X$  represents the quantity of good  $Y \in \{P, NP\}$  consumed in country  $X \in \{N, S\}$ .<sup>7</sup> The analysis extends easily to the case where the consumption aggregate between the two goods is CES with an elasticity of substitution smaller than 1.<sup>8</sup> Goods  $P$  and  $NP$  are the only goods that are traded internationally. Good  $P$  represents tradable goods the production of which

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<sup>6</sup>The notion of sustainability is defined in the literature on exhaustible resource. A consumption path is sustainable if the consumption flow is bounded away from zero. Here, environmental quality affects utility directly, so a path can be defined as sustainable if the utility flow is bounded away from the utility flow obtained with zero consumption. Therefore the economy is on an unsustainable path if a disaster occurs.

<sup>7</sup>Whenever this does not lead to confusion, I drop the time subscript but it should be clear that allocations, technologies and policies are time-dependent.

<sup>8</sup>A previous version of the paper (CEPR Discussion Paper 9733) does so. On the other hand, the analysis would be different if the elasticity of substitution is greater than 1 (see section 3.6).

generates a lot of greenhouse gases emissions (in particular energy-intensive goods), while good  $NP$  represents the other tradable goods. When the model is calibrated, good  $P$  is identified with the sectors which have the highest CO<sub>2</sub> emissions over value-added ratio, namely the manufacture of chemicals and chemical products (ISIC code 24), other nonmetallic mineral products (26), and basic metals (27), good  $NP$  is identified with the rest of manufacturing (see Table A.1 in Appendix A.15). Even though not all emissions can be traced to the tradable sector, the paper initially focuses on tradable goods, since it is because of international trade that policymakers fear that unilateral policies may have adverse consequences. Emissions for the production of tradable goods represent a significant share of CO<sub>2</sub> emissions—once electricity and heat are allocated to consuming sectors, manufacturing and construction represented 36.9 % of world CO<sub>2</sub> emissions in 2010 according to the International Energy Agency.<sup>9</sup> The inclusion of nontradables is discussed in Section 5.

Good  $P$  is produced competitively with a clean input  $Y_c^X$  and a dirty input  $Y_d^X$  according to

$$Y_P^X = \left( (Y_c^X)^{\frac{\varepsilon-1}{\varepsilon}} + (Y_d^X)^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}, \quad (3)$$

where  $\varepsilon > 1$  is the elasticity of substitution between the clean and the dirty input. The clean input models nonpolluting inputs that could substitute for polluting inputs, for instance, renewable energies to replace fossil fuel energy or bioplastics to replace traditional petroleum products.

Goods  $c, d$  and  $NP$  in country  $X$  are produced competitively following

$$Y_{NP}^X = \left( \int_0^1 A_{NPi}^X (x_i^X)^\gamma di \right) \left( (K_{np}^X)^\beta (L_{np}^X)^{1-\beta} \right)^{1-\gamma} \quad \text{and} \quad (4)$$

$$Y_{zt}^X = \left( \int_0^1 A_{zi}^X (x_{zi}^X)^\gamma di \right) \left( (K_z^X)^\alpha (L_z^X)^{1-\alpha} \right)^{1-\gamma} \quad \text{for } z \in \{c, d\}. \quad (5)$$

$K_{np}^X$  and  $L_{np}^X$  are the capital and labor employed in the assembly of good  $NP$  in country  $X$ ;  $x_{NPi}^X$  is the quantity of intermediates  $i$  employed in sector  $NP$ ;

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<sup>9</sup>Construction is nontradable, but agriculture and forestry, which are tradable activities, are not included in this figure. Using input-output tables Davis and Caldeira (2010) estimates that today, 23% of carbon emitted is attributable to the production of goods that will be exported.

and  $A_{NPi}^X$  is its productivity, which is specific to the country and the sector.  $K_z^X$ ,  $L_z^X$ ,  $x_{zi}^X$  and  $A_{zi}^X$  are defined similarly for good  $z \in \{c, d\}$ .  $\gamma$  is the factor share of intermediates. Intermediates cannot be traded internationally and are produced monopolistically according to

$$x_{NPi}^X = \psi^{-1} (K_{NPi}^X)^\beta (L_{NPi}^X)^{1-\beta} \quad \text{and} \quad x_{zi}^X = \psi^{-1} (K_{zi}^X)^\alpha (L_{zi}^X)^{1-\alpha} \quad \text{for } z \in \{c, d\}. \quad (6)$$

$K_{npi}^X$  and  $L_{npi}^X$  are the capital and labor employed in the production of intermediate  $i$  for good  $NP$  in country  $X$  (and  $K_{zi}^X$  and  $L_{zi}^X$  are defined similarly). Since the same factor share is used in the production of intermediates and in the final assembly of the good,  $\beta \in (0, 1)$  is the overall factor share of capital in sector  $NP$ , and  $\alpha \in (0, 1)$  is the overall factor share of capital in sector  $z \in \{c, d\}$ .<sup>10</sup> Therefore the production of goods  $c$  and  $d$  and the production of good  $NP$  only differ in the capital share. I assume throughout that  $\alpha > \beta$ , which is true empirically: within tradables, polluting sectors tend to be more capital intensive. All results hold when  $\alpha < \beta$  and the analysis of this section can be extended to a pure Ricardian model with  $\alpha = \beta$ .<sup>11</sup>

I use  $K_{NP}^X$  and  $K_P^X$  to denote total employment of capital in sectors  $NP$  and  $P$  in country  $X$ , so that:

$$K_{NP}^X \equiv K_{np}^X + \int_0^1 K_{NPi}^X di \quad \text{and} \quad K_P^X \equiv K_c^X + K_d^X + \int_0^1 K_{ci}^X di + \int_0^1 K_{di}^X di. \quad (7)$$

Similarly,  $L_{NP}^X$  and  $L_P^X$  denote the total employment of labor in sectors  $NP$  and  $P$  in country  $X$ . Factor market clearing and good market clearing imply:

$$K_P^X + K_{NP}^X \leq K^X \quad \text{and} \quad L_P^X + L_{NP}^X \leq L^X, \quad (8)$$

$$C_P^N + C_P^S \leq Y_P^N + Y_P^S \quad \text{and} \quad C_{NP}^N + C_{NP}^S \leq Y_{NP}^N + Y_{NP}^S. \quad (9)$$

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<sup>10</sup>The Cobb-Douglas structure of production for intermediates is important because it ensures that monopolists get a constant share of the sector's revenues, which matters for the incentives to innovate. Yet, the analysis can be extended straightforwardly to production functions for which aggregation between capital and labor is not Cobb-Douglas.

<sup>11</sup>A Ricardian model would pose some technical difficulties for section 4 as explained below. With different factor shares in the two sectors, the analysis is not significantly more complex, the model can account for situations where both countries do not fully specialize and it will later be easy to introduce knowledge spillovers, as another reason for trade than technological differences is then needed. There is nothing special about capital and labor being the two factors here instead of high-skill and low-skill labor for instance. This is why the paper abstracts from capital accumulation.

Intermediates producers face an iso-elastic demand with a price elasticity of  $1/(1-\gamma)$  and therefore charge a mark-up  $1/\gamma$  over marginal cost. This leads to a classic monopoly distortion, as too few intermediates are produced. A subsidy  $(1-\gamma)$  to the purchase of intermediates ensures that the consumer price is equal to marginal costs and therefore corrects for the monopoly distortion (see Appendix A.1). To simplify the exposition and focus the comparison between first-best and second-best on environmental issues, I assume throughout that this subsidy is implemented in both countries. Since the share of intermediates is the same for all sectors, the monopoly distortion only has a scale effect, and this assumption is completely innocuous. Henceforth I abuse language by referring to the "laissez-faire" case as one where governments only implement the subsidy to the use of all intermediates.

### 2.3. Innovation

At the beginning of every period, one-period monopoly rights are allocated to entrepreneurs (such that each entrepreneur holds monopoly rights on only a finite number of intermediates). Entrepreneurs can hire scientists to increase the productivity of their variety. By hiring  $s_{zit}^X$  scientists, the monopolist for intermediate  $i$  in (sub)sector  $z \in \{NP, c, d\}$  can increase the initial productivity  $A_{zi(t-1)}^X$  of her intermediate to

$$A_{zit}^X = \left(1 + \kappa (s_{zit}^X)^\iota (A_{z(t-1)}^X/A_{zi(t-1)}^X)^{\frac{1}{1-\gamma}}\right)^{1-\gamma} A_{zi(t-1)}^X \text{ for } z \in \{c, d, NP\}, \quad (10)$$

where  $0 < \iota < 1$ .  $A_{zt}^X$  is the average productivity of (sub)sector  $z \in \{c, d, NP\}$  at time  $t$ , and is defined as

$$A_{zt}^X \equiv \left(\int_0^1 (A_{zit}^X)^{\frac{1}{1-\gamma}} di\right)^{1-\gamma} \text{ for } z \in \{c, d, NP\}. \quad (11)$$

The factor  $(A_{zi(t-1)}^X)^{-1/(1-\gamma)}$  captures decreasing returns to scale in innovation (the more advanced is a technology, the more difficult it is to innovate further), and  $(A_{z(t-1)}^X)^{1/(1-\gamma)}$  denotes knowledge spillovers from the other intermediates in the same sector and country. The innovation technology exhibits decreasing returns to scale in the mass of scientists hired (e.g., because scientists hired for the same intermediate in the same period risk reproducing the same innovation) and  $\iota$  measures the concavity of the innovation function.  $\kappa$  measures the size of innovations ( $\kappa$  is related to the length of a time period, a shorter time period will be associated with a lower  $\kappa$ ).

Since the mass of scientists is equal to 1 in both countries, the market clearing equation is given by

$$\int_0^1 (s_{NPit}^X + s_{cit}^X + s_{dit}^X) di \leq 1. \quad (12)$$

Because an entrepreneur has monopoly rights for one period only, she will hire scientists so as to maximize current profits instead of the entire flow of profits generated by the innovations of her scientists. The allocation of scientists across (sub)sectors is therefore myopic. One-period monopoly rights are the only inefficiency in innovation and they allow one to model as simply as possible the “building on the shoulder of giants” externality, the existence of which has long been recognized by the endogenous growth literature. In the specific context of climate change, this externality plays a crucial role in explaining why clean technologies have so far failed to really take off, and why direct research incentives in addition to carbon taxes are welfare improving, a point made by AABH and Gerlagh et al. (2014).<sup>12</sup>

There are no knowledge spillovers between sectors. Cross-country spillovers are absent for the moment but introduced in Section 5. A fixed mass of scientists in both countries implies that the amount of resources devoted to productivity improvements (in particular R&D) remains the same in both countries and over time. It allows us to focus on the direction of technical change and ensures that one country does not become arbitrarily large relative to the other. This assumption is further discussed in section 3.6.

#### 2.4. Environment

Within the bounds 0 and  $\bar{S}$ , environmental quality evolves according to

$$S_t = (1 + \Delta) S_{t-1} - (\xi^N Y_{dt}^N + \xi^S Y_{dt}^S). \quad (13)$$

The parameter  $\xi^X > 0$  measures the rate of environmental degradation from the production of dirty inputs (which may differ across countries) and  $\Delta > 0$  is the regeneration rate of the environment. Without loss of generality, I assume that  $S_0 = \bar{S}$ . Such a law of motion captures the idea that the environment’s regeneration capacity decreases with greater environmental

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<sup>12</sup>With permanent monopoly rights, infinitely lived agents, and no environmental externality, the efficient innovation allocation would be an equilibrium, but usually not the only one.

degradation—the type of negative feedback that climatologists worry about, e.g., the change in Earth’s albedo and the release of captured greenhouse gases which may occur as the polar ice cap melts. It is adopted for simplicity’s sake but, unless explicitly mentioned, the analytical results do not depend on it. The only important assumption is that if emissions become too large,  $S_t$  reaches the disaster level.<sup>13</sup> The dirty input is directly responsible for environmental degradation, which is equivalent to a situation where it can be combined with a (cheap) fossil fuel resource in a Leontieff way.<sup>14</sup>

### 2.5. Policy tools

Section 4 solves the social planner’s problem, but Section 3 studies only whether or not an environmental disaster can be prevented with specific policy instruments, the ones that will eventually be used to decentralize the optimal policy. A policy is characterized by a sequence of *ad valorem* taxes on the dirty input  $\tau_t^X$  in each country (the equivalent of a carbon tax), a sequence of *ad valorem* subsidies for scientists in each country and each subsector,<sup>15</sup> and a sequence of *ad valorem* trade taxes  $b_t$  on the polluting good (by Lerner symmetry, they could equally be on the other good). All subsidies and taxes are financed or rebated through lump-sum taxation at the country level.

The trade tax is implemented by the North, so that prices in the South are equal to international prices:  $p_{NPt}^S = p_{NPt}$  and  $p_{Pt}^S = p_{Pt}$ , while prices in the North follow  $p_{NPt}^N = p_{NPt}$  and  $p_{Pt}^N = p_{Pt}(1 + b_t)$ . A positive trade tax corresponds to a tariff (resp., export subsidy) when the North imports

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<sup>13</sup>Real climate dynamics are much more complicated. In particular, emissions have a lagged impact on temperature, part of their impact is essentially infinitely-lived and there is a lot of uncertainty in the magnitude of the impact of CO<sub>2</sub> on temperatures. This matters for the numerical exercise but not the results of section 3.

<sup>14</sup>Therefore, we abstract from resource exhaustion. This is not a bad assumption since oil does not play a major role in emissions for the manufacturing sector, while reserves of coal, natural gas and non-traditional fossil fuels are in large supply relative to the time scale of critical environmental degradation. Note that changes in the type of fossil fuel used (from coal to natural gas) can significantly affect the emission rate, yet, modeling such a possibility would not affect the propositions of the paper.

<sup>15</sup>In order to ensure uniqueness of the equilibrium allocation of scientists, I assume that it is possible to subsidize only a given mass of scientists; hence the social planner can use the subsidy to determine the exact allocation. If the subsidy is greater than 100 percent, then a monopolist may be willing to hire scientists even if she is not producing any good.

(resp., exports) good  $P$ .<sup>16</sup> When the North is the only country intervening, I assume that trade balance must be maintained every period (there is no intertemporal trade):

$$p_{Pt} (Y_{Pt}^S - C_{Pt}^S) + p_{NPt} (Y_{NPt}^S - C_{NPt}^S) = 0. \quad (14)$$

The trade tax is *not* explicitly related to the carbon content of imports. If the South does not undertake any policy, then relating the tax to the *average* carbon content of imports from a given country and in a given sector would not alter the results; since each Southern firm is atomistic, its impact on average emission is infinitesimal and so its behavior will not affect the trade tax it pays. Changing the behavior of Southern firms would require either the North to know the exact carbon content of each specific import, which seems implausible, or the South to implement its own policy.

### 3. A positive analysis of unilateral environmental policies

This section presents a positive analysis of unilateral environmental policies. The first two subsections solve for the allocation of innovation, in particular subsection 3.2 shows how directed technical change reinforces the pollution haven effect. The following three subsections focus on whether an environmental disaster can be prevented. Section 3.3 shows that the economy reaches a disaster in laissez-faire and how such disaster may be prevented if there is only one country. Section 3.4 explains why taxing the North's polluting sector likely fails to prevent a disaster. Section 3.5 describes how a disaster can be avoided using unilateral policies in the North. Finally, Section 3.6 discusses some of the assumptions. For a given policy, the equilibrium is defined as follows.

**Definition 1.** *A feasible allocation is a sequence of demands for capital  $(K_{npt}^X, K_{NPt}^X, K_{ct}^X, K_{cit}^X, K_{dt}^X, K_{dit}^X)$ , demands for labor  $(L_{npt}^X, L_{NPt}^X, L_{ct}^X, L_{cit}^X, L_{dt}^X, L_{dit}^X)$ , demands for intermediates  $(x_{zit}^X \text{ for } z \in \{c, d, NP\})$ , demands for inputs  $(Y_{ct}^X, Y_{dt}^X)$ , goods production  $(Y_{Pt}^X, Y_{NPt}^X)$ , demands for goods  $(C_{Pt}^X, C_{NPt}^X)$ , research allocations  $(s_{zit}^X \text{ for } z \in \{c, d, NP\})$ , and quality of the environment*

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<sup>16</sup>Starting from a situation where the North imports good  $P$  under free trade, an increasing higher trade tax corresponds to a positive tariff up to the point where it implements autarky. Beyond that point, the North begins to export good  $P$  and the trade tax is a positive export subsidy.

$S_t$  such that, in each period  $t$  and in each country  $X \in \{N, S\}$ , factor and good markets clear (i.e., (8), (9), and (12) hold).

**Definition 2.** For a given policy, an equilibrium is given by a feasible allocation and sequences of wages of workers ( $w_t^X$ ), returns to capital ( $r_t^X$ ), wages of scientists ( $v_t^X$ ), consumer prices for intermediates ( $\varphi_{zit}^X$  for  $z \in \{c, d, NP\}$ ), producer prices for clean and dirty inputs ( $p_{ct}^X, p_{dt}^X$ ), and international prices of goods ( $p_{Pt}, p_{NPt}$ ) for  $X \in \{N, S\}$  such that: (i)  $(\varphi_{zit}^X, x_{zit}^X, s_{zit}^X, K_{zit}^X, L_{zit}^X)$  maximizes profits by the producer of intermediate  $i$  in sector  $z \in \{c, d, NP\}$  in country  $X$ ; (ii)  $L_{zt}^X$ , and  $K_{zt}^X$  maximize the profits of the producer of good  $z \in \{c, d, NP\}$ ; (iii)  $Y_{ct}^X$  and  $Y_{dt}^X$  maximize the profits of producer of good  $P$ ; (iv)  $C_{Pt}^X$  and  $C_{NPt}^X$  maximize consumers' utility under the trade balance constraint (14).

### 3.1. Trade and innovation allocation

**Trade pattern.** Here I analyze the equilibrium when the only policy implemented is a carbon tax in the North  $\tau_t^N \geq 0$ ; the results are derived and generalized in Appendix A.1. In each country, aggregate production in each sector can be written as

$$Y_{Pt}^X = \frac{\zeta A_{Pt}^X}{1 - \delta_t^X} (K_{Pt}^X)^\alpha (L_{Pt}^X)^{1-\alpha} \quad \text{and} \quad Y_{NPt}^X = \zeta A_{NPt}^X (K_{NPt}^X)^\beta (L_{NPt}^X)^{1-\beta}, \quad (15)$$

where  $\zeta \equiv \gamma^\gamma (1 - \gamma)^{1-\gamma} \psi^{-\gamma}$ ,  $A_{Pt}^X \equiv \left( (A_{ct}^X)^{\varepsilon-1} + (1 + \tau_t^X)^{1-\varepsilon} (A_{dt}^X)^{\varepsilon-1} \right)^{\frac{1}{\varepsilon-1}}$  and  $\delta_t^X \equiv \tau_t^X (A_{dt}^X / A_{Pt}^X)^{\varepsilon-1} (1 + \tau_t^X)^{-\varepsilon} \in [0, 1)$  (as  $\tau_t^S = 0$ ,  $\delta_t^S = 0$ ).  $A_{Pt}^X / (1 - \delta_t^X)$  decreases in  $\tau_t^X$  and measures the effective average productivity of sector  $P$  in country  $X$ . This formulation highlights that, in a given period, the model collapses to a Heckscher–Ohlin model with varying productivity across countries. In laissez-faire (that is for  $\tau_t^N = 0$ ), the South has the comparative advantage in the polluting good  $P$  if and only if

$$\left( \frac{A_{Pt}^S}{A_{NPt}^S} \right)^{\frac{1}{\alpha-\beta}} \frac{K^S}{L^S} > \left( \frac{A_{Pt}^N}{A_{NPt}^N} \right)^{\frac{1}{\alpha-\beta}} \frac{K^N}{L^N}. \quad (16)$$

Trade results from Ricardian forces (relative productivity) as well as Heckscher–Ohlin forces (relative factors endowment). Provided the difference in comparative advantage is not too large, both countries produce both goods. When the difference in comparative advantage is larger, one and eventually

both countries fully specialize. Besides, a positive carbon tax in the North ( $\tau_t^N > 0$ ) reduces the productivity of sector  $P$  there and therefore increases the chance that the South has a comparative advantage in that sector.

**Emissions.** Emissions are given by  $E_t^X = \xi^X (1 + \tau_t^X)^{-\varepsilon} (A_{dt}^X/A_{Pt}^X)^\varepsilon Y_{Pt}^X$ . Thus the emission rate in sector  $P$  is increasing in the ratio of dirty to clean productivities  $A_{dt}^X/A_{ct}^X$  and decreasing in the carbon tax  $\tau_t^X$ .

**Allocation of innovation.** Entrepreneurs face a two-stage problem. In the second stage, they choose prices to maximize their profits given their productivity. Post-innovation profits in sector  $z \in \{c, d, NP\}$  are given by:

$$\pi_{zit}^X = (1 - \gamma) (A_{zit}^X/A_{zt}^X)^{\frac{1}{1-\gamma}} p_{zt}^X Y_{zt}^X. \quad (17)$$

These profits are proportional to the revenues of the intermediate's (sub)sector (because of the Cobb-Douglas specification) and are increasing in the productivity of the intermediate,  $A_{zit}^X$ . In the first stage, entrepreneurs hire scientists to increase the productivity of their intermediate. Thanks to the knowledge spillovers across varieties, all monopolists in a given (sub)sector hire the same number of scientists and average productivity grows following

$$A_{zt}^X = (1 + \kappa (s_{zt}^X)^\iota)^{1-\gamma} A_{z(t-1)}^X \text{ for } z \in \{c, d, NP\}.$$

Therefore, regardless of the technology and its level of development, the same amount of innovation resources (scientists) is required for a given proportional increase in productivity. Such formulation is common in endogenous growth models as it is consistent with steady-state growth.

**Path dependence in clean versus dirty technologies.** Assume that country  $X$  produces good  $P$  (otherwise,  $s_{ct}^X = s_{dt}^X = 0$ ). Combining the first-order conditions with respect to the number of scientists in the clean and dirty subsector yields the following equation:

$$\frac{(s_{ct}^X)^{1-\iota} (1 + \kappa (s_{ct}^X)^\iota)}{(s_{dt}^X)^{1-\iota} (1 + \kappa (s_{dt}^X)^\iota)} = \frac{p_{ct}^X Y_{ct}^X}{p_{dt}^X Y_{dt}^X} = (1 + \tau_t^X)^\varepsilon \left( \frac{A_{ct}^X}{A_{dt}^X} \right)^{\varepsilon-1}. \quad (18)$$

The second equality follows from the demand equation for both inputs in sector  $P$  (knowing that the production technologies differ only by their productivity level). The ratio of revenues in the clean sector to those in the dirty sector increases with the ratio of clean to dirty technologies. This association reflects two counteracting forces: a larger technology ratio leads to a larger market share ratio but also to a lower price ratio; the former effect dominates

when the inputs are substitutes ( $\varepsilon > 1$ ). Thus, in laissez-faire ( $\tau_t^X = 0$ ), for a sufficiently small innovation size  $\kappa$ , more scientists are allocated to the dirty than to the clean subsector if and only if the dirty sector is already the most advanced  $A_{d(t-1)}^X > A_{c(t-1)}^X$ : there is path dependence (see Appendix A.2).<sup>17,18</sup> A carbon tax in the North reduces demand for the dirty input. Therefore, for a given mass of scientists in sector  $P$ , it leads to a reallocation of innovation within that sector towards clean technologies, which is stronger the larger the elasticity of substitution between the two inputs,  $\varepsilon$ , is.

**Amplification of comparative advantage.** Assume that production occurs in both sectors (otherwise, innovation occurs only in the active sector). By combining the first-order conditions with respect to the number of scientists in (sub)sectors  $NP$ ,  $c$  and  $d$ , I obtain

$$\frac{(s_{ct}^X)^{1-\iota} (1 + \kappa (s_{ct}^X)^\iota) + (s_{dt}^X)^{1-\iota} (1 + \kappa (s_{dt}^X)^\iota)}{(s_{NPt}^X)^{1-\iota} (1 + \kappa (s_{NPt}^X)^\iota)} = \frac{(1 - \delta_t^X) p_{Pt}^X Y_{Pt}^X}{p_{NPt}^X Y_{NPt}^X}. \quad (19)$$

$(1 - \delta_t^X) p_{Pt}^X Y_{Pt}^X$  are the net of tax revenues of the polluting sector. Therefore, for a given ratio  $A_{d(t-1)}^X/A_{c(t-1)}^X$  of initial productivities within sector  $P$  and given carbon tax  $\tau_t^X$ , the number of scientists allocated to sector  $P$  is increasing in the ratio of sector  $P$  to sector  $NP$  revenues. Under free trade, prices are equalized in both countries, and each tends to innovate relatively more in its exporting sector (it necessarily does so when  $A_{ct}^N/A_{dt}^N = A_{ct}^S/A_{dt}^S$  and  $\tau_t^N = 0$ ). In laissez-faire, comparative advantages are typically amplified over time, so that one and eventually both countries fully specialize.

By contrast, in autarky, consumer demand implies that

$$p_{NPt}^X Y_{NPt}^X / (p_{Pt}^X Y_{Pt}^X) = (1 - \nu) / \nu, \quad (20)$$

<sup>17</sup>If  $\kappa$  is large, however, and  $A_{d(t-1)}^X$  and  $A_{c(t-1)}^X$  are close to each other, multiple equilibria may exist (as in AABH): if more scientists are allocated to clean than to dirty technologies at time  $t$ , clean technologies may become more developed than dirty ones at time  $t$  (even though they were not at time  $t - 1$ ), which in return would justify that more scientists got allocated to clean than to dirty technologies.

<sup>18</sup>One might think however that innovation could be easier for new technologies (such as clean technologies) where low-hanging fruits are more common. For instance we could have  $A_{ct}^X = \left(1 + \kappa \max\left(1, \left(\frac{\bar{A}}{A_{ct}^X}\right)^\eta\right) (s_{ct}^X)^\iota\right)^{1-\gamma} A_{c(t-1)}^X$  for some  $\bar{A} > 0$  and  $\eta > 0$ . Such formulation would go against path dependence in clean versus dirty technologies but only temporarily (as long as  $A_{ct}^X < \bar{A}$ ). Yet, Aghion et al. (forthcoming) find evidence of path dependence in the car industry.

so that innovation always occurs in both sectors in that case.

**Equilibrium uniqueness.** As innovating more in a sector increases a country's comparative advantage in that sector, which, in turn, prompts more innovation in the same sector, multiple equilibria could arise when the innovation size  $\kappa$  is large enough. On the other hand, with a small  $\kappa$ , the concavity of the innovation technology ensures that the equilibrium is unique. Although the main results of this section could be extended to a case with multiple equilibria, focusing on a unique equilibrium simplifies the exposition. Henceforth, I assume that the conditions of the following lemma are satisfied (proof in Appendix A.2).<sup>19</sup>

**Lemma 1.** *If  $\kappa$  is small enough and  $\iota \geq 1/2$ , the equilibrium is unique.*

### 3.2. The dynamic pollution haven effect

The following proposition characterizes the existence of a dynamic pollution haven effect under free trade (proof in Appendix A.3).

**Proposition 1.** *For  $\kappa$  small enough, the introduction at time  $t$  of a positive carbon tax  $\tau_t^N > 0$  in the North increases innovation in the polluting sector in the South,  $s_{Pt}^S$ . If  $A_{d(t-1)}^N \geq A_{c(t-1)}^N$  and  $(1 + \tau_t^N) \leq \left( A_{d(t-1)}^N / A_{c(t-1)}^N \right)^2$ , then innovation in the polluting sector in the North,  $s_{Pt}^N$ , decreases. An increase in  $s_{Pt}^S$  and a decrease in  $s_{Pt}^N$  further increases emissions in the South (relative to a situation where innovation does not respond), provided that the Southern dirty technologies are more advanced than clean ones ( $A_{d(t-1)}^S \geq A_{c(t-1)}^S$ ) and  $A_{Pt}^N / (1 - \delta_t^N)$  increases in  $s_{Pt}^N$  (which is the case if  $\left( A_{c(t-1)}^N / A_{d(t-1)}^N \right)^{\varepsilon-1} > (\tau(\varepsilon - 1) - 1) (1 + \tau_t^N)^{-\varepsilon}$  or  $A_{d(t-1)}^N / A_{c(t-1)}^N > (1 + \tau_t^N)^{\frac{\varepsilon}{\varepsilon-1}}$ ).*

The introduction of a positive carbon tax  $\tau_t^N$  in the North increases the production cost of the polluting good  $P$  there and therefore reduces its production. This raises its world price which leads to an increase in its production in the South, and therefore an increase in Southern emissions (this is

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<sup>19</sup>The technical assumption  $\iota \geq 1/2$  is further necessary to ensure that the equilibrium is unique when one country is close to a corner of specialization (i.e., to a point at which a producer of the imported good would break even only if he produces an infinitesimal amount of the good). The lemma does not extend to the Ricardian case where  $\alpha = \beta$ : in that case, no matter how small  $\kappa$  is, there are multiple equilibria when the initial comparative advantage is small.

the classic static pollution haven effect). Following (19), and for a sufficiently small innovation size (such that the equilibrium is unique), an increase in the relative revenues of sector  $P$  in the South leads to an increase in innovation in that sector in the South ( $s_{Pt}^S$  increases), while a decrease in the relative revenues of sector  $P$  in the North leads to a decrease in innovation in that sector in the North ( $s_{Pt}^N$  decreases). This changes technology levels in a way which further favors production of good  $P$  by the South and so further increases Southern emissions (creating a dynamic pollution haven effect).

For this logic to go unabated, a few additional assumptions are necessary. First, the further the ratio of clean to dirty revenues, the more innovation in sector  $P$  is attractive. If the carbon tax in the North is very large, the ratio of clean to dirty revenues may be further from unity post-tax than it was pre-tax, which might lead to an increase in  $s_{Pt}^N$  (this is what the assumption  $A_{d(t-1)}^N \geq A_{c(t-1)}^N$  and  $1 + \tau_t^N \leq \left( A_{d(t-1)}^N / A_{c(t-1)}^N \right)^2$  prevents). Second, more innovation in sector  $P$  in the South will increase the emission rate only if  $A_{d(t-1)}^S > A_{c(t-1)}^S$  (otherwise it decreases it). Third, because of the distortion created by the carbon tax, for some very specific combination of parameters, a decrease in  $s_{Pt}^N$  might increase  $A_{Pt}^N / (1 - \delta_t^N)$  and thereby  $Y_{Pt}^N$ , which would push towards a decrease of Southern emissions (this case is ruled out for instance if  $\tau$  is small).

Whether world emissions are more likely to increase when innovation responds to the policy change depends on the pattern of comparative advantage and the emission rates. The dynamic pollution haven effect increases Southern emissions but it also further decreases Northern emissions. Moreover, the dynamic pollution haven effect has permanent consequences: in all subsequent periods, the relative productivity of the South in sector  $P$  will have increased, which favors innovation in that sector itself and therefore tends to increase Southern emissions. Proposition 2 below further characterizes the dynamic consequences of a Northern carbon tax.

A carbon tax has an ambiguous effect on clean innovation in the North: as the market for good  $P$  shrinks, overall sector  $P$  innovation is reduced, but within that sector, it gets reallocated towards clean technologies.

### 3.3. *Environmental disaster in laissez-faire, with a global social planner or in autarky*

Under laissez-faire, as long as dirty technologies are more advanced than clean ones in both countries, innovation in sector  $P$  remains directed primar-

ily toward dirty technologies. Since innovation in sector  $P$  does not asymptotically vanish (the exporting country innovates more in that sector than it would under autarky), the production of good  $P$  grows unboundedly and so do emissions. At some point, the regenerative capacity of the environment becomes overwhelmed and the economy reaches an environmental disaster.

In contrast, if there were only one country (and therefore no trade), the logic of AABH applies. The social planner could use clean research subsidies, taxes on dirty research or carbon taxes to redirect innovation from the dirty toward the clean subsector. Once clean technologies acquire a sufficient lead over dirty intermediates, market forces will ensure that most research is directed toward the clean subsector, which is now the most advanced. Eventually, the emission rate of good  $P$  approaches zero—sufficiently fast to offset growth good  $P$ 's production—and a disaster can be avoided for sufficiently high initial environmental quality. A social planner who can intervene in both countries can use the same instruments and avert a disaster (for high enough  $S_0$ ) by redirecting sector  $P$  innovation towards clean technologies in countries which produce good  $P$  (proof in Appendix A.4).

Consider now the case of a social planner who can only intervene in the North, but assume that both countries are in autarky. Then, without knowledge spillovers, no policy restricted to the North can prevent a disaster because Southern emissions grow unboundedly regardless of what the North does. Therefore, absent international cooperation, trade is necessary to avoid an environmental disaster.

#### *3.4. Taxes on the polluting good in the North only*

I now consider the case where trade is possible and only the North can implement some policy (in particular, this implies that the North cannot pay the South to implement a policy). The key to avoid an environmental disaster in this context is to ensure that the South asymptotically fully specializes in the nonpolluting sector  $NP$ . Otherwise, there is always innovation in the polluting sector  $P$  in the South, and the production of good  $P$  and therefore emissions grow unboundedly (see Appendix A.5 for a formal proof). I first focus on the case where the North can implement a positive carbon tax and/or a positive tax on dirty research. Both instruments can reduce emissions in the North, and prompt clean innovation there. However, such policies may be incompatible with a South specializing in sector  $NP$  and thus may fail to prevent an environmental disaster. More formally, one can show (proof in Appendix A.6).

**Proposition 2.** *If innovation size  $\kappa$  is small enough then, no matter how high initial environmental quality  $S_0$  is, no combination of a positive carbon tax and a positive tax on dirty research can prevent an environmental disaster if: (i) clean technologies are less developed than dirty ones in both countries ( $A_{c0}^N/A_{d0}^N \leq 1$  and  $A_{c0}^S/A_{d0}^S \leq 1$ ), (ii) the South has a weak initial comparative advantage in the polluting sector  $P$  (i.e.,  $(A_{P0}^S/A_{NP0}^S)^{\frac{1}{\alpha-\beta}} K^S/L^S \geq (A_{P0}^N/A_{NP0}^N)^{\frac{1}{\alpha-\beta}} K^N/L^N$ ), and (iii) either clean technologies are sufficiently less developed than dirty ones in the South ( $A_{c0}^S/A_{d0}^S$  is sufficiently small) or the South has a sufficiently strong initial comparative advantage in  $P$ .*

Under laissez-faire and with the assumptions of the proposition, the South innovates more than the North in the polluting sector  $P$ , which reinforces its comparative advantage over time eventually leading it to specialize in that sector (the “amplification of comparative advantage effect” described above). The North government cannot reverse this pattern simply by using a positive tax on dirty research or a positive carbon tax. In contrast, a carbon tax reduces the productivity of sector  $P$  in the North, which leads to an increase in sector  $P$  innovation in the South and a decrease in the North (as specified in Proposition 1). This further strengthens the comparative advantage of the South in sector  $P$ . A positive tax on dirty innovation in the North has similar effects to a carbon tax: it drives scientists away from sector  $P$  toward the nonpolluting sector  $NP$ ; and, within sector  $P$ , it allocates innovation toward the initially backward clean subsector, which further reduces the growth rate of average productivity  $A_{Pt}^N$ —the resulting increase in the price of good  $P$  also leads to more innovation in sector  $P$  in the South. Accordingly, positive Northern taxes on good  $P$  can only accelerate the Southern specialization in that sector. In fact, the economy typically grows faster since more specialization entails less overlap in the type of innovations being undertaken by both countries, and, as a result, such policies are then likely to *accelerate* environmental degradation.<sup>20</sup>

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<sup>20</sup>The extreme version of this argument is illustrated by the knife-edge case where  $A_{c0}^N/A_{d0}^N = A_{c0}^S/A_{d0}^S < 1$  and  $(A_{P0}^S/A_{NP0}^S)^{\frac{1}{\alpha-\beta}} K^S/L^S = (A_{P0}^N/A_{NP0}^N)^{\frac{1}{\alpha-\beta}} K^N/L^N$ , with no carbon tax, there would be no trade in equilibrium, and emissions and the economy would grow at rate  $(1 + \kappa 2^{-\iota})^{1-\gamma} - 1$ . A small carbon tax  $\tau_t^N$  is enough to ensure that both countries eventually specialize so that emissions (and the economy) asymptotically grow at rate  $(1 + \kappa)^{1-\gamma} - 1$ .

Condition (iii) in Proposition 2 is necessary because when the ratio of clean to dirty revenues is farther from unity in the North than in the South, more innovation in sector  $P$  might take place in the North even if the South exports good  $P$ .<sup>21</sup> The assumption that  $\kappa$  is small could also be relaxed if  $A_{c0}^S/A_{d0}^S$  is sufficiently small and the South has a sufficiently strong initial comparative advantage in  $P$ : in this case, all possible equilibria would feature the South specializing in sector  $P$  leading to an environmental disaster.

The crucial hypothesis of Proposition 2 is that the South has a comparative advantage in sector  $P$ . When the North is identified with Annex I countries, this hypothesis seems to hold since the CGE literature systematically finds that developed countries are net carbon importers as mentioned in the introduction (and I also find that the South has a comparative advantage in sector  $P$  initially in the numerical exercise in section 4.3). Yet, with a different definition of the North, this hypothesis may not hold, in which case, the North might be able to prevent an environmental disaster with a carbon tax only as the pollution haven and the amplification of initial comparative advantage effects work in opposite directions.

### 3.5. Introducing clean research subsidies and the trade tax

Allowing the North to use clean research subsidies and a trade tax leads to the following result.

**Proposition 3.** *A combination of a temporary trade tax and a temporary clean research subsidy in the North can prevent an environmental disaster provided that the initial environmental quality  $\bar{S}$  is sufficiently high.*

The key difference between clean research subsidies and the carbon tax or the tax on dirty research is that the former can also reallocate scientists

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<sup>21</sup>That is this condition plays a similar role to the assumption that  $A_{d(t-1)}^N \geq A_{c(t-1)}^N$  and  $(1 + \tau_t^N) \leq \left( A_{d(t-1)}^N / A_{c(t-1)}^N \right)^2$  in Proposition 1. More specifically: the incentive to innovate in sector  $P$  is, *ceteris paribus*, lower when the revenues in the clean and dirty sectors are close to each other—that is when  $\left( A_{c(t-1)}^X \right)^{\varepsilon-1}$  and  $(1 + \tau_t^X)^{-\varepsilon} \left( A_{d(t-1)}^X \right)^{\varepsilon-1}$  are comparable. Given carbon taxes that are high enough or taxes on dirty research that are of sufficient duration, the ratio of clean to dirty revenues may become farther from unity in the North than in the South. In that event, assumption (iii) ensures that this effect is dominated, either directly if the initial comparative advantage is large enough, or because the difference in comparative advantage would have had to become large before this occurs when  $A_{c0}^S/A_{d0}^S$  is sufficiently small.

who were working in the nonpolluting sector  $NP$  toward the clean subsector. This boosts innovation in clean technologies in the North, even when the North does not have the comparative advantage in sector  $P$ . Increasing innovation in clean technologies makes sector  $P$  less polluting and helps build a comparative advantage in that sector. In the meantime, a positive trade tax reduces production and therefore innovation in sector  $P$  in the South, which also helps reverse the pattern of comparative advantage. For sufficiently high initial environmental quality, a policy combining these two instruments can prevent a disaster. To see this, consider the following two-phase approach (this is not the optimal policy, which is derived in Section 4). First, a social planner implements a tariff large enough to shut down trade, so that innovation in the South must be balanced between the two sectors  $P$  and  $NP$ . Simultaneously, she implements large clean research subsidies so that nearly all Northern scientists innovate in the clean subsector, and the North innovates more in sector  $P$  than the South. Once the North has acquired the comparative advantage in that sector and  $A_{c(t-1)}^N/A_{d(t-1)}^N$  is sufficiently large, the social planner can discontinue all policies and re-open up to trade. Market forces then ensure that the production of good  $P$  eventually moves entirely to the North where it relies essentially on clean technologies,<sup>22</sup> emissions go down to zero in both countries, and a disaster can be avoided.<sup>23</sup> The absence of a nontradable polluting sector is crucial here: otherwise (and without knowledge spillovers), even if the South were not to produce the tradable polluting good, it would still produce the nontradable one, and therefore it would still be impossible to prevent an environmental disaster.

From this discussion one might think that clean research subsidies alone should be enough to prevent an environmental disaster. This is true if the initial comparative advantage of the South is not too large, but as the following remark stipulates, it does not always hold (proof in Appendix A.7).

**Remark 1.** There exist initial factor endowments and technologies, such that no matter how high  $S_0$  is, no combination of a carbon tax, a tax on dirty research, and a subsidy for clean research can prevent a disaster.

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<sup>22</sup>This follows lemma A.3, applied to the case where the North now has the comparative advantage in sector  $P$  at some date  $\tau$ , with  $A_{d\tau}^N/A_{c\tau}^N < A_{c\tau}^S/A_{d\tau}^S < 1$ .

<sup>23</sup>This result does not rest on the assumption that  $\kappa$  is small as the logic can be extended to a scenario with multiple equilibria.

Clean research subsidies alone cannot prevent a disaster when the South fully specializes in sector  $P$  and clean technologies in the South are sufficiently less advanced than dirty ones. In that case, all Southern scientists are allocated to sector  $P$  and, asymptotically, to dirty technologies. So even if the North were to allocate all its scientists to clean technologies,  $A_{Pt}^S$  would grow as fast as  $A_{Pt}^N$ . That situation is irreversible and an environmental disaster cannot be avoided. Full specialization in the South occurs in the first place when its initial comparative advantage in sector  $P$  is sufficiently large or when clean technologies are sufficiently backward in the North, as the average productivity of sector  $P$  in the North,  $A_{Pt}^N$ , grows slowly during the period when clean technologies are catching up with dirty ones.<sup>24</sup>

### 3.6. Discussion

Here, I discuss some of the assumptions of the model. Appendix A.8 presents additional results regarding alternative instruments.

**Size and mass of scientists.** The relative size of the two countries in terms of capital and labor endowments plays a role quantitatively: the larger the North is, the easier it is to reverse comparative advantages. In the long-run, the relative size of the two economies depends on the mass of scientists, which is a proxy for the amount of resources spent on innovation. The assumption that the two countries have the same fixed mass of scientists implies that the analysis is implicitly restricted to a case where the two countries (or groups of countries) are of similar size.

If the mass of scientists in the North ( $s^N$ ) were much smaller than in the South ( $s^S$ ), the North would eventually become a small economy relative to the South, and the South's economy will behave as if it were in autarky: regardless of the policies undertaken by the North, a disaster would be unavoidable. In contrast, if  $s^N$  was much larger than  $s^S$ , a disaster could be avoided using clean research subsidies without the need for a tariff (as  $A_{Pt}^N$  could grow faster than  $A_{Pt}^S$  allowing the North to progressively build a comparative advantage in sector  $P$  even if the South has fully specialized in sector  $P$ ). Depending on parameters, a disaster may also be avoided using taxes on dirty research or a carbon tax under the assumptions of Proposition 2.<sup>25</sup>

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<sup>24</sup>This is the only result of this section that would not hold if goods  $P$  and  $NP$  were strict complements (instead of Cobb-Douglas): in this case the South could not stay fully specialized in sector  $P$  if both countries innovate only in that sector.

<sup>25</sup>For instance, if the consumption share of good  $P$  ( $\nu$ ) is close to 1 and  $s^N$  is large

This suggests that the inclusion of the United States in the North is crucial. However, one may think that  $s^S$  is bound to increase, making it harder and harder for the North to intervene decisively as time passes.

The assumption that the mass of scientists is exogenous is not innocuous either. With an endogenous mass of scientists, clean research subsidies become an even more potent instrument, as they can ensure that the amount of resources spent in R&D in the North becomes greater than that in the South (so that a disaster becomes avoidable with clean research subsidies only). The impact of a carbon tax depends on the specific way in which innovation is endogenized, but in models where the cost of innovation moves with GDP, a carbon tax is likely to reduce overall innovation since innovation depends on firms' profits which are proportional to the revenues net of taxes (this would reinforce Proposition 2).

**Three sectors.** The results of the paper crucially depend on the assumption that innovation may occur in all three (sub)sectors (clean, dirty and non-polluting). If innovation were limited to clean and dirty technologies within the polluting sector, then the North could not build a comparative advantage in a specific sector. With clean innovation in the polluting sector only (as in Di Maria and Smulders, 2004; Di Maria and van der Werf, 2008 and Acemoglu, Aghion and Hémous, 2014), the model would falsely assume that all innovations in the polluting sector decrease emissions. In contrast, with only dirty innovations in the polluting sector, no innovations could replace existing polluting technologies since the final good is a Cobb-Douglas aggregate of the polluting and the nonpolluting goods.<sup>26</sup>

The assumption that the clean and dirty inputs are substitute ( $\varepsilon > 1$ ) is crucial, as otherwise avoiding a disaster with unilateral policies is not possible.<sup>27</sup> Yet, this is a very natural assumption, first if  $\varepsilon \leq 1$ , both in-

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enough,  $A_{Pt}^N/A_{NPt}^N$  can grow faster than  $A_{Pt}^S/A_{NPt}^S$ , leading to a reversal of comparative advantage; if  $\nu = 1/2$ , on the contrary, the previous analysis still holds.

<sup>26</sup>Here clean innovations allow to develop an input which substitutes for the dirty one, and the polluting sector's productivity can grow at the same rate whether it relies mostly on the clean or the dirty inputs. If the clean alternative had some growth's costs, then preventing a disaster with unilateral policies would be more difficult (this would be the case in a model where the clean alternative refers to energy efficiency improvements, and where energy is complement to other inputs in the polluting sector).

<sup>27</sup>Doing so requires positive growth in the polluting sector in the North to ensure that Southern emissions do not grow unboundedly, but positive growth in the polluting sector is not possible without positive growth in dirty input production.

puts would be essential in the production of the polluting good and therefore clean inputs would not really represent an alternative to dirty inputs; second, Papageorgiou, Saam and Schulte (2013) show empirically that the elasticity of substitution between clean and dirty inputs (notably in energy) is significantly greater than 1. The assumption of a unit elasticity between the polluting and non-polluting good is very common in the literature, and, as already mentioned, the analysis extends to the case where goods  $P$  and  $NP$  are complements.<sup>28</sup> It does not extend to the case where  $P$  and  $NP$  are substitutes (and therefore not essential). Then whether an environmental disaster can be avoided or not depends crucially on how large  $A_d^S$  is relative to  $A_{NP}^S$ : a large  $A_d^S$  may push the South towards producing the dirty input rather than the non-polluting good, regardless of the policy in the North.

Importantly, dirty innovations generally include not only innovations in the energy sector that make fossil fuel energy cheaper (for instance by allowing the use of shale gas or bituminous sands), but also innovations in components that are complements to fossil fuel energy and thus increase its demand, or the introduction of new goods or inputs that rely on fossil fuel energy. In practice, some innovations in the polluting sector may complement both fossil fuel energy and alternative forms of energy; one could represent such innovations as improving the productivity of an additional input in the polluting sector complement to both the clean and dirty inputs. This would not affect the economic intuitions developed and my results could be extended to this scenario.

**The South's behavior.** The paper assumes that the South does not implement any policy. Regarding environmental policy today, this seems a reasonable assumption: several countries seem willing to move forward, while others are opposing a global agreement while often undertaking very limited domestic policies (Barrett, 1994, explains why designing a self-enforcing international agreement on climate change is difficult). A reason why these

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<sup>28</sup>The CGE literature often assumes a unit elasticity of substitution between manufacturing goods, which often include a non-polluting sector and a more detailed representation of polluting goods (see for instance Babiker and Rutherford, 2005 or Boehringer et al., 2010). Copeland and Taylor (2005) assume that polluting and non-polluting goods are both essential (which rules out the substitute case). This also seems very reasonable given what the two sectors stand for: for instance the polluting good includes the manufacture of basic metals (code 24) while the non-polluting good includes the manufacture of machinery and equipment (code 28).

divisions may persist in reality is the significant delay between emissions and damages that climate models predict, an aspect that I abstract from here: as a result, it may be too late before skeptic countries get convinced that they should start undertaking significant policy actions. Even if one expects that these divisions will eventually end, the results of the paper are still useful for countries who are willing to intervene before the rest of the world.

Even if the South does not implement any environmental policy, it may still want to implement trade policies, particularly if the North's trade policy hurts the South. Yet, South's consumption is not necessarily negatively affected by the North's unilateral policies, and the South benefits from better environmental quality. For instance, if the North's temporary policy reverses the pattern of comparative advantages, both countries fully specialize in the long run. Income shares are linked to the consumption share of the good that the country exports; therefore, if the income share for the polluting good is smaller than for the nonpolluting one ( $\nu < 1 - \nu$ ), the South's income share will be larger under the North unilateral policy than under laissez-faire.<sup>29</sup>

Although a full analysis of the strategic interactions between two governments is beyond the scope of this paper, one can consider the case where the South government is myopic and maximizes current consumption. This government implements its own trade tax to improve its terms of trade. As long as the South retains an initial comparative advantage in the polluting good, this trade tax moves both countries closer to autarky and thus does not prevent the North from reversing the pattern of comparative advantage. Once the North exports the polluting good, the South implements its own tariff. This tariff slows down the South's specialization in the nonpolluting sector. Yet, once the North has acquired a sufficiently large comparative advantage, it does not prevent the South from fully specializing in the non-polluting sector. Therefore, a disaster can still be avoided for sufficiently high initial environmental quality.

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<sup>29</sup>Even in the short run, the South might benefit: a tariff implemented by the North hurts the South when the South exports the polluting good, but a trade tax high enough to reverse the pattern of trade immediately may benefit the South (this trade tax is then an export subsidy).

## 4. Optimal policy and numerical illustration

I now turn to the normative part of the paper, characterizing the first-best policy and the second-best policy under the constraint that the social planner cannot intervene in the South. I then use a numerical example to illustrate both policies and compute their welfare costs, and to show that both trade and directed technical change act as double-edge swords.

### 4.1. First-Best: North and South Policy

Before solving for the optimal unilateral policy, the focus of this paper, I briefly present the first-best which is a useful benchmark—the solution is derived in Appendix A.9. In the first-best, the social planner maximizes (1) subject to the following constraints: the production function equations (2), (3), (4), (5), (6) and; the factor market-clearing equations (8) and (12); the goods market-clearing equation (9); the environmental degradation equation (13); and the knowledge accumulation equation (10).

The first-best policy can be decentralized in the following way. As already mentioned, a subsidy  $1 - \gamma$  to all intermediates corrects for the monopoly distortion. The environmental externality is corrected by a carbon tax in both countries that equalizes the marginal cost of the tax (lower current consumption) with the marginal benefit (higher environmental quality in all subsequent periods). Carbon taxes in the North and the South differ in *ad valorem* values across countries but are identical as a tax per unit of CO<sub>2</sub>. The social planner corrects for the myopia of monopolists in their innovation decisions by allocating scientists in accordance with the discounted value of the entire stream of additional revenues generated by their innovation.

Since utility flow is minimized during a disaster and since the social planner can always reduce world emissions, the optimal policy always avoids a disaster. In addition (as shown in Appendix A.10), if the discount rate  $\rho$  is sufficiently small and the inverse elasticity of intertemporal substitution  $\eta \leq 1$ , then both countries specialize in finite time and innovation in sector  $P$  switches to mostly clean,<sup>30</sup> so that emissions eventually vanish. With the law of motion (13), the quality of the environment reverts to  $\bar{S}$ —and the carbon tax reaches zero—in finite time.<sup>31</sup>

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<sup>30</sup>These are only sufficient conditions, and the optimal policy is likely to feature a switch to clean innovations also when  $\eta > 1$ .

<sup>31</sup>For an alternative law of motion where environmental regeneration decreases as the

#### 4.2. Second-Best: Policy only in the North

I now turn to the case where the social planner cannot implement any policy in the South, whose economy is in laissez-faire, and cannot transfer income from one country to another. Trade balance must be maintained at every point in time. The second-best policy is defined by the social planner maximizing (1) subject to the following constraints: (2) for the North and the South; constraints (3), (4), (5), (6), (8), (12) and (10) for the North only; the environmental degradation constraint (13); the goods market-clearing constraints in both countries, which are now written as

$$C_{Yt}^N = Y_{Yt}^N + M_{Yt} \text{ and } C_{Yt}^S = Y_{Yt}^S - M_{Yt}, \text{ for } Y \in \{P, NP\}, \quad (21)$$

where  $M_{Yt}$  denotes net imports of the North of good  $Y$ ; the trade balance constraint

$$p_t M_{Pt} + M_{NPt} = 0, \quad (22)$$

where  $p_t \equiv p_{Pt}/p_{NPt}$  is the international price ratio; and constraints describing the South's laissez-faire economy. These latter constraints (detailed in Appendix A.11) are: a consumer demand equation

$$\left( \frac{\partial C^S}{\partial C_P^S} \right) \left( \frac{\partial C^S}{\partial C_{NP}^S} \right)^{-1} = \frac{\nu}{1-\nu} \frac{C_{NPt}^S}{C_{Pt}^S} = p_t; \quad (23)$$

offers equations in the South of the type

$$Y_{Pt}^S = y_P^S(p_t, A_{Pt}^S, A_{NPt}^S) \text{ and } Y_{NPt}^S = y_{NP}^S(p_t, A_{Pt}^S, A_{NPt}^S); \quad (24)$$

an emissions equation  $Y_{dt}^S = (A_{dt}^S/A_{Pt}^S)^\varepsilon Y_{Pt}^S$ ; an equation that specifies the mass of scientists allocated to sector  $P$ ,

$$s_{Pt}^S = s_P^S(p_t, A_{dt}^S, A_{ct}^S, A_{NPt}^S); \quad (25)$$

and the resulting law of motion of aggregate productivity in the South:

$$\begin{aligned} A_{NPt}^S &= (1 + \kappa (1 - s_{Pt}^S)^\iota)^{1-\gamma} A_{NP(t-1)}^S, \\ A_{zt}^S &= (1 + \kappa (s_{zt}^S (s_{Pt}^S, a_{t-1}^S))^\iota)^{1-\gamma} A_{z(t-1)}^S, \text{ for } z \in \{c, d\}. \end{aligned} \quad (26)$$

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quality of the environment  $S_t$  approaches  $\bar{S}$ , or where a share of emissions stay permanently in the atmosphere,  $S_t$  may not reach  $\bar{S}$  asymptotically. The optimal carbon tax may then not converge to 0 but it becomes irrelevant in the sense that a 0 carbon tax would only have a negligible effect on welfare.

The allocation between clean and dirty innovation  $s_{ct}^S, s_{dt}^S$  is uniquely determined by the total mass  $s_{Pt}^S$  and the ratio  $a_{t-1}^S \equiv \left( A_{c(t-1)}^S / A_{d(t-1)}^S \right)^{\varepsilon-1}$ . For the problem to be well-defined, the South's equilibrium must be unique given the North's allocation. An argument similar to that of Appendix A.2 shows that it is the case when  $\kappa$  is sufficiently small and  $\iota \geq 1/2$ . (This is where the Ricardian case would pose a technical difficulty, with  $\alpha = \beta$ , even for a small  $\kappa$ , the South's equilibrium may not be uniquely defined.) This leads to the following result (proof in Appendix A.11).

**Proposition 4.** *The second-best policy can be decentralized through a carbon tax in the North, research subsidies/taxes in the North, a subsidy for the use of all intermediates, and a trade tax.*

Therefore, the social planner uses the same instruments as before to address the inefficiencies in the North's economy: the environmental externality, the knowledge externality and the monopoly distortion. The trade tax,  $b_t$ , allows the social planner to distort prices in the South thereby affecting the allocation of factors there. The optimal allocation satisfies:

$$\begin{aligned} & \nu^\nu (1-\nu)^{1-\nu} p_t^{-\nu} \left( (1+b_t)^{-\nu} b_t p_t \frac{\partial y_P^S}{\partial p_t} + ((1+b_t)^{1-\nu} - 1) \frac{\nu Y_{NPt}^S}{p_t} \right) \\ &= \widehat{\omega}_t \xi^S \left( \frac{A_{dt}^S}{A_{Pt}^S} \right)^\varepsilon \frac{\partial y_P^S}{\partial p_t} - \widehat{\phi}_t \frac{\partial s_{Pt}^S}{\partial p_t} \end{aligned} \quad (27)$$

where  $\widehat{\omega}_t$  is the shadow value of a unit of environmental quality at time  $t$  (in units of consumption at time  $t$ ) and  $\widehat{\phi}_t$  is the shadow value of moving an additional scientist in the South from the nonpolluting sector  $NP$  to the polluting sector  $P$ . In this expression, the left-hand side has the sign of  $b_t$ , which shows that the social planner imposes a wedge between relative prices in the North and in the South. This wedge is generated by an environmental motive (the first term on the right-hand side) and an innovation motive (the second term). The first term is always positive. A positive trade tax on good  $P$  imposed by the North reduces its relative price in the South, which decreases its production there and emissions. The second term is generally also positive as there is typically too much innovation in sector  $P$  in the South ( $\phi_t < 0$ ) for two reasons. First, more innovation in sector  $P$  in the South leads to more emissions. Second, to avoid a disaster—which the

social planner generally does—the South must at least asymptotically fully specialize in sector  $NP$ , so that current innovations in sector  $P$  will be of little use in the future. Because of their myopia, Southern innovators do not internalize this and their innovation efforts are tilted too much toward sector  $P$ . By reducing the production of good  $P$  in the South, a positive trade tax moves Southern scientists away from sector  $P$ . Therefore, the trade tax is generally positive; it takes the form of a tariff when the North imports good  $P$  and of an export subsidy otherwise. The next proposition further characterizes the optimal policy (proof in Appendix A.13).

**Proposition 5.** (i) *For a sufficiently high initial environmental quality  $S_0$ , the social planner avoids a disaster if the inverse elasticity of intertemporal substitution  $\eta \geq 1$ ; or if  $\eta < 1$  and the discount rate  $\rho$  is sufficiently low. The South must asymptotically be fully specialized in the nonpolluting sector if initially clean technologies are less developed than dirty ones there ( $A_{c0}^S \leq A_{d0}^S$ ).*

(ii) *If  $A_{c0}^S \leq A_{d0}^S$ ,  $S_0$  is sufficiently high,  $\rho$  is sufficiently small, and  $\eta \leq 1$ , then the mass of scientists allocated to clean technologies in the North is asymptotically 1, both countries fully specialize and the optimal trade tax reaches 0 in finite time.*

Since the North cannot fully control the Southern economy, avoiding a disaster may not be feasible when  $S_0$  is low. Yet, when it is feasible, a social planner will do so if the elasticity of intertemporal substitution  $\eta \geq 1$  (as then a disaster brings a utility of  $-\infty$ ), or if  $\eta < 1$  and the discount rate is sufficiently low (as then the social planner maximizes long-run utility growth and  $S = 0$  is an absorbing state). To avoid a disaster, the South must asymptotically fully specialize in sector  $NP$ , and production of good  $P$  in the North must be limited or a switch to clean innovations must occur. Statement (ii) specifies *sufficient* conditions under which innovation does indeed switch to mostly clean innovation in the North. The optimal policy maximizes long-run growth when  $\eta \leq 1$  and the discount rate is low enough. Long-run growth, in return, is maximized if the North asymptotically innovates only in clean technologies and the South in sector  $NP$ , in this case both countries fully specialize in finite time and the trade tax reaches 0 (since environmental quality can fully recover, the optimal carbon tax also reaches 0 but this result may not extend to different law of motions for environmental quality).

In the problem considered so far, the social planner cares equally about consumption in the North and the South. This allows to separate climate

issues from redistribution issues. An alternative set-up is to consider that the economy admits infinitely lived representative agents in each country, whose utilities are given by  $\sum_{t=0}^{\infty} (v(S_t) C_t^X)^{1-\eta} / ((1-\eta)(1+\rho)^t)$ . The social planner maximizes a weighted sum of these utilities:

$$U = \sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} \frac{v(S_t)^{1-\eta}}{1-\eta} \left( \Psi (C_t^N)^{1-\eta} + (1-\Psi) (C_t^S)^{1-\eta} \right), \quad (28)$$

where  $\Psi \in [0, 1]$  is the weight on the North's representative agent. Then, the social planner also cares about the distribution of consumption. Appendix A.14 discusses this approach and solves for this case. The first-best is identical up to lump-sum transfers between the two countries. The second-best is similar, but the trade tax must now also reflect terms-of-trade issues and it is modified so as to favor the country with the largest social marginal value of consumption. If the social planner cares only about the North ( $\Psi = 1$ ), then this motive pushes toward a tariff when the North imports good  $P$  and an export tax otherwise. If the social planner cares equally about both countries ( $\Psi = 1/2$ ) but the South is poorer, then it pushes toward an import or an export subsidy. Proposition 5 still applies, except that full specialization may only occur asymptotically and the trade tax may not asymptote 0 (because of terms-of-trade motives).

#### 4.3. Parameter Choices

Here, I briefly describe the parametrization; details are given in Appendix A.15. A period corresponds to 5 years, and initial values are based on the 2003–2007 world economy while assuming *laissez-faire* in both countries. The elasticity of intertemporal substitution is unity ( $\eta = 1$ ). The annual time discount rate is 0.015, as in Nordhaus (2008). In line with the CGE literature, the North comprises 33 countries in Annex I of the Kyoto protocol (including the United States) and the South 18 major countries in the rest of the world. Restricting attention to manufacturing, I compute the world rate of emissions per dollar of value-added in each sector at the available aggregation level, here using data on sectoral emissions of CO<sub>2</sub> from fossil fuel combustion given by the International Energy Agency (IEA, 2010a), and data on sectoral value added by the United Nations Industrial Development Organization (UNIDO, 2011). The sectors with the highest rate are identified with sector  $P$ —namely the manufacture of chemicals and chemical products, ISIC code 24, of other nonmetallic mineral products, 26, and of

basic metals, 27—and the others with sector  $NP$ .<sup>32</sup> As already mentioned, Southern production is tilted toward sector  $P$  relative to Northern production ( $Y_{P0}^N/Y_{P0}^S \times Y_{NP0}^S/Y_{NP0}^N = 0.77$ ), so that the South has a small initial comparative advantage in sector  $P$ .

The consumption share of good  $P$  is computed using world production of both sectors:  $\nu = 0.257$ . The capital shares are  $\alpha = 0.5$  for sector  $P$  and  $\beta = 0.3$  for sector  $NP$ , here using the ratio of capital to labor compensations in both sectors in the United States according to the EU KLEMS dataset, [48], and the share of intermediates  $\gamma = 1/3$ , a common value in endogenous growth models. The elasticity of substitution between the clean and the dirty input,  $\varepsilon$  is fixed at 5, but Appendix A.16 considers the cases of  $\varepsilon = 3$  and 10. The innovation size  $\kappa$  is adjusted so that the long-run annual growth rate is 2%, and the concavity of the innovation function is fixed by choosing  $\iota = 0.55$  ( $\geq 0.5$  so that the equilibrium is unique for a small  $\kappa$ ).

The quality of the environment  $S_t$  is linearly and negatively related to the atmospheric concentration of  $\text{CO}_2$ ; the assumption that  $S_0 = \bar{S}$  is relaxed, and the initial environmental quality  $S_0$  corresponds to the atmospheric concentration in 2003-2007 (379 ppm).  $\Delta$  is chosen such that, for  $S_t = S_0$ , half of  $\text{CO}_2$  emissions are absorbed and do not add to atmospheric concentrations. Changes in atmospheric  $\text{CO}_2$  concentrations are mapped against changes in temperature, and  $S = 0$  is chosen to correspond to a disaster temperature level of 6°C. The function  $\nu(S_t)$  is the same as in AABH and mimics the cost function of Nordhaus (2008) for temperature increases up to 3°C. I identify the ratio  $Y_{c0}^X/Y_{d0}^X$  with the ratio of nonfossil to fossil fuel energy produced for country  $X$ 's primary energy supply (following IEA, 2010b). From this, I derive the ratio  $A_{c0}^X/A_{d0}^X$ . This, together with the emission rates in sector  $P$  in both countries, gives the emission rates per unit of dirty input  $\xi^X$ .<sup>33</sup>

Yet, the model is still very stylized and the numerical exercise should not be taken too literally. A more complete calibration would feature a more realistic carbon cycle, a more detailed trade model where domestic production and imports are not perfect substitutes, a nontradable sector, and some technologies in sector  $P$  common to the clean and the dirty inputs.

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<sup>32</sup>According to the model, I ignore emissions from sector  $NP$ , which corresponds to the other sectors in manufacturing (except 23, 25, 33, 36 and 37, for which data are not available).

<sup>33</sup>Overall the emission rate in sector  $P$  in the South is nearly 4 times that of the North's, so that  $\xi^S > \xi^N$ , even though  $A_{d0}^N/A_{c0}^N < A_{d0}^S/A_{c0}^S$ .

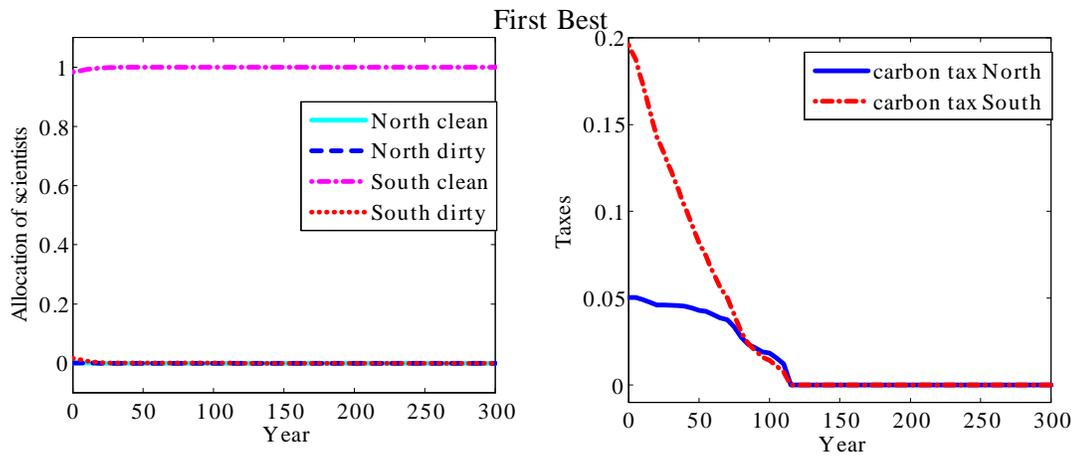


Figure 1: First-best policy. From left to right, figures: 1.A and 1.B.

Such an exercise would deserve a separate paper and is left for future research.

#### 4.4. Simulation results

Figure 1 describes the first-best policy. Figure 1.A shows that sector- $P$  innovation switches to clean technologies (here immediately), and is rapidly only carried out in the South, since both countries rapidly fully specialize (the North clean, North dirty and South dirty lines are indistinguishable from the x-axis and the scientists allocated to sector  $NP$  are not represented). This rapid full specialization results from a relatively large growth rate (2% a year), combined with a small difference in capital shares between the two sectors ( $\alpha - \beta = 0.2$ ) and a small initial comparative advantage. Either imperfect mobility of factors, cross-sector or cross-country knowledge spillovers, or imperfect substitutability between domestic and foreign goods would have the effect of slowing down the specialization process. Figure 1.B shows the *ad valorem* carbon taxes in both countries, they decline and eventually reach 0 as the environment recovers; it declines faster in the South where clean technologies catch up with dirty ones.

Figure 2 shows the second-best policy. Contrary to the first-best case, the North must now export good  $P$  in the long run. For these parameter values, a large trade tax on good  $P$  (Figure 2.B) ensures that, right from the first period, the South specializes in sector  $NP$ , and thus does not innovate in sector  $P$  (in Figure 2.A, the South clean and South dirty lines are indistinguishable

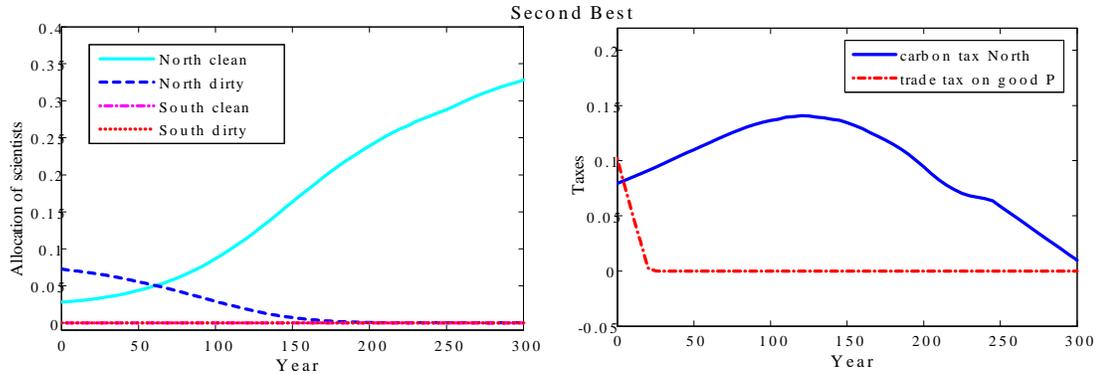


Figure 2: Second-best policies. From left to right, figures 2.A and 2.B.

from the x-axis, all Southern innovation is in sector  $NP$ ). Several factors explain this feature: the high emission rate in the South means that it should specialize rapidly in sector  $NP$ , its low initial comparative advantage that the pattern of trade is easily reversed, and its smaller size together with a small difference  $\alpha - \beta$  in factor shares between the two sectors imply that full specialization there is reached quickly. The switch from predominantly dirty to clean innovation in sector  $P$  occurs after 65 years. The switch is delayed relative to the first-best because the North starts with a lower emission rate in sector  $P$ , so that the initial temperature increase is lower, and because continuing to invest in dirty technologies helps the North build a large comparative advantage in sector  $P$ . The amount of clean innovation increases over time and, beyond the time frame of the simulation, eventually reaches one when the North fully specializes in sector  $P$  (in line with Proposition 5).

The unilateral policies which are able to avoid a disaster are quite radical since they involve a reversal in the pattern of trade, so the welfare costs from not being able to intervene in the South may be very large. Table 1 reports the welfare costs of the first-best and second best-policies, computed as the equivalent percentage loss of world consumption every period relative to the first-best case in a “miracle” scenario under which the dirty input would cease to pollute (i.e.  $\xi^N = \xi^S = 0$ ). As already emphasized, the numbers should not be taken literally considering the limits of the numerical exercise. Yet, comparing the costs of the first-best and second-best policies is still of interest: in this simple model, not being able to intervene in the South increases the welfare costs by a factor 4. The reason is that reversing the

pattern of comparative advantages leads to significant static costs in the first periods and to lower productivity levels in subsequent periods. Therefore unilateral intervention is possible here but a global one is much preferred.<sup>34</sup>

Table 1: Disaster and welfare cost

	First-best	Second-best	Third-best
Welfare cost (%)	6.36	24.64	24.75

Table 1 also presents the case of a “third” best in which the North can implement a positive carbon tax and research subsidies/taxes but cannot implement trade, consumption, or production taxes. With the calibrated parameter values it is still possible to avoid a disaster under such a policy (which is not always the case, see Remark 1), and the welfare costs of dispensing with the trade tax are small. With these parameters, the difference in initial comparative advantages is small and innovation is very effective in affecting technological levels. As a result, the North can quickly acquire a comparative advantage in sector  $P$  without the help of a trade tax by innovating more in that sector than in the second-best and implementing a low carbon tax initially. As before, the South quickly specializes in sector  $NP$ . Appendix A.16 discusses the distributional impacts and presents the case where the social planner maximizes (28).

#### 4.5. Trade and Directed Technical Change, Two Double-Edged Swords

Figure 3 shows the temperature increase for different policies when trade is allowed for and when the two countries are in autarky, in laissez-faire and under various policies. Laissez-faire leads to an environmental disaster after 50 years for the open economy case but occurs later in autarky, since economic growth is lower in that case. Under free-trade and following Proposition 2, no combination of a positive carbon tax or a tax on dirty research in the North can prevent an environmental disaster. Figures 3.A depicts the combination that minimizes CO<sub>2</sub> emissions (“Taxes on Good  $P$  in the North Only”), the curve is indistinguishable from the laissez-faire one, as it is not even possible to delay a disaster with such a policy when trade is allowed.<sup>35</sup> In contrast, in

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<sup>34</sup>This increase in cost is almost entirely due to the environmental externality. In the miracle case, the inability to intervene in the South generates welfare cost since innovation there is not allocated optimally, but these costs are very small: 0.03%.

<sup>35</sup>The dynamic aspect is key in obtaining this result, since it also holds when North and South initially have the same emission rates (when  $A_{c0}^S/A_{d0}^S = A_{c0}^N/A_{d0}^N$  and  $\xi^S = \xi^N$ ):

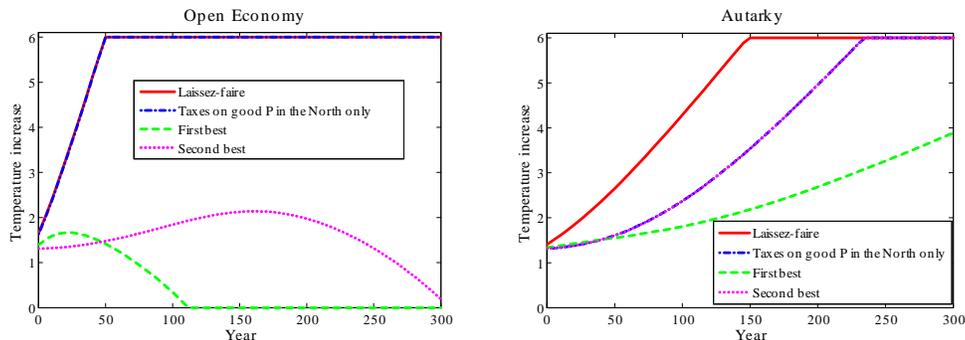


Figure 3: Temperature increase in open economy and in autarky. From left to right: Figures 2.A and 2.B.

autarky, such a policy can postpone the disaster for 85 years, as there is no pollution haven effect. The second-best curve in Figure 3.A shows how the appropriate unilateral intervention avoids an environmental disaster, while adding the same instrument (research subsidies) does not affect emissions much in autarky (in Figure 3.A, the second-best refers to the maximization of (1), while in Figure 3.B, it is the combination of research subsidies and positive carbon tax which minimizes CO<sub>2</sub> emissions). Even in the first-best case temperature increases more in autarky because the growth rate of clean technologies is lower than in the open economy scenario.<sup>36</sup> Overall, Figure 2 illustrates the double-edged nature of trade: without it, unilateral policies cannot prevent a disaster; but opening up to trade accelerates environmental degradation if the North does not undertake the appropriate policy (this relates this paper to the literature on the impact of trade on the environment, e.g. Copeland and Taylor, 1995).

Directed technical change (DTC) plays a similar role. To study it, I compare the current scenario with DTC to one in which the allocation of innovation is exogenous and equal in all subsectors ( $s_{ct}^X = s_{dt}^X = s_{NPt}^X = 1/3$ ). With the calibrated values, however, Northern taxes on the polluting good cannot postpone the disaster even in the exogenous growth case. So as

<sup>36</sup>Comparing the increase in temperature between the first-best and the second-best in the open economy case is interesting. The temperature is initially higher in the first-best because the South's emission rate is higher, but since the switch to clean innovation occurs sooner, the temperature decreases faster.

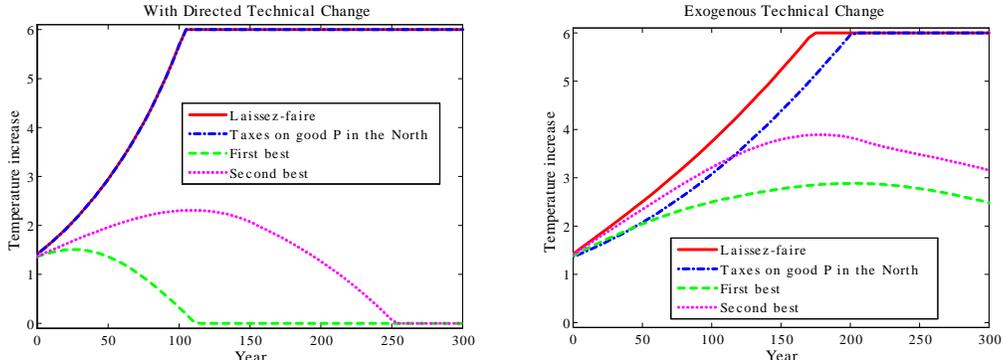


Figure 4: Temperature increase with and without directed technical change (different capital shares than in the baseline scenario:  $\alpha = 0.7$ ,  $\beta = 0.1$ ). From left to right: figures 3.A and 3.B.

to better illustrate the impact of DTC, I perform the same exercise but now assume that  $\alpha = 0.7$  and  $\beta = 0.1$ . (A larger difference in capital shares limits the pollution haven effect in a static model and therefore better illustrates how it is amplified by the innovation response.) Figure 4 shows that DTC accelerates the disaster under laissez-faire because it accelerates the economy’s growth rate. With DTC, a disaster cannot be postponed with a combination of positive carbon tax and tax on dirty research in the North: in fact the combination that minimizes  $\text{CO}_2$  emissions is no taxes. Without DTC, it is possible to delay an environmental disaster for up to 30 years with this policy because the dynamic pollution haven effect that this paper emphasizes is absent. Here, the second-best policy can avoid a disaster both with and without DTC, but without DTC, the increase in temperature is much larger—despite a much lower growth rate—and a large trade tax must be permanently maintained in order to reverse the pattern of trade.

In fact, there are parameters for which unilateral policies cannot prevent a disaster *without* DTC, regardless of initial environmental quality. To avoid a disaster, the North should be able to produce good  $P$  relying mostly on clean technologies and to force the South to asymptotically fully specialize in sector  $NP$ . The most extreme way for the North to do this is to produce only good  $P$  (with nearly only the clean input) and to give it for free to the South. Yet, without DTC, the ratio of relative productivities stay the same over time, so if initially the South has a large comparative advantage in sector  $P$ , or if clean technologies in the North are sufficiently backward,

this is not enough to push the South towards full specialization and to avoid a disaster. This thought experiment demonstrates that innovation’s ability to affect comparative advantage is essential in deriving the previous results.

## 5. Knowledge Diffusion

I now relax the assumption that productivity improvements are entirely country specific. In reality, some productivity improvements cross borders, mitigating the amplification of comparative advantage effect, which partly drove the previous results.<sup>37</sup> This brings into question the robustness of the previous analysis. Here I consider an extension of the original model whereby the lagging country can benefit from the diffusion of innovations produced in the leading country, while Appendix A.18 considers a different extension where innovation is undertaken by multinational firms so that technologies are the same in both countries.

To model knowledge diffusion in a simple way, I assume that, at the beginning of every period, the country with the less advanced average productivity in a given sector can partially catch up exogenously. That is, before any innovation occurs, the producer of intermediate  $i$  in sector  $z \in \{c, d, NP\}$  gains access to the technology  $\overline{A_{zit}^X} = \max((A_{z(t-1)}^{-X}/A_{z(t-1)}^X)^\Omega, 1)A_{zi(t-1)}^X$ , where  $\Omega \in [0, 1]$  measures the strength of the technological diffusion. This equality then delivers the following law of motion for aggregate productivity:

$$A_{zt}^X = (1 + \kappa (s_{zt}^X)^\iota)^{1-\gamma} \max \left( \left( A_{z(t-1)}^{-X} / A_{z(t-1)}^X \right)^\Omega, 1 \right) A_{z(t-1)}^X$$

for  $z \in \{c, d, NP\}$ . Under this formulation, the ratio of the technological levels across countries cannot diverge: as soon as one country acquires a strong advantage over the other one, the catching-up process ensures that this difference is reduced in the next period. Unless factor endowments are significantly different across countries, this limits considerably the scope for full specialization. Yet, the main intuitions of the baseline model carry through.

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<sup>37</sup>One should not expect all productivity improvement to cross borders easily, because some may be embedded in capital or may depend on local know-how. Dechezleprêtre et al. (2011) suggest that clean technology transfers between developing and developed countries exist but are limited: for the period 2000–2005, only 15 percent of the clean innovations were patented in more than one country; this is slightly less than the share (17 percent) of all innovations patented in more than one country.

Northern policies that foster clean innovation in the North now also increase the productivity of clean Southern technologies. They may even put the South on a clean innovation track. If, in some period, pre-innovation clean Southern technologies become more advanced than dirty ones (i.e., for some  $t$ ,  $\overline{A}_{ct}^S > \overline{A}_{dt}^S$ ), market forces will induce more clean than dirty innovations in the South from that period onwards. Preventing a disaster does not necessarily involve pushing the South toward specializing in sector  $NP$  any more; it can also be achieved by ensuring a switch to clean innovation there. That transition will occur if more scientists are allocated to clean technologies in the North than to dirty technologies in the South for a sufficient amount of time. Clean innovation in the North and dirty innovation in the South enter a horse race, which determines whether or not good  $P$  will be produced in a clean way in the long-run. Who wins depends on the policies that the North allows for and on the pattern of comparative advantage, much as in Section 3, which leads to the following result (proof in Appendix A.17).

**Proposition 6.** *Assume that initially: (i) technologies are sufficiently close to each other across countries, that  $\kappa$  is sufficiently small, and that the spillovers  $\Omega$  are sufficiently strong; (ii) the South is relatively well-endowed in capital,  $K^S/L^S > K^N/L^N$ ; and (iii) clean technologies are sufficiently less advanced than dirty ones ( $A_{c0}^S/A_{d0}^S$  sufficiently small). Then no combination of a carbon tax and a tax on dirty research in the North can prevent a disaster irrespective of how high initial environmental quality  $S_0$  is.*

This proposition mirrors Proposition 2. Assumption (i) implies that technology levels remain sufficiently close to each other across countries. When combined with assumption (ii), it ensures that the South maintains its comparative advantage in sector  $P$  (before the implementation of a carbon tax). Assumption (iii) plays the same role as in Proposition 2, ensuring that, when the South has the comparative advantage in sector  $P$ , it innovates there more than the North does. Since a carbon tax in the North can only reinforce the South's comparative advantage in  $P$  (and in fact, a carbon tax still increases Southern innovation in sector  $P$ ), there are more Southern scientists innovating in dirty technologies than Northern scientists innovating in clean ones. Hence Southern clean productivity  $\overline{A}_{ct}^S$  never catches up, so a switch in the South to clean innovation never occurs. Intuitively, the Northern market for good  $P$  is too small to generate enough clean innovations.

When the South is identified with non-Annex I countries, assumption (ii) seems less likely to hold relative to its counterpart in Proposition 2, which

only stipulates that the South has a comparative advantage in sector  $P$ —though it may hold if one interprets  $L^X$  as human capital and not simply labor. In fact, if the North has a large “endowments”-comparative advantage in sector  $P$  (that is for  $(K^N/L^N) / (K^S/L^S)$  large enough) and knowledge spillovers are strong enough, it can prevent a disaster using a combination of a carbon tax and a tax on dirty research for sufficiently high  $S_0$ . One may then argue that knowledge spillovers weaken the conclusion that Annex I countries could not prevent worldwide emissions from growing using a carbon tax only. Yet assumption (ii) could also be more generally interpreted as assuming that the South has a comparative advantage in  $P$  for reasons beyond imitable technological factors, which could include factor endowments (capital, labor but also natural resources), policies, different market distortions, etc... This broader interpretation is more likely to hold, in which case the conclusion that Annex I countries could not prevent worldwide emissions from growing without research subsidies would be reinforced.

Indeed, as before, a temporary combination of clean research subsidies and a tariff can prevent a disaster for sufficiently large initial environmental quality (i.e., Proposition 3 still holds). Clean research subsidies can reallocate Northern innovation to clean technologies, and a tariff can limit Southern innovation in dirty technologies. Then  $\overline{A_{ct}^S}$  grows faster than  $\overline{A_{dt}^S}$ , and a switch to clean innovation eventually occurs in the South.<sup>38</sup>

Table 2: Welfare cost in the presence of knowledge spillovers

	First-best	Second-best
$\Omega = 0.4$ (%)	5.71	6.92
$\Omega = 0.8$ (%)	5.95	6.58

The structures of the first-best and second-best policies are broadly similar, but the trade tax and subsidies for research must take knowledge spillovers into account, and the second-best policy may prevent a disaster with a South exporting good  $P$  in the long-run. In addition, the welfare costs of unilateral

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<sup>38</sup>Remark 1 no longer holds when clean and dirty inputs are imperfect substitutes. Because of knowledge spillovers the ratio  $A_{ct}^S/A_{dt}^S$  cannot approach zero if the North allocates all its scientists to clean technologies, so that the South always allocate some scientists to clean technologies.  $\overline{A_{ct}^S}$  becomes greater than  $\overline{A_{dt}^S}$  at some  $t$ , after which a switch to clean innovation occurs in the South. Remark 1 still holds if  $\varepsilon = \infty$ , or with a different innovation function which does not satisfy the Inada condition (such as  $\kappa((s + \Upsilon)^t - \Upsilon^t)$  with  $\Upsilon > 0$ ).

intervention are typically lower than without knowledge spillovers. Indeed, the reversal in comparative advantages, which generated the large welfare cost in the no-spillover case, may not happen, and even if it does, is much less costly since the South ends up benefiting from the technologies that the North had developed. Accordingly, Table 2 shows the welfare costs in the first-best and the second-best cases with knowledge spillovers ( $\Omega = 0.4$  and  $\Omega = 0.8$ ): the welfare costs of the first-best policy are very similar to those in Table 1, but those of the second-best policy are much lower.<sup>39</sup>

To some extent, technological diffusion itself is a parameter that can be affected by policy: laxer intellectual property rights, direct financing of projects abroad, or migrations of skilled workers could all contribute to a faster diffusion of technology. Therefore, according to the analysis presented here, the diffusion of clean technologies from North to South renders a tariff less necessary, and significantly reduces the costs of a unilateral policy.

*5.1. An extended model: knowledge spillovers, nontradables and different endowments of scientists*

The inclusion of knowledge spillovers allows to obtain non-trivial results when the economy also features a nontradable sector. I now assume that final consumption is a Cobb-Douglas aggregate of nontradable ( $C_{NT}^X$ ) and tradable goods ( $C_T^X$ ), where the consumption share of tradables is given by  $a$ , that is:

$$C^X = (C_T^X)^a (C_{NT}^X)^{1-a}. \quad (29)$$

Both goods are produced according to (2), with the associated goods  $P$  and  $NP$  (and the associated subsectors  $c$  and  $d$ ), but for the nontradable good, the polluting and non-polluting inputs must be sourced locally. The same intermediates are used whether the good is produced for the tradable or nontradable sector. In the no-spillovers case, it is impossible to prevent a disaster because Southern emissions from nontradables will increase unboundedly regardless of Northern policy. In addition, I allow for the mass of scientists in the South ( $s^S$ ) and the North to differ ( $s^N$ ). For simplicity, I focus on the case where the clean and dirty inputs are perfect substitutes ( $\varepsilon = \infty$ ).<sup>40</sup> I intro-

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<sup>39</sup>Here, the reversal of comparative advantage still takes place in the presence of knowledge spillovers because the difference in factor endowments is small.

<sup>40</sup>Focusing on this case allows to write a simpler proposition. It is possible to generalize the results provided that the initial ratio  $A_{c0}^S/A_{d0}^S$  is small enough.

duce the notations  $\underline{d} \equiv 1 + \left( \frac{1}{(1-\nu)(1-a)} - 1 \right)^{-\frac{1}{1-\epsilon}}$  and  $\bar{d} = 1 + \left( \frac{1}{\nu(1-a)} - 1 \right)^{\frac{1}{1-\epsilon}}$ , such that  $\bar{d} > \underline{d} > 1$ . Propositions 2 and 3 are then modified according to the following proposition (proof in Appendix A.19).

**Proposition 7.** *Assume that  $\kappa$  is sufficiently small and that dirty technologies are initially more advanced than clean ones in both countries.*

- a) *No combination of a carbon tax and a tax on dirty research in the North can prevent a disaster irrespective of how high initial environmental quality  $S_0$  is, provided that knowledge spillovers  $\Omega$  are strong enough and -either i) the South is relatively well-endowed in capital ( $K^S/L^S > K^N/L^N$ ) and  $s^S \geq s^N$ ;*
- *or ii)  $(K^N/K^S)^\alpha (L^N/L^S)^{1-\alpha}$  is small enough,  $(K^N/K^S)^\beta (L^N/L^S)^{1-\beta}$  is large enough, and  $s^N/s^S < \bar{d}/\underline{d}$ .*
- b) *A combination of a carbon tax and a tax on dirty research in the North can prevent a disaster if  $S_0$  is high enough and  $s^N/s^S > \bar{d}/\underline{d}$ .*
- c) *Research subsidies in the North alone can prevent a disaster if  $S_0$  is high enough and  $s^N/s^S > 1/\underline{d}$ .*
- d) *Unilateral policies can never prevent a disaster if  $s^N/s^S < 1/\bar{d}$ .*

Therefore, the logic of Proposition 2 carries through. A carbon tax is generally unable to prevent a disaster particularly when the South has a large comparative advantage in sector  $P$ . It is only if the North has much more innovation resources than the South that such a policy may succeed regardless of the pattern of comparative advantage. In addition, since  $\bar{d}/\underline{d}$  increases in  $a$ , a larger share of tradables makes it more likely that a carbon tax fails. Proposition 3 survives as long as the North innovation resources are not too small relative to the South. Otherwise, and especially if the share of tradables is small, it may be impossible to prevent a disaster with any unilateral policies, as the South innovates more in dirty for its nontradable sector than the North innovates in clean, preventing clean technologies from catching up.<sup>41</sup>

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<sup>41</sup>The assumptions that  $\kappa$  is small and that  $\epsilon = \infty$  allow to derive exacts expressions regarding the thresholds  $\bar{d}/\underline{d}$ ,  $1/\underline{d}$  and  $1/\bar{d}$ , otherwise the expressions are more complicated (see the proof). Part c) of the proposition characterizes a range of parameters for which a disaster can be avoided with research subsidies only, allowing for a trade tax expands this range (within the limit of part d).

## 6. Conclusion

On the backdrop of a literature on trade and the environment, which has largely ignored innovation, this paper presents a simple model which puts innovation at the center. It shows that when evaluating the long-term consequences of unilateral environmental policies, it is essential to consider their impact on the allocation of innovation within the polluting sector between technologies (clean/dirty) and between countries (intervening/non-intervening). The propositions in the text model-specific but they allow to illustrate fundamental intuitions. First, the pollution haven effect becomes worse in a dynamic setting. Positive taxes on the polluting sector in the North risk placing the economy on a path that leads to the South having a comparative advantage in the polluting sector. This leads to the relocation of not only the production of the polluting good but also of innovation in that sector, which dramatically hampers the benefits of such a policy on worldwide emissions. The South innovates more in dirty technologies, while innovation in clean technologies in the North does not take off because the market share for the polluting sector is reduced. Second, sustainable growth can be achieved without cooperation from the South, but this requires a “green industrial policy” (with clean research subsidies and perhaps a trade tax) in order to ensure that there is more clean than dirty innovation worldwide. Such a policy can guarantee that either the North acquires a long-run comparative advantage in the polluting sector, or, with knowledge spillovers, that a switch towards clean innovation occurs in the South.

Therefore, in practice, the paper argues that unilateral environmental policies should be devoted to developing clean technologies, which have the potential to reduce emissions in the North, but also in the South either through technology diffusion or by slowing down the move of polluting industries there. These policies should be thought of as transitory until a satisfactory global agreement is reached. The paper aims at analyzing what “well-intentioned” countries should do until then, and therefore, as a first step, it has taken as given the absence of such an agreement. The next logical step is to analyze why some countries are willing to participate and others are not, and how unilateral policies shape their intentions in the long-run. This is, however, a complex issue as the incentive to sign a global agreement depends on the benefit that the reluctant country would get from it. Unilateral policies can affect this potential benefit in at least three dimensions: by decreasing environmental damages which discourages a reluctant country

from joining (the free-rider problem), by developing clean technologies which can diffuse and therefore reduce the costs of an environmental policy for the reluctant country, and by affecting comparative advantages and therefore the impact of a potential environmental policy on the reluctant country's terms of trade (as analyzed in a static framework by Copeland and Taylor, 2005).

Another aspect left for future research is to study policies that directly boost technological diffusion. Such policies (e.g., the clean development mechanism) are already part of climate negotiations. Studying technological diffusion would, however, require a proper model of intellectual property rights (IPR), whose impact on emissions is ambiguous. On the one hand, laxer IPR could lead to more rapid diffusion of clean technologies to the South, which would facilitate the switch to a clean path there. On the other hand, they might reduce the incentives to develop Northern clean technologies in the first place. Finally, the paper's results suggest that directed technical change renders Southern emissions much more responsive to Northern policies in the long run. This finding calls into question existing estimates of the carbon leakage rate obtained from static models. To properly evaluate the impact of local carbon taxes and carbon tariffs, numerical models of the world economy should incorporate directed technical change.

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